Perception of Friction-Related Cues Induced by Temperature Variation on a Surface Display

Matej Mayet, Jean-Loïc Le Carrou, David Gueorguiev

Perception of Friction-Related Cues Induced by Temperature Variation on a Surface Display

Matej MAYET
Sorbonne Université, CNRS
Institut Jean Le Rond D'Alembert
Lutheries-Acoustique-Musique Team
F-75005 Paris, France
matej.mayet@dalembert.upmc.fr

Jean-Loïc LE CARROU
Sorbonne Université, CNRS
Institut Jean Le Rond D'Alembert
Lutheries-Acoustique-Musique Team
F-75005 Paris, France
jean-loic.le_carrou@sorbonne-universite.fr

David GUEORGUIEV
Sorbonne Université, CNRS
Institut des Systèmes Intelligents et de Robotique
Interactions Multi-Échelles Team
F-75005 Paris, France
david.gueorguiev@sorbonne-universite.fr

***Abstract*—Frictional cues enable us to perceive material properties and topography, which has prompted a dynamic research on methods for friction modulation. Recently, a novel method based on local heating of a screen was proposed for modulating friction and create the sensation of shape when exploring the surface. We built a setup able to reproduce this method to investigate how three parameters, the width of the heater, its temperature, and the duration of the pre-heating before the interaction, influence perception of purely tactile cues. The results show that raising the temperature of the heater increases the perception of tactile cues but that the width of the heater or the pre-heating duration had no effect on it. Surprisingly, the increase of the coefficient of friction at the heated location was only impacted by the width of the heater and the pre-heating duration. Our study confirmed that non-thermal tactile cues can be induced by local heating of a tactile display but we did not observe a direct relationship between the variation of the coefficient of kinetic friction and perception.**

***Index Terms*—thermal haptics, friction modulation, surface haptics.**

I. Introduction

The importance of a haptic feedback while interacting with an object is central to humans [1]. Whether it is a thermal or a mechanical feedback, it increases the immersion and enables the user to adapt and react according to tactile afferent information [2], [3].

During the last two decades, research on how to integrate a feedback stimulating the sense of touch in a device has largely developed [4], and haptics are now a growing subject of interest in several fields [5]–[8]. However, we can observe quite universally a lack of haptics in interactive devices such as tablets or smartphones. These devices can provide complex visual and auditory cues, but its haptic feedback is still often limited to a buzzing sensation that transmits to the user an information of a poor nature [9].

One of the challenges with these devices is to integrate a tactile feedback coming from the part the user directly interacts with (i.e. the screen of the smartphone), whose actuation represents a serious challenge to the development of novel Surface Haptic Devices (SHDs). Currently, two major methods exist for rendering frictional cues on displays: ultrasonic lubrication and electroadhesion [10]. Ultrasonic lubrication consists in vibrating a glass plate interface at an ultrasonic frequency to generate a squeeze film effect between the interface and the finger of the user, which results in a decrease of friction [11], [12]. One of the major challenges with this method is to sustain uniformity in the amplitude of the vibrations throughout the plate, especially when the size of the plate gets bigger. On the other hand, electroadhesion (or electrovibration) aims at increasing the friction between the surface and the finger. The contact between the finger, an electrical conductor, and the charged surface results in an augmentation of the electrostatic attraction force [13], [14].

In addition to these two well-known methods, a novel method able to perform a localized change of friction on a surface was proposed by Choi et al. [15], [16], based on studies that demonstrate the close relation between the visco-elastic properties of skin-like materials and their temperature [17], [18]. This method has the advantage of not being as power consuming and complex to implement as the methods mentioned above. The results of Choi et al. show that when exploring a glass plate, the temperature of the surface has an impact on the mechanical properties of the fingertip's outer layer. Specifically, increasing the temperature of the plate decreases the mechanical rigidity of the fingertip when in contact, causing an increase of the real contact area between the skin and the interface, inducing greater frictional forces. At controlled pressure force and sliding speed, [16] observed an increase in friction of about 50% when the surface temperature increases from 23°C to 42°C. They suggest that the physical mechanism responsible for this change of friction is due to temperature dependency of both the viscoelastic modulus and moisture level of the fingertip. Based on these observations, they designed three-dimensional (3D) shapes generated by changes in friction on a two-dimensional (2D) surface. They were able to create a Surface Haptic Device (SHD) consisting in a flexible heater diffusing heat at the middle of a glass plate. The device creates a temperature gradient on the surface which causes the friction forces to vary across the plate. Using this device, they suggested that friction force could be modulated up to 0.4 N. Such an increase in friction force corresponds to a 6 mm high bump according to the relationship between the lateral force and a Gaussian shaped bump [19]. When

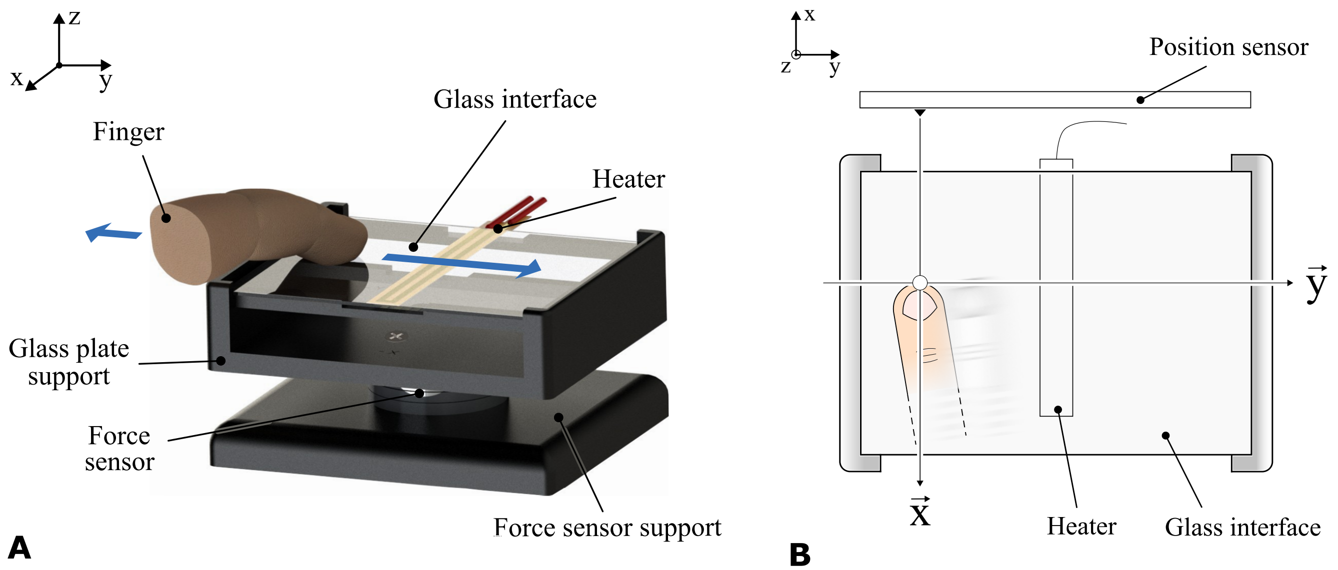

Fig. 1. (A) Experimental setup where the finger slides along $\overrightarrow{Y}$ (blue arrows). (B) Upper view of the experimental setup, the position sensor sweeps and get the position of the finger on ($\overrightarrow{X}$,$\overrightarrow{Y}$) plane.

sliding their finger across the glass plate, the participants were able to correctly locate the heater from 76% to 96% of the cases. While their finger crossed the heated zone, participants felt a ”bump” or a ”sticky zone”, sensations likely induced by the increase of friction within the heated zone [1]. The study also explored how strongly the exploration speed and the normal force applied by the finger on the surface impacted the coefficient of kinetic friction [16].

In this study, we aim at expanding the knowledge about the potential to induce frictional cues with localized heat bands. To that end, we propose a parametric study that explores how parameters such as the width of the heater, its temperature, and the pre-heating time impact the perception of tactile and thermal cues on a plane surface. We also investigate how the variation of these parameters influence the coefficient of kinematic friction between the plate and the fingertip during sliding.

II. Materials and Methods

A. Experimental setup

For this study we built a device able to change the temperature profile of a glass plate and to measure the forces generated by the interaction of a fingertip on the surface. An illustration of our experimental setup is shown in Fig. 1. The normal and tangential forces between the fingertips and the glass surface were measured with a 6 axis force / torque sensor (FTN-Mini-40 SI-20-1, Schunk) with a 0.01 N resolution on $\overrightarrow{X}$ and $\overrightarrow{Y}$, and 0.02 N on $\overrightarrow{Z}$. Signal was digitalized at 1 kHz by a 16-bit acquisition card (PCIe-6323, National Instruments) and filtered by a low-pass Butterworth filter with a 45 Hz cut-off frequency. The force sensor was held to the table with a fixed 3D printed support (PLA) such as its $\overrightarrow{Z}$ is collinear to table's normal axis. The support was tightly fixed to the table using 2 screws and an aluminium bar. On the top of the sensor, a 3D printed support (PLA) was maintaining the glass plate unmoving. The glass plate interface was made out of clear glass whose dimensions are 9.95 mm × 8.30 mm × 1.00 mm (± 0.01mm). This plate was graduated so that the heater was centered at the same point every time, independently from its size. The polyimide heating plate (10 mm × 93 mm polyimide heater plate, Icstation) was then fixed under the glass plate to generate a temperature gradient at its surface (see Fig. 2). Three models of heaters were available : the regular heater was left as it is, the thin model was obtained by cutting the regular one in half, and the large heater by putting two regulars side by side. A DC generator (VSP 1220,Voltcraft) was used to power the heaters during the experiment. Finally, a Neonode sensor (zForce Air 90°, Neonode) was fixed on the side of the Glass Support in order to get the position of the user's finger moving on the plate. The sensor detects and traces the finger with a resolution of 0.1 mm along both $\overrightarrow{X}$ and $\overrightarrow{Y}$ axis by detecting diffusely reflected infrared light it emitted previously (see Fig. 1-(B)).

B. Experimental procedure

The goal of this experiment was to perform a parametric study highlighting the impact of three specific parameters on both the modulation of friction and participants' feeling, during a 5 seconds long exploration of the surface with the fingertip. These parameters are: the width of the heater, the temperature of the heater, and the pre-heating duration. We chose to test three levels for each parameter, allowing 27 possible combinations. The numerical values taken by all three parameters are shown in Table I. We chose heater temperature as a parameter rather than the surface's temperature since the heater's temperature could be more consistently controlled within the trials than the latter.

TABLE I

VALUES USED FOR THE PARAMETRIC STUDY FOR THE TEMPERATURE, THE WIDTH AND THE PRE-HEATING DURATION OF THE HEATER.

Parameter	Value 1	Value 2	Value 3
Heater's temperature	35.6°C	47°C	62.5°C
Heater's width	3.5mm	6.5mm	15mm
Pre-heating duration	30s	120s	240s

A total of 9 participants took part in the experiment (7 males and 2 females, all right-handed and with no reported injury or impairment to the hand). Each participant was independently brought into an air conditioned room set at 19°C; their hands and the glass plate were cleaned with isopropyl alcohol, and they were asked to take a 10 minute pause before the experiment in order to let their body acclimatize to the controlled environment.

At each trial, the participant explored the glass plate with the index fingertip for 5 seconds (see Fig. 1). 27 timestamped trials were performed, one for each combination. In addition, the participant had to perform a "control exploration" where a heater was placed but not activated without the participant being aware of it. In total, the experiment consisted of 28 trials lasting 5 seconds, with mandatory pauses between each trial for the glass plate to return to room temperature.

For each trial, the participant was told to cross the glass plate along $\overrightarrow{Y}$ about 4-5 times, and to apply a normal force not exceeding 0.8 N. Before the experiment started, the participant had to perform a monitoring session to acquaint with the setup and the rules of the experiment. These rules were set to prevent extreme behaviors, but they allowed for some flexibility to the way the participant could explore the plate in terms of speed, trajectory and normal force applied. Every trial was conducted the same way: participants first start to explore the surface with their index fingertip for 5 seconds, they have then 20 seconds to fill a multiple-choice questionnaire based on what they felt while exploring. Once they have filled it they are asked to wait until the next trial is ready.

This experiment uses a device generating haptic feedback through a variation of temperature on its surface. To understand what kind of tactile stimulus is mainly felt with such a device, we set a predefined number of categories in the questionnaire. The participant had to choose amongst five categories of stimuli to describe best what they felt: an edge, a bump, a sticky zone or heat. They could choose as many categories as needed, or none in case they did not feel anything. These categories were the same for every participant and were mainly based on the results reported in [16].

C. Coefficient of Friction (COF)

We computed the coefficient of kinetic friction μ_k, defined as

$$\mu_k = \frac{F_y}{F_z}$$

where F_y is the norm of the tangential force along $\overrightarrow{Y}$ and F_z is the norm of the normal force along $\overrightarrow{Z}$ (see Fig. 1). The coefficient of kinetic friction was used to assess the stimuli's impact on the friction that the fingertip experiences during the exploration. In this paper, we will refer to μ_k as the coefficient of friction (COF). Figure 2 shows the evolution of the COF according to the position of the finger on the plate for the trial n°28 of the participant n°7. The heatmap of the glass plate above the graph is specific to this trial but is very similar for the other participants. The heat distribution was measured with an infrared camera (C5, FLIR) and fitted with an 8^{th} order Gaussian function.

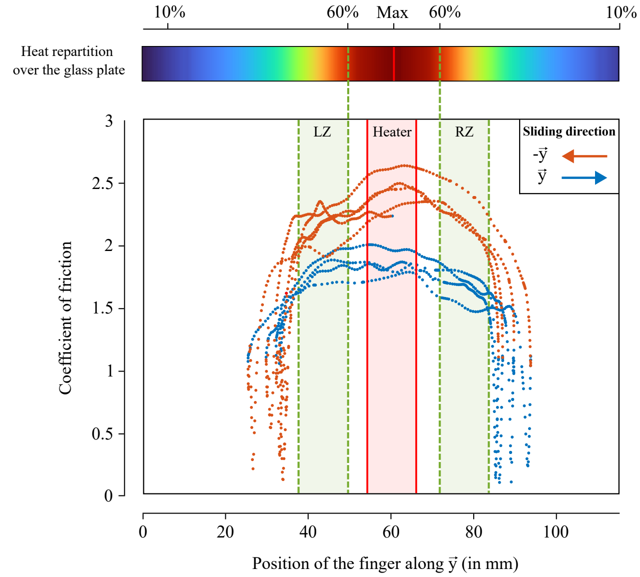

Fig. 2. COF computed during the trajectory of the finger along Y axis for a one-participant 5 s trial. Blue and red dots indicate the direction of the sliding. Red area shows the heater location. Green areas are the same width as the heater for measurement consistency. They start at 60% of the highest temperature on the left (LZ) and on the right (RZ) of the heater. The heat distribution on the plate along Y axis is shown by the colorbar above.

In order to quantify the impact of temperature modulation on friction, we measured the average COF in three intervals: before, during, and after the finger crossed the heater (hence the use of a position sensor).

For that sake, we defined 3 zones on the glass plate, as shown in Fig. 2. The shaded red zone corresponds to the area occupied by the heater on the plate. We defined two boundaries on the plate located where the temperature gradient was at 60% of its maximum. These boundaries defined three zones: the spatial interval between the two boundaries, the shaded green zone at the left of the heater (*LZ*) and the one at the right of the heater (*RZ*) both corresponding to areas explored before or after the heater was crossed, depending on the sliding direction. The spatial width of the right and left zones was defined identical as the heater zone to enable consistent comparisons while the distance between the zones depended on the temperature gradient which was trial specific.

We then measured the average COF in each of the three zones and calculated its variation between zones. Despite the symmetry of the temperature gradient, we noticed overall strong differences in the COF values between before and after the participants have crossed the heater. Consequently we decided to separate them for our analyses, and since crossing the heater seems to affect the COF up to the end of the sliding, we chose to study the change of the COF only between its value in the heater's area and the zone that was explored just before.

As slidings were executed in both directions along $\overrightarrow{Y}$, the zone to which we would compare the heater's COF was relative to the direction of motion: when the participant slid towards Y = 0 mm we compared the average COF of the *Heater* zone noted μ_{heater} to the average COF of *RZ* noted μ_{before} ; when the participant slid towards Y = 120 mm we compared the average COF of the *Heater* zone to the average COF of *LZ* noted μ_{before}.

$$COF_{var}(\%) = \frac{\langle \mu_{heater} \rangle \times 100}{\langle \mu_{before} \rangle} \quad (1)$$

As highlighted in Fig. 2, the COF amplitude is significantly different when sliding in one or in the other direction. And even though we tried to control as many parameters as possible in this experiment, the unique physiology of each participant could not be controlled and has an impact on the COF. Thereby, throughout the experiment, the COF changes were calculated as a percentage of variation (see Eq. 1).

We hypothesized that when the participants were exploring the glass plate, they either relied on the full length of the exploration to build their perception, or they identified the most salient sensation and based their answers according to this particular feeling. Therefore, we analysed our experimental data for both cases:

(1) For each tactile stimulation within a trial, we measured the corresponding COF variation. All the variations were averaged to obtain the COF variation corresponding to the trial. The values for each type of trial were then averaged amongst all participants, which provided a mean variation value for each specific trial (Fig. 4-(A)). This variation is referred to as the "Mean coefficient of friction variation".
(2) For each tactile stimulation within a trial, we measured the corresponding COF variation but selected only the biggest COF variation amongst the full length of the exploration. This maximal COF variation for each trial was then averaged amongst all participants, which provided a maximal variation value for each specific trial (Fig. 4-(B)). This variation is referred to as the "Maximal coefficient of friction variation".

III. Results

A. Psychophysical results

First, we estimated how often the possible types of sensation that participants could report occurred during the psychophysical tasks. Results showed that participants felt predominantly non-thermal sensations (Fig. 3). A one-way ANOVA analysis with a Geisser-greenhouse correction confirmed a difference between the reported cues ($F(2.469, 19.75) = 5.400$, $p = 0.01$) and a post-hoc Tukey test showed a significant difference between reporting the feeling of a sticky area and reporting a hotter zone. Moreover, none of the participants reported a sensation in the first trial in which no heating was performed.

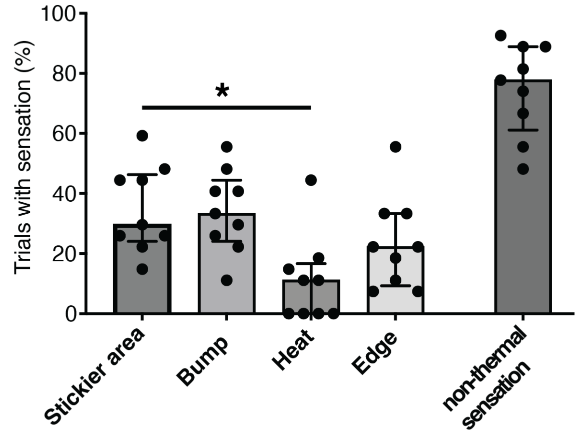

Fig. 3. Percentage of the trials in which a tactile or thermal sensation was perceived (Mean ± S.D). The slightly detached barplot on the right represents the percentage of trials in which at least one type of non-thermal stimulus was perceived.

To investigate the impact of the experimental conditions on participant's perception, we performed a Generalized Linear Model analysis, in which a logistic binary model was selected. The independent variables were the temperature of the heater, the width of the heater, and the pre-heating duration. The dependent variable was defined as the perception of at least one of the proposed tactile sensations with the exception of heat. The results showed only a significant effect of the temperature of the heater ($\chi^2 = 4.082$, $df = 2$, $p < 0.001$). The statistical analysis showed no significant interaction between the independent variables.

B. Analysis of the Coefficient of kinetic friction

First, we analysed the impact of each parameter related to the heater on both the mean and the maximal COF variation. A GLM statistical analysis showed a significant impact on the mean variation of the COF by the width of the heater ($F(2, 14) = 10.43$, $p = 0.002$) and the duration of the pre-heating ($F(2, 14) = 6.61$, $p = 0.1$) but not by the temperature of the heater ($F(2, 14) = 0.45$, $p = 0.64$). A post-hoc analysis performed with Bonferroni-corrected pairwise t-tests showed that all differences between the different heater widths are significant ($p < 0.05$) for the mean variation of the COF. Only the difference between 30 s and 240 s was significant for the duration of the pre-heating ($n = 72$, $t = 3.654$, $df = 71$, $p = 0.0015$).

As for the impact of the independent variables on the maximum increase in the COF that occurred in each trial, the GLM statistical analysis showed an impact of the two same independent variables as for the mean variation of the COF. The width of the heater ($F(2, 14) = 16.80$, $p < 0.001$) and the duration of the pre-heating ($F(2, 14) = 6.61$, $p = 0.1$) had a significant impact on the maximum increase of the COF but

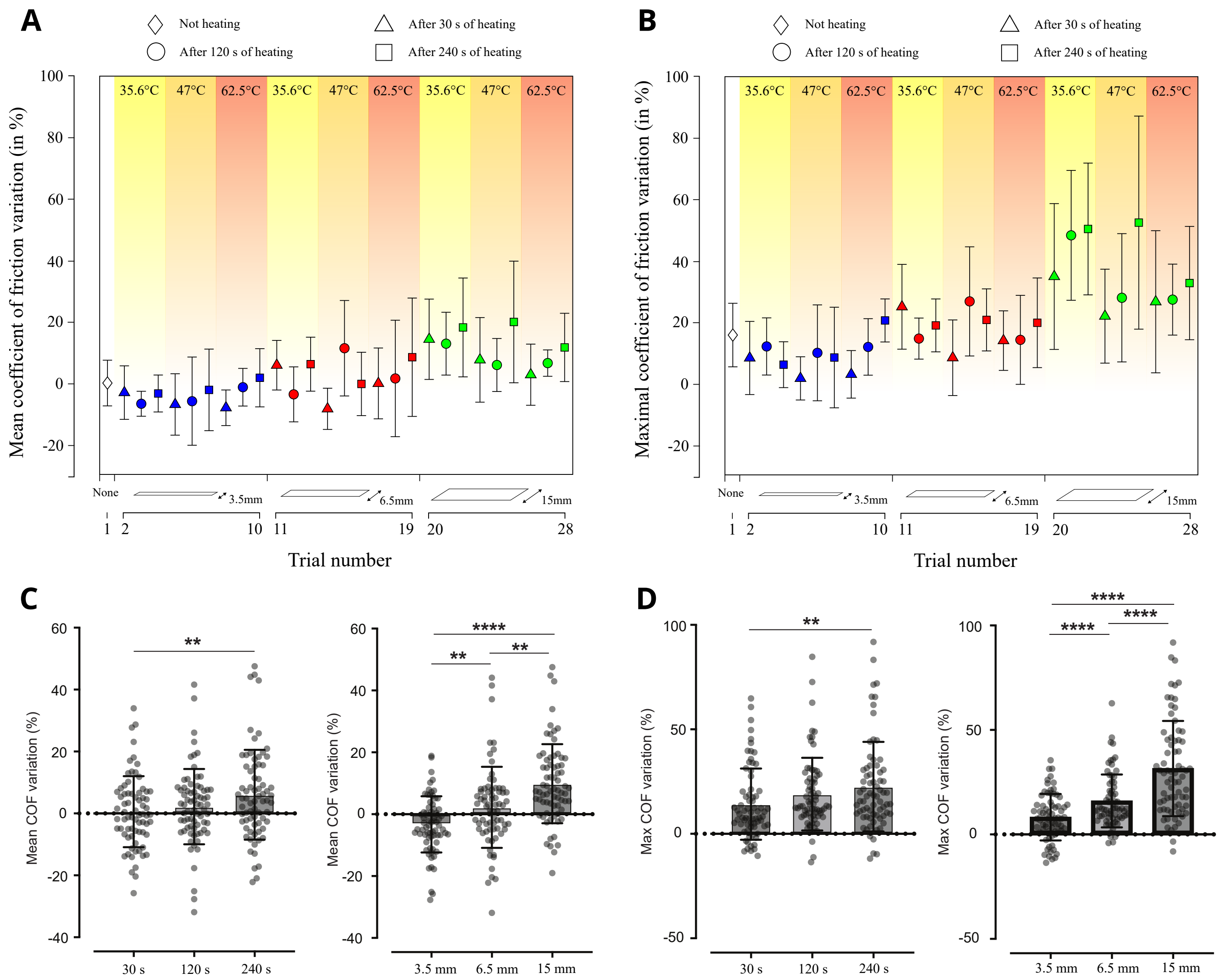

Fig. 4. Mean COF variation (A) or Maximal COF variation (B) in percent for each trial. The shape and the fill color of each dot indicate the pre-heating duration and the width of the heater, respectively. Color zones represent the temperature at which the heater was set. Errors bars represent the mean and standard deviation (S.D.) of 9 repetitions for each trial. Mean COF variation (C) and Maximal COF variation (D) in percent for each condition: the pre-heating duration and the width of the heater. The barplots depict the Mean and S.D. and the data points represent individual values for a specific trial.

not the temperature of the heater ($F(2, 14) = 1.4$, $p = 0.26$). A post-hoc analysis performed with Bonferroni-corrected pairwise t-tests showed that all differences between the different heater widths are significant ($p < 0.0001$) for the maximum variation of the COF. Only the difference between 30 s and 240 s was significant for the duration of the pre-heating ($n = 72$, $t = 3.219$, $df = 71$, $p = 0.006$).

Once we found which parameters impacted either the perception or the COF variation, we further investigated the impact the COF variation amplitude had on perception. To that end, we conducted a correlation analysis on the data represented in Fig. 5, which depict the relationship between the mean COF variation and the percentage of participant who perceived a non-thermal sensation. It appears that there is no correlation between participants' perception and the mean COF variation ($r = -0.03$, $p = 0.88$). The same correlation analysis was performed with the maximal COF variation and there no correlation was found between participants' perception and the maximal COF variation either ($r = -0.05$, $p = 0.81$).

IV. Discussion

First of all, the psychophysical results show that this method generates mainly non-thermal haptic cues. Thereby, our observations confirm previous research that showed that it is possible to create a tactile effect without triggering a large thermal response. Thus, this method fulfills its purpose but we noticed that the intensity of the haptic feedback was relatively subtle and participants did not feel the tactile cues as obvious. Our results also showed that varying the temperature of the heater had a significant impact on participants' perception, but that changing the values of both the width of the heater and the pre-heating duration does not impact the perception of non-thermal sensations.

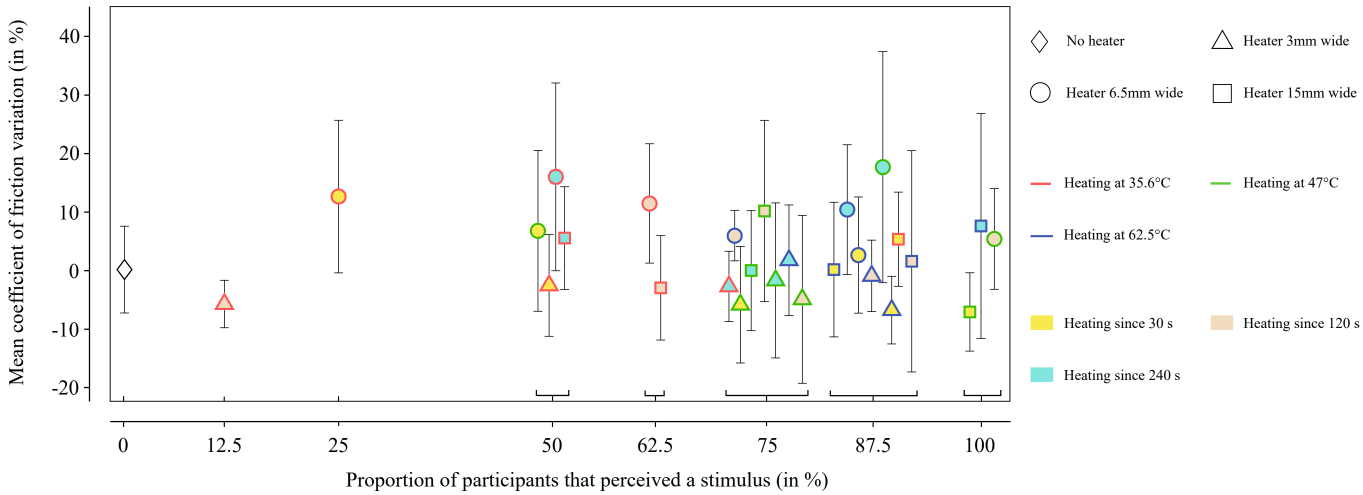

Fig. 5. Mean COF variation in percent for each trial, in function of the proportion of participants that felt a stimulus during the exploration. The shape, the border color and the fill color of each dot indicate the width, the temperature and the pre-heating duration of the heater, respectively. The brackets indicate the same proportion of participants that felt a non-thermal sensation. Error bars represent the Mean and S.D. for each type of trial.

In previous studies, shape perception was triggered by a large change in the coefficient of kinetic friction [16]. We calculated the variation of the coefficient of friction for each sliding through the heater and performed a statistical analysis on two measures of COF variation: averaged across all the slidings occurring within the trial, and the maximal change of friction that occurs when the finger goes across the heater during the trial. The analyses show that varying the width of the heater or the pre-heating duration has a significant impact on COF variations. These results are somewhat astonishing considering that only the temperature of the heater had a significant impact on the perception of tactile cues and that [16] suggested that the haptic stimulus perceived by the participants is likely generated by the variation of the COF during the sliding.

Following this assumption, we hypothesized that the larger the coefficient of friction the bigger the proportion of participants that perceived a stimulus would be. However, the correlation study we conducted between the COF and the percentage of participants who perceived a non-thermal cue (Fig. 5) shows no correlation between participants' answers and the variation of the COF. This means that the coefficient of friction as calculated in our study does not relate to the perception of the tactile cues.

Still, these results do not rule out the role of frictional cues in the perception. It is possible that participants used transient frictional cues to which touch is especially sensitive [20]. These variations might be captured by more precise measurements. Moreover, participants were left with some freedom to perform exploratory movements with their preferred speed and normal force. Individual differences might also have impacted the time course of the frictional variation and made them less salient in the analysis.

Regarding both mean (Fig. 4-(A)) and maximal (Fig. 4-(B)) COF variations, we observed the expected increase in the coefficient of kinetic friction. Interestingly, both graphs show strong similarities. In Choi et al. study, a COF augmentation of about 50% was measured between an exploration of a surface at 23°C and a surface at 42°C, our results show the maximal COF variation for a 15 mm wide heater is relatively close to this value.

V. Conclusion

This paper investigates the viability of friction variation by temperature modulation to generate a haptic stimulus when applied to a surface. This phenomenon is due to the particular properties of the *stratum corneum*, the outermost layer of human skin, which when heated decreases its mechanical rigidity, increasing the real contact area. We built a surface haptic device that uses this phenomenon, and were able to thoroughly investigate the impact of this technique on perception of non-thermal cues and finger-surface friction.

Lastly, we confronted our results to the ones obtained by [16], and found similarities in the perception study and differences regarding the modulation of the COF. However, when increasing the width of the heater we observed a convergence towards the same results in terms of COF modulation. Yet, we did not observe a direct relationship between the variation of the coefficient of friction and perception, which is somewhat astonishing considering the initial assumptions and the psychophysical results from [16]. Generally, the apparition and development of friction modulation by temperature variation opens new opportunities in this field of research, which might prove valuable for future haptic devices. More specifically, we imagine future devices applying this method to surfaces on which frictional and thermal dimensions are simultaneously rendered.

VI. Acknowledgments

We thank the UFR 919 of Sorbonne Université and the ANR 20-CE33-0013 (Maptics) for funding this research.

REFERENCES

[1] R. S. Johansson and J. R. Flanagan, “Coding and use of tactile signals from the fingertips in object manipulation tasks,” *Nature Reviews Neuroscience*, vol. 10, pp. 345–359, May 2009.

[2] V. Macefield and R. Johansson, “Control of grip force during restraint of an object held between finger and thumb: Responses of muscle and joint afferents from the digits,” *Experimental Brain Research*, vol. 108, Feb. 1996.

[3] M. Dimitriou and B. B. Edin, “Discharges in Human Muscle Receptor Afferents during Block Grasping,” *Journal of Neuroscience*, vol. 28, pp. 12632–12642, Nov. 2008.

[4] A. Peer and C. D. Giachritsis, eds., *Immersive Multimodal Interactive Presence*. Springer Series on Touch and Haptic Systems, London: Springer London, 2012.

[5] S. Hirche and M. Buss, “Human-Oriented Control for Haptic Teleoperation,” *Proceedings of the IEEE*, vol. 100, pp. 623–647, Mar. 2012.

[6] X. Yu, Z. Xie, Y. Yu, J. Lee, A. Vazquez-Guardado, H. Luan, J. Ruban, X. Ning, A. Akhtar, D. Li, B. Ji, Y. Liu, R. Sun, J. Cao, Q. Huo, Y. Zhong, C. Lee, S. Kim, P. Gutruf, C. Zhang, Y. Xue, Q. Guo, A. Chempakasseril, P. Tian, W. Lu, J. Jeong, Y. Yu, J. Cornman, C. Tan, B. Kim, K. Lee, X. Feng, Y. Huang, and J. A. Rogers, “Skin-integrated wireless haptic interfaces for virtual and augmented reality,” *Nature*, vol. 575, pp. 473–479, Nov. 2019.

[7] I. El Rassi and J.-M. El Rassi, “A review of haptic feedback in teleoperated robotic surgery,” *Journal of Medical Engineering & Technology*, vol. 44, pp. 247–254, July 2020.

[8] S. Papetti and C. Saitis, eds., *Musical Haptics*. Springer Series on Touch and Haptic Systems, Cham: Springer International Publishing, 2018.

[9] H. Culbertson, S. Schorr, and A. Okamura, “Haptics: The Present and Future of Artificial Touch Sensation,” *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 1, May 2018.

[10] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, “A Review of Surface Haptics:Enabling Tactile Effects on Touch Surfaces,” *IEEE Transactions on Haptics*, vol. 13, pp. 450–470, July 2020.

[11] M. Wiertlewski, R. Fenton Friesen, and J. E. Colgate, “Partial squeeze film levitation modulates fingertip friction,” *Proceedings of the national academy of sciences*, vol. 113, no. 33, pp. 9210–9215, 2016.

[12] D. Gueorguiev, E. Vezzoli, T. Sednaoui, L. Grisoni, and B. Lemaire-Semail, “The Perception of Ultrasonic Square Reductions of Friction With Variable Sharpness and Duration,” *IEEE Transactions on Haptics*, vol. 12, pp. 179–188, Apr. 2019.

[13] O. Bau, I. Poupyrev, A. Israr, and C. Harrison, “TeslaTouch: Electrovibration for touch surfaces,” in *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology*, (New York New York USA), pp. 283–292, ACM, Oct. 2010.

[14] J. Guo, J. Leng, and J. Rossiter, “Electroadhesion Technologies for Robotics: A Comprehensive Review,” *IEEE Transactions on Robotics*, vol. 36, pp. 313–327, Apr. 2020.

[15] C. Choi, Y. Ma, S. Sequeira, S. Chatterjee, X. Li, J. R. Felts, and M. C. Hipwell, “Effect of Surface Temperature on Finger Friction and Perception in Electroadhesion,” in *2021 IEEE World Haptics Conference (WHC)*, (Montreal, QC, Canada), pp. 680–684, IEEE, July 2021.

[16] C. Choi, Y. Ma, X. Li, S. Chatterjee, S. Sequeira, R. F. Friesen, J. R. Felts, and M. C. Hipwell, “Surface haptic rendering of virtual shapes through change in surface temperature,” *Science Robotics*, vol. 7, p. eabl4543, Feb. 2022.

[17] A. Tiwari, N. Miyashita, N. Espallargas, and B. N. J. Persson, “Rubber friction: The contribution from the area of real contact,” *The Journal of Chemical Physics*, vol. 148, p. 224701, June 2018.

[18] K. Ludema and D. Tabor, “The friction and visco-elastic properties of polymeric solids,” *Wear*, vol. 9, no. 5, pp. 329–348, 1966.

[19] G. Robles-De-La-Torre and V. Hayward, “Force can overcome object geometry in the perception of shape through active touch,” *Nature*, vol. 412, pp. 445–448, July 2001.

[20] D. Gueorguiev, E. Vezzoli, A. Mouraux, B. Lemaire-Semail, and J.-L. Thonnard, “The tactile perception of transient changes in friction,” *Journal of The Royal Society Interface*, vol. 14, no. 137, p. 20170641, 2017.