The Role of Damping in Ultrasonic Friction Reduction

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***Abstract*— We observed the dynamic interaction between a fingertip and an ultrasonically vibrating plate using Laser Doppler Vibrometry in order to investigate the causes of ultrasonic friction reduction. Observations were made both for a human finger and for artificial fingertips constructed to exhibit different amounts of damping. The data suggest that fingertip dynamics play an important role in friction reduction. In particular, the fingertips were all found to oscillate at the same fundamental frequency as the plate with a phase shift apparently related to damping. These results are reflected in a model.**

I. INTRODUCTION

Several approaches to surface-haptic devices, which display haptic stimuli to the bare fingertip, make use of ultrasonic vibrations either to manipulate friction or to apply shear forces to the skin [1], [2], [3]. The mechanics of skin-surface interaction in the presence of high frequency vibrations (in the tens of kilohertz) are, however, poorly understood. To enable more carefully controlled experiments than are possible with the human finger, we have recently turned to the use of artificial fingertips. Artificial fingertips have been described in the literature [4] and are available commercially [5]. Many of these designs use silicone rubber to approximate the softness of human tissue under slow deformation. At the higher frequencies of interest here, differences between the mechanical characteristics of human tissue and those of rubber become clearly apparent. Specifically, most rubber fingers experience little or no friction reduction in the presence of transverse vibrations, in stark contrast to the order of magnitude reduction experienced by human fingers [6].

We are motivated to develop artificial fingertips that behave dynamically much like a human fingertip in order to improve understanding and design of surface haptic devices such as the TPad [1]. Additionally, having an artificial finger that does *not* experience friction reduction on a TPad helps elucidate the relevant characteristics of fingers that allow friction reduction to happen in the first place. This is of particular importance because, at present, there are several competing theories that strive to explain the friction reduction effect. These are discussed next.

A. *Theories of Friction Reduction*

The most commonly cited explanation for friction reduction via transverse ultrasonic vibration is based on squeeze film theory [7], [2]. At high frequencies, air does not have time to escape from between the vibrating plate and the surface of the object contacting it, and instead acts as a spring-like lubricating layer between the two surfaces. This effect has been well studied with smooth flat plates in opposition [8], but less so with rough, compliant surfaces such as fingertips. Moreover, it has recently been shown that the predictions of the theory are a relatively poor match to data [9].

An alternative to the squeeze film is that the surface of the finger bounces on the vibrating surface, and this intermittent contact leads to lower overall friction [10]. Previous work using Laser Doppler Vibrometry simultaneously tracked the surface of vibrating glass and a finger in contact [3], and found that the finger surface moves relatively out of phase with the glass, as if it were bouncing.

The behavior of a ball bouncing on vibrating surface has been extensively studied in the dynamical systems literature [11], [12], [13], [14]. In this system, a ball sits on a sinusoidally vibrating surface. At low surface amplitudes, the ball stays in contact with the vibrating surface, but as the amplitude increases, the ball starts to detach from the surface at the top of the peaks, resulting in a slight phase shift of the ball trajectory from the surface trajectory. At even higher amplitudes, the ball can fall into a stable bouncing mode where it bounces off the tops of the peaks, and at even higher amplitudes it will switch to a period doubled orbit; this is known as the period-doubling path to chaos. Both period one and period two bouncing are also seen in [3]. Interestingly, the type of periodic or chaotic path the ball follows depends only on the coefficient of restitution, i.e. damping, and the violence of vibration (a combination of amplitude and frequency), as well as initial conditions.

B. *Role of Damping*

Unlike rubber, the human finger is heavily damped [15]. Previously, we have shown that this damping may play a crucial role in friction reduction. Two types of artificial fingers constructed from very elastic rubber experienced little to no friction reduction on ultrasonically vibrating plates, while a heavily damped artificial finger saw drastic decreases in friction in line with that experienced by human fingers [6]. Several artificial fingers used in these friction reduction experiments with divergent behavior differed only in the material of the 1mm thick artificial skin. These artificial skins were similar in stiffness but had very different coefficients of restitution, suggesting that the damping properties of the tissue plays a large role in the the finger behavior.

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Yet, while we suspect damping properties affect friction reduction, the exact mechanism remains unknown. Since we know that damping also affects bouncing behavior in the bouncing ball problem, and the phase and amplitude of bouncing determine the average distance between the interacting surfaces, we have hypothesized that damping affects the friction *indirectly* by influencing how the finger bounces (or doesn't bounce) on the surface. In the remainder of this paper, we present both experimental data and model results that aim to elucidate this hypothesis.

II. Fabricated Apparatus

A. Artificial Fingers

For this study, two artificial fingers were constructed. Both fingers were built with an aluminum core, soft sponge filling, and 1mm thick rubber skin layer. The rubber material between the two fingers differed: while of similar stiffness, the finger that experienced little friction reduction was constructed from highly elastic DragonSkin (SmoothOn Inc, Easton PA, USA), a moldable silicone rubber, and the finger that experienced significant friction reduction was constructed from more heavily damped TangoPlus (Stratasys Ltd., Eden Prairie, MI, USA), a 3D printed rubber-like material. Our previous work with fingers of this construction shows that using different skin materials results in very different coefficients of restitution (CoR) when a weight is dropped onto the finger at a similar speed of an ultrasonically vibrating plate; moreover, this value correlates well with the amount of friction reduction the finger experiences [6]. Relevant parameters from these experiments are shown in Table I.

TABLE I
FINGER CHARACTERISTICS [6]

Finger	skin hardness	Linearized Stiffness (N/mm)	CoR	% Friction Reduction
Tango Plus	27 Shore A	0.55	0.00	89.7%
Dragon Skin	20 Shore A	0.55	0.32	18.9%
human finger[4]	≈20 Shore A	0.33	0.17	70.2%

We assume the coefficient of restitution is inversely proportional to how damped the finger is on impact [16], [17], and hereafter explore the damping properties of the artificial and real fingers.

B. TPad

The TPad used in the following experiments consists of a pane of glass driven at 32112 Hz in the normal direction by piezo-actuators glued to the surface. This specific frequency corresponds to a resonant frequency of the glass, in order to maximize amplitude for a given voltage to the piezos. Voltage range was limited by the range of our amplifier to +/- 200 V, corresponding to an amplitude of +/- 1.3 μm.

III. Experiment 1: Extracting Damping Term

We measured the impedance of the finger using the TPad by assuming that at low amplitude, the finger and plate stay in contact, an assumption that was later borne out with laser Doppler vibrometry data. With this assumption, we can treat the vibrating plate as a mass-spring-damper system in which the contacting finger merely contributes to the parameter values; see Fig. 1.

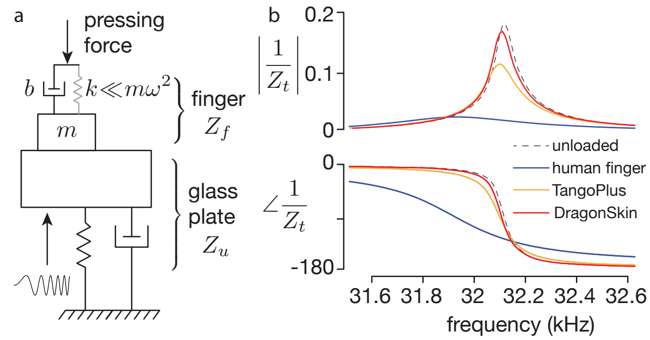

Fig. 1. a. Diagram of the measurement procedure. b. Admittance plots used for extracting dynamic parameters of the each fingertip.

During measurements, each finger was held against the 63g TPad with 0.5 N normal force, and the frequency of excitation was swept from 30 to 34 kHz while magnitude and phase of the velocity of the system were measured. The voltage sent to the piezos was 2 Vpp, corresponding to a displacement amplitude ≈ 10 nm at the resonant frequency. Impedance of the finger Z_f at the vicinity of the resonant frequency is obtained by subtracting the unloaded impedance of the TPad, Z_u from the loaded impedance Z_l:

$$Z_f = Z_l - Z_u \tag{1}$$

The admittance plot presented in Fig.1b unequivocally shows a reduction of the resonant frequency of the coupled finger-TPad system. In the limited frequency bandwidth of excitation, the finger can be approximated by a mass-spring damper system such as:

$$Z_f = b + i(m\omega - k/\omega) = |Z_f| \exp(i\angle Z_f) \tag{2}$$

As the resonant frequency of the loaded system is lower than that of the unloaded case, we can safely assume that the contribution of the stiffness of the finger is small compared to the inertia. Mass and damping added to the TPad by the finger can be recovered from:

$$m \approx \Im(Z_f)/\omega \qquad \text{and} \qquad b = \Re(Z_f) \tag{3}$$

The experimental data show that the mass for TangoPlus, Dragonskin, and human finger are 0.04g, 0.02g and 0.4g respectively. Using the excitation frequency of the TPad, normalized damping values for the TangoPlus, Dragonskin, and human finger can be calculated as $\bar{b} = b/(2m\omega) = 0.60$, 0.13, and 0.53, respectively. These damping values reflect the findings of [6], as the TangoPlus is the most heavily damped of the fingers and also the most sensitive to friction reduction. Conversely, DragonSkin is under-damped and its friction is barely affected by ultrasonic vibration.

IV. Experiment 2: Tracking Finger Position

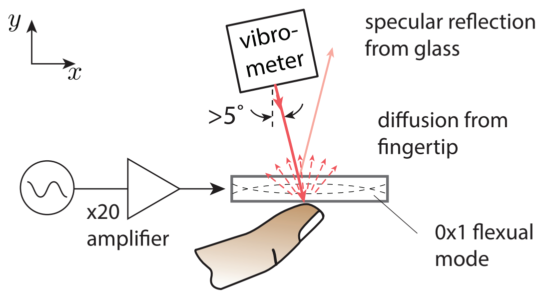

Fig. 2. A schematic of the setup for LDV measurements. A voltage of +/-200V excites piezo actuators on the glass, causing it to vibrate vertically. The LDV laser and surface of the glass are kept at a slight angle to avoid reflections off the glass interfering with reflections off the finger surface.

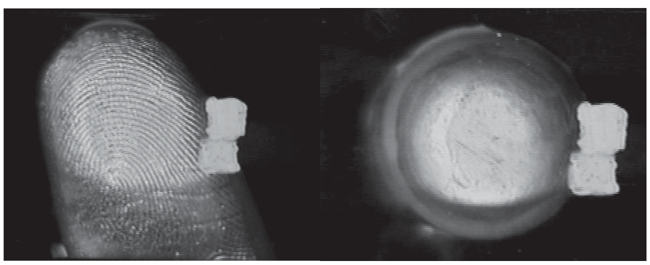

Fig. 3. Closeup of the human and TangoPlus finger touching the glass plate during measurements. Painted silver squares for tracking glass movement can be seen on the right.

A. Laser Doppler Vibrometer setup

A Polytec scanning Laser Doppler Vibrometer (LDV) was used to track the velocity of the TPad surface as well as the velocity of the finger. The finger was placed touching the glass from underneath, with the laser looking down from above, as demonstrated in Fig. 2. A small square patch of silver paint was applied to the underside of the glass, as well as to the surface of the finger in order to reflect the laser light off these surfaces. It should be noted that not only does is the silver paint necessary in order to reflect adequate amounts of light for measurement, it also ensures that all fingers have the same material interface with the glass. Additionally, the glass was tilted at a slight angle (< 5 degrees) to avoid direct laser reflections off the glass itself.

All fingers were placed lightly touching the TPad surface; exact force measurements were not made in these experiments. However, the two artificial fingers have previously been determined to have quasi-static stiffnesses similar to that of the human finger [6], and so finger contact area on the glass was kept consistent.

The LDV recorded the velocity of single points both on the silver patch on the glass and within the contact patch area of the finger. We then integrated the velocity signal to find the position of both surfaces as a function of time. By syncing measurements to the sinusoidal voltage input going to the piezo actuators moving the glass, we were able to align the data for each point in time. However, since we obtain position data by integrating the velocity, we do not know the exact vertical position shift between data points. Using the fact that the finger cannot penetrate the glass, we shift the finger position data downwards so that the two signals do not overlap.

B. DragonSkin Dynamics

Data points taken close to the center of the DragonSkin finger were much closer to being in phase with the glass compared to the other fingers; see Fig. 4 left column for two representative traces. While the vertical shift between the two surfaces can only be surmised due to velocity integration, the in-phase motion leaves open the possibility that the surfaces could be quite close or even touching.

C. TangoPlus Dynamics

Data points of the TangoPlus contact area are shown in Fig. 4 center column. The surface of this artificial finger was always almost completely out of phase with the glass, resulting in only short periods of time when they could come into close contact. Period doubling sometimes also occurred.

D. Human Finger

While LDV data from the artificial fingers was remarkably consistent day to day, the human finger was much more variable. Depending on the trial, the position traces often appeared jagged and contained high frequency content, or sometimes tracked the surface of the plate. However, several points also showed patterns of movement remarkably similar to that seen with the TangoPlus finger, and also matching that seen in previous work [3]. Inconsistent data could be due to the sweat that quickly builds up between the finger and glass and interferes with reflection, or due to the uneven surface of the finger, which exhibits roughness at a wide range of length scales.

V. Modeling Finger-TPad Interaction

A. The Model

In order to model the fingertip interacting with a vibrating glass surface, we treated the fingertip itself as a mass-spring-damper system with an applied load F_a. In the absence of compelling reasons to treat the tissue mechanics as nonlinear, we chose a linear model for simplicity. We further treated it as a disk shaped piece of tissue with radius L and thickness w. The fingertip mass rests on a flat surface vibrating with amplitude h and frequency ω, and is assumed to have an initial gap u_o between the two surfaces due to small asperities on the finger (although this gap is adjusted in the simulation in the manner described below) [18]. We ignored the fingertip dermal ridges because the length scale for lateral displacement of air at TPad amplitudes and frequencies is less than the width of a ridge. In addition, the crevices between ridges are deep enough that they contribute little to the squeeze film pressure. Thus, it is sufficient to treat

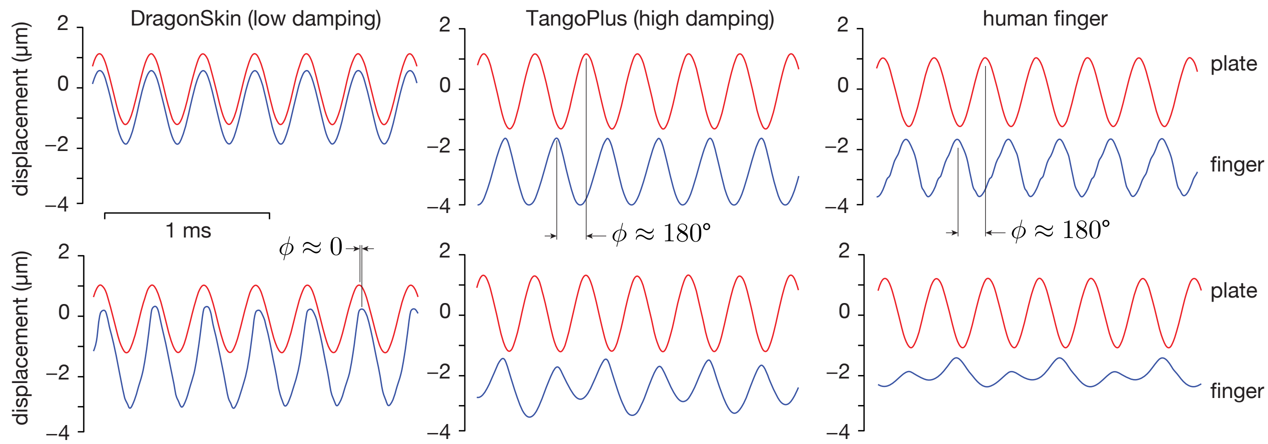

Fig. 4. Representative traces of movement for DragonSkin, TangoPlus, and human finger. For each plot, TPad surface is shown in red, and the finger position underneath the TPad is in blue. Note that absolute position is not known, so the actual surfaces could be further apart than shown here.

the true area of the fingertip as the contact area of the ridge crests, and to ignore other effects associated with the ridges. A schematic of the model is shown in Fig. 5.

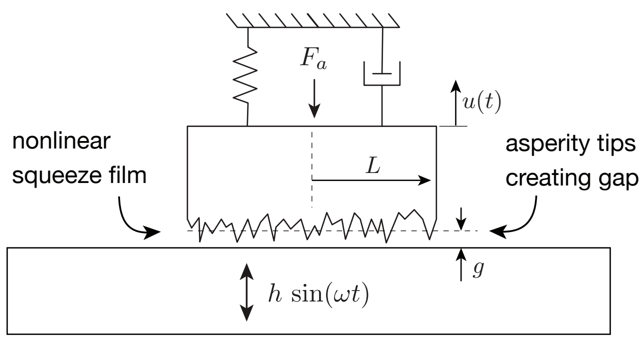

Fig. 5. Schematic of the Model.

The model was nondimensionalized. The actual tissue pressure is $P_T = P_{atm} + F_a/(\pi L^2)$, resulting in a normalized tissue pressure of $\hat{P}_T = P_T/P_{atm}$. Similarly, an inertia number was defined as $I = P_{atm}/(\omega^2 \rho w)$, where ρ is the density of tissue, leading to a normalized inertia number of $\hat{I} = I/dh$, where dh is the characteristic vertical dimension.

Due to a high "squeeze number" associated with fluid flow in the gap between the finger and TPad, we assumed that the squeeze film pressure obeyed Boyle's Law rather than the full Reynolds Equation [8]. With Boyle's Law, pressure is inversely proportional to gap, essentially acting as a highly nonlinear spring. Thus, in our model "bouncing" does not refer to skin-surface contact, but rather to a high degree of compression of the air in the gap. An issue with the use of Boyle's Law, however, is the initial condition: what gap thickness corresponds to atmospheric pressure? In a note that was published along with Salbu's classic paper on the squeeze film effect [8], Malanoski and Pan used a mass content rule along with periodicity to derive a solution. While their solution assumed a sinusoidally varying gap and cannot be used directly, we were able to derive a similar condition that can be applied to the average gap:

$$\hat{P}\,.\,g = \sqrt{\langle g^3 \rangle / \langle g \rangle} \tag{4}$$

where $\hat{P}$ is the squeeze film pressure, g is the instantaneous gap between the two surfaces and $\langle \ldots \rangle$ the time average operator. This condition is enforced by feedback in our simulation. The amount of air in the gap was slowly adjusted until this condition was met. While a full discussion of the mass content rule is beyond the scope of this paper, we note that, when the plate is not moving, the gap and average gap are the same, and normalized $\hat{P}$ simply equals 1.

Combining the tissue dynamics, tissue pressure and air pressure results in the following normalized dynamical equation for the finger displacement:

$$\ddot{u} = -2\zeta\omega_n \dot{u} - \omega_n^2 (u - u_o) + (\hat{P} - 1)/\hat{I} - \hat{P}_T/\hat{I} \tag{5}$$

Where u is the normalized vertical displacement of the finger, ζ is the damping ratio of the tissue, and ω_n is the natural frequency of the tissue, normalized to the frequency of the TPad.

B. Model Results

Even with a fairly simple model, the number of parameters quickly multiplies and values must be chosen for each. For the following simulations, we chose $F_a = 0.5$ N and $h = 1$ μm, in the range of forces and amplitudes used in experimental data collection. The relevant tissue mass was assumed to be a 1cm diameter disk, corresponding to the average contact area in experiments, 5mm thick, corresponding to the distance from the finger surface to bone, and with density of 1kg/m^3.

For the purposes of simulation, we selected $\omega_n = 1$. This choice is somewhat arbitrary since we do not have a direct measurement, and therefore bears additional investigation in the future. Nonetheless, we have reason to believe that this is a reasonable value. In a distributed system such as the fingertip, there are typically many resonant frequencies, each corresponding to a distinct mode shape. Of course, the finger is highly damped, so the concept of mode shape cannot be strictly applied, but we would nonetheless expect to find numerous damped resonances at frequencies close to the excitation frequency, and by selecting $\omega_n = 1$ we are effectively saying that one of those damped resonances dominates the finger's relevant dynamic behavior. Additionally, this value is consistent with stiffness based on the bulk compressibility of human tissue (roughly that of water). It makes sense that, especially near the center of the contact patch, the response would be dominated by bulk compressibility, and therefore compression waves. This is because shear waves travel slowly enough through tissue that they are unable to contribute to tissue displacement near the center of the contact patch, leaving only compression effects. Near the edge of the contact patch, shear effects would be expected to be much more prominent, leading to much lower mechanical impedance. This is consistent with our observation that the skin tends to track the TPad at the edge of the contact patch, which will be reported in a future publication.

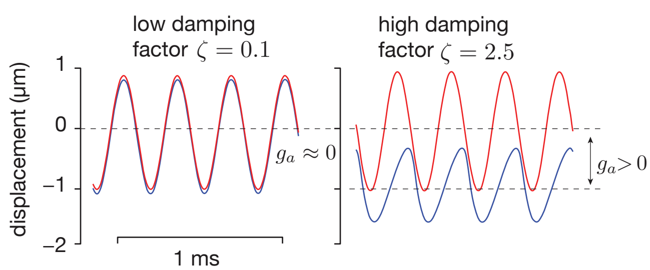

Fig. 6. Results from simulation. In phase bouncing observed with low damping value. High damping values reveal out-of-phase motion.

Having fixed tissue thickness and ω_n, we examined the effect of varying the damping ratio ζ. Simulation results for $\zeta = 0.1$ and 2.5 are show in Fig.s 6.

By shifting the phase of finger motion as we increase ζ, the model also demonstrates the corresponding increase in the average gap between the finger and plate, which has a direct effect on friction.

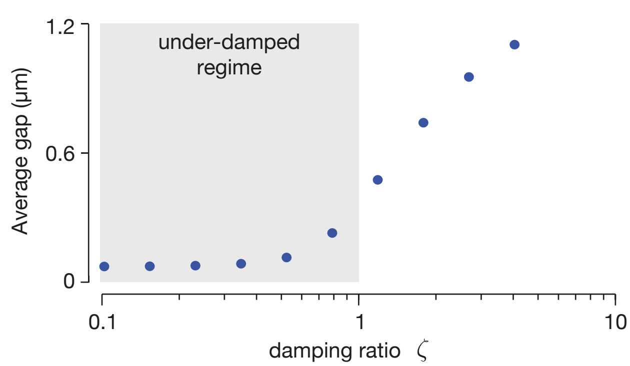

Fig. 7. Model dependence of average gap on zeta.

VI. Discussion

Experiment 2 and the model both demonstrate that by increasing the damping of a finger, artificial or real, we can expect to see a corresponding change in the bouncing behavior on an ultrasonically vibrating plate. In both experimental data and simulation results, this change appears as a shift in phase of the finger oscillations with respect to those of the plate. Additionally, in simulation the change in phase corresponds to an increases in average gap between the two surfaces as shown in Fig. 7. An increase in average gap would lead to fewer asperities in contact and, therefore, lower friction. This decrease in friction for more heavily damped fingers has been shown experimentally in [6].

Of course other factors beside damping may be at play and warrant further investigation. For instance, different amounts of surface roughness would change the amount of air initially under the finger and may impact the amount of friction reduction. Similarly, the adhesive properties of the surface may play a role (although that was controlled in our experiments by painting all fingertips with the same refletive paint). Nonetheless, our results make a strong case that fingertip dynamics, and especially damping, play a role. We find it compelling that, both experimentally and in our model, increases in damping dependably led to greater friction reduction.

A significant limitation of the model is that it depends on several parameter values that are difficult to measure. For instance, we are currently not able to measure the effective mass and stiffness of the finger at the frequencies of interest. Moreover, varying ω_n, ζ, tissue thickness w and applied force F_a results in several regions of parameter space that show behavior similar to that seen in experimental LDV data. Ongoing work will focus on further exploring this parameter space and refining the model.

Another rich vein to explore experimentally is the dependence of the relative phase on vibration amplitude. Our preliminary results from ongoing experiments suggest that phase shift increases with amplitude, as would be expected as the finger switches from sticking to bouncing on the plate surface. Of course, friction also decreases with increasing amplitude. A clear relationship between phase and friction levels could help confirm that out-of-phase motion is playing a crucial role in friction reduction. Additionally, further exploration of the dependence of finger bouncing on amplitude would help guide fitting our model to experimental data.

We would also like to study multiple subjects in future work. Anecdotally, some people report not being able to feel the friction reduction effects on TPads. We often attribute this to different levels of sweat the users exude, or perhaps decreased sensitivity. However, considering the impact that mechanical properties of tissue can have on friction reduction behavior, it would be interesting to explore the range of mechanical differences between subjects' fingers and their relationship to friction reduction levels.

VII. Conclusions

While it is difficult to completely isolate damping, the data presented here and in past work [6], as well as the model predictions, point to its possible importance in friction reduction. The damping coefficient of a finger may have an indirect impact on friction by changing the way it bounces on the vibrating plate, specifically by shifting the phase, increasing the average gap between the two surfaces and thereby decreasing the real area of contact.

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REFERENCES

[1] L. Winfield, J. Glassmire, J. E. Colgate, and M. Peshkin, "T-pad: Tactile pattern display through variable friction reduction," in *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint*. IEEE, 2007, pp. 421–426.

[2] M. Biet, F. Giraud, and B. Lemaire-Semail, "Squeeze film effect for the design of an ultrasonic tactile plate," *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, vol. 54, no. 12, pp. 2678–2688, 2007.

[3] X. Dai, J. E. Colgate, and M. A. Peshkin, "Lateralpad: A surface-haptic device that produces lateral forces on a bare finger," in *Haptics Symposium (HAPTICS), 2012 IEEE*. IEEE, 2012, pp. 7–14.

[4] D. Roy, N. Wettels, and G. E. Loeb, "Elastomeric skin selection for a fluid-filled artificial fingertip," *Journal of Applied Polymer Science*, vol. 127, no. 6, pp. 4624–4633, 2013.

[5] N. Wettels, V. J. Santos, R. S. Johansson, and G. E. Loeb, "Biomimetic tactile sensor array," *Advanced Robotics*, vol. 22, no. 8, pp. 829–849, 2008.

[6] R. Fenton Friesen, M. Wiertlewski, M. A. Peshkin, and J. E. Colgate, "Bioinspired artificial fingertips that exhibit friction reduction when subjected to transverse ultrasonic vibrations," in *World Haptics Conference (WHC), 2015 IEEE*. IEEE, 2015, pp. 208–213.

[7] T. Watanabe and S. Fukui, "A method for controlling tactile sensation of surface roughness using ultrasonic vibration," in *Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on*, vol. 1. IEEE, 1995, pp. 1134–1139.

[8] E. Salbu, "Compressible squeeze films and squeeze bearings," *Journal of Fluids Engineering*, vol. 86, no. 2, pp. 355–364, 1964.

[9] T. Sednaoui, E. Vezzoli, B. Dzidek, B. Lemaire-Semail, C. Chappaz, and M. Adams, "Experimental evaluation of friction reduction in ultrasonic devices," in *World Haptics Conference (WHC), 2015 IEEE*. IEEE, 2015, pp. 37–42.

[10] L. Winfield and J. E. Colgate, "Variable friction haptic displays," in *Haptic rendering: Foundations, algorithms and applications*, M. C. Lin and M. Otaduy, Eds. AK Peters, Ltd., 2008.

[11] P. J. Holmes, "The dynamics of repeated impacts with a sinusoidally vibrating table," *Journal of Sound and Vibration*, vol. 84, no. 2, pp. 173–189, 1982.

[12] N. Tufillaro, T. Mello, Y. Choi, and A. Albano, "Period doubling boundaries of a bouncing ball," *Journal de Physique*, vol. 47, no. 9, pp. 1477–1482, 1986.

[13] J. J. Barroso, M. V. Carneiro, and E. E. Macau, "Bouncing ball problem: stability of the periodic modes," *Physical Review E*, vol. 79, no. 2, p. 026206, 2009.

[14] N. B. Tufillaro, T. Abbott, and J. Reilly, *An experimental approach to nonlinear dynamics and chaos*. Addison-Wesley Redwood City, CA, 1992.

[15] M. Wiertlewski and V. Hayward, "Mechanical behavior of the fingertip in the range of frequencies and displacements relevant to touch," *Journal of biomechanics*, vol. 45, no. 11, pp. 1869–1874, 2012.

[16] K. Hunt and F. Crossley, "Coefficient of restitution interpreted as damping in vibroimpact," *Journal of applied mechanics*, vol. 42, no. 2, pp. 440–445, 1975.

[17] R. M. Brach, "Mechanical impact dynamics: rigid body collisions," 1991.

[18] J. Greenwood and J. Williamson, "Contact of nominally flat surfaces," in *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, vol. 295, no. 1442. The Royal Society, 1966, pp. 300–319.