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Tactile Perception Characteristics of Lips Stimulated by Airborne Ultrasound

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***Abstract*— Tactile presentation to faces is an unexplored field of study with significant potential. Considering the hygiene and the physical burden on users, non-contact tactile stimulation to faces is an effective method. Even though lips have a particularly high tactile sensitivity in the face, the tactile perception characteristics of lips in non-contact tactile presentation have hardly been investigated. This study is the first to investigate the tactile perception characteristics of lips in airborne ultrasound tactile presentation, which is a non-contact haptic technology that generates a force on a remote object by focusing ultrasound waves. From acoustic simulations and two subject experiments, it was confirmed that the lowest tactile thresholds of the lips were achieved at the valley-shaped area of the lips in terms of location, lateral modulation with periodic circular trajectories (LM_C) in terms of modulation type, and 40 Hz in terms of modulation frequency. Furthermore, the tactile detection threshold of the lips could be lower by 3 dB than that of the palms with an appropriate presentation method. Although there are some limitations in the current devices, non-contact tactile presentation to lips using airborne ultrasound is potentially applicable to various fields, such as notifications, alerting, and virtual reality.**

***Index Terms*— mid-air haptics, airborne ultrasound, lip**

I. INTRODUCTION

Tactile presentation to faces is an unexplored field of study with significant potential. For contact tactile stimulation, some detailed perception characteristics of faces [1], [2] have been studied. Considering the hygiene and the physical burden on users, non-contact tactile stimulation is another effective method. However, there have been only a few studies on the tactile properties of faces [3], [4], [5]. In particular, the tactile perception characteristics of lips in non-contact tactile presentation have hardly been investigated.

In the face, lips have special features such as high spatial resolution in tactile perception [6], complex shapes, and ease of deformation. For non-contact tactile presentation, although a few wind-based applications [7], [8] have been proposed, there is currently no basic information about which part of the lips should be stimulated and how.

Therefore, we investigate the basic characteristics of lips in airborne ultrasound tactile presentation (Fig. 1 (a)). Mid-air ultrasound haptics [9] is a non-contact haptic technology that generates a force on a remote object by focusing ultrasound waves. This technology was adopted because of its high spatiotemporal resolution, which made it suitable for non-contact tactile presentation to lips.

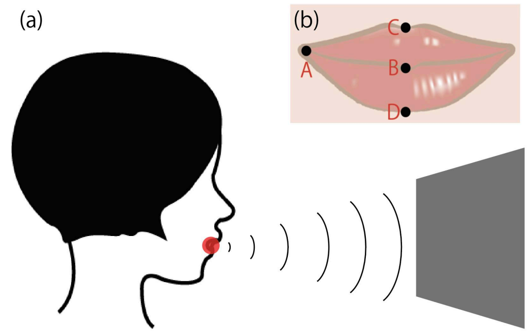

Fig. 1. (a) Non-contact tactile presentation to lips using airborne ultrasound. (b) Target locations on the lips.

The experimental results showed that the lowest tactile thresholds of the lips were achieved at the valley-shaped area of the lips in terms of location, lateral modulation with periodic circular trajectories (LM_C) in terms of modulation type, and 40 Hz in terms of modulation frequency. Furthermore, the tactile detection threshold of the lips could be lower by 3 dB than that of the palms if the appropriate presentation method was chosen.

Although the limitations of the current devices make it difficult to immediately apply the technology in actual environments, it is likely to be used in a variety of situations in the future. For example, it could be used for information notifications while driving a car or concentrating on work, and even for personally alerting pedestrians. In addition, it could contribute significantly to virtual reality applications, such as the sensory reproduction of eating or kissing.

II. RELATED WORK

A. Tactile Perception on Lips

Human lips are considered highly sensitive to touch. They were one of the body parts with the highest spatial resolution in tactile perception; they had a two-point discrimination threshold as low as fingertips [6]. They were innervated by both quickly and slowly adapting units [10].

Similar to human hands, lips have been reported to have three types of mechanoreceptors: Ruffini corpuscles, Meissner corpuscles, and Merkel cell disks [2]. Ruffini corpuscles especially respond to skin stretching, Meissner corpuscles to stroking and fluttering of the skin, and Merkel cell disks to the stationary pressure applied on the skin. Unlike hands, no

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Pacini corpuscles or hair follicle fibers have been found on the lips [11].

Based on the response characteristics of human lips [1], lips are expected to have a minimum threshold between 30 and 60 Hz in tactile sensations. Hence, to stimulate the lips efficiently, a tactile presentation system covering this range is considered effective.

B. Mid-Air Ultrasound Haptics

Mid-air ultrasonic tactile presentation utilizes the acoustic radiation pressure generated when an object interrupts the propagation of high-density ultrasound. This technology enables non-contact force presentation with high spatiotemporal resolution, which is difficult to achieve with conventional tactile presentation devices. Iwamoto et al. [12] proposed the first mid-air ultrasonic tactile presentation device. Since then, there has been a lot of research done on this technology, such as spatial control of a focal point using phased array focusing [13] or multi-point haptic feedback [14].

To enhance the perceived tactile sensation, some methods have been proposed to modulate the ultrasonic carrier waves to match the frequency characteristics of mechanoreceptors. There are three modulation types that have been examined: amplitude modulation (AM), lateral modulation (LM) [15], [16], and spatiotemporal modulation (STM) [17]. In AM, the position of the focused ultrasound is fixed, and the output intensity varies temporally. On the other hand, in LM, the output intensity is kept constant, and the position of the focused ultrasound varies temporally. Takahashi et al. defined two trajectories of LM: periodic linear movement (LM_L) and periodic circular movement (LM_C) [16]. Compared with AM, LM presented significantly stronger vibrotactile stimuli in palms and forearms [15]. Similarly, in STM, the focal point is moved continuously along an arbitrary shape to provide tactile presentation to the entire path.

Additionally, focused ultrasound presentation on faces has been studied. Gil et al. compared the response characteristics to focused ultrasound presentation at three facial sites for use as haptic cues [4]. Similarly, Mizutani et al. compared six facial locations for use as a personal warning system [5].

To the best of our knowledge, no studies have been conducted on ultrasonic presentation to lips, despite the high tactile sensitivity of lips and the wide range of applications. This study addresses this gap by exploring this new area.

III. ULTRASONIC PRESENTATION TO LIPS

We investigate the tactile perception characteristics of lips in airborne ultrasound tactile presentation. An airborne ultrasound phased array (AUPA) [18] was used to stimulate the lips using focused ultrasound. An AUPA consists of 249 ultrasonic transducers with 40 kHz carrier waves, which is capable of presentation in the modulation frequency range where lips are expected to be most sensitive (Section II-A). The presentation system (Fig. 4) used in this study was constructed using six AUPAs and a depth camera (Intel RealSense D435). A point cloud was rendered in Unity 3D based on the color and depth information obtained from the depth camera, and the 3D coordinates of the ultrasound focus were manually adjusted to be placed in the desired position. The coordinates were sent to the AUPAs, and based on the values, the amplitude and phase of each ultrasonic transducer were calculated. As shown in Fig. 1 (b), four locations were chosen on the lips as presentation sites: the right commissure (A), the center of the valley-shaped area between the upper and lower lips (B), the upper vermilion border (C), and the lower vermilion border (D).

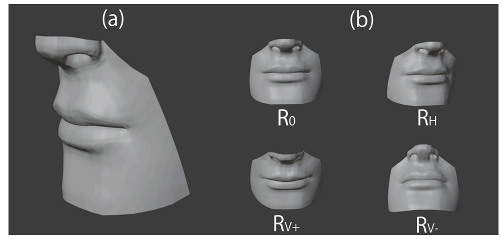

Fig. 2. (a) 3D model of the lips used in acoustic simulations. (b) Four tilting conditions under which the model was placed.

In this study, utmost care was taken to ensure safety. All the subject experiments in this study were approved by the Ethical Committee of the University of Tokyo. The subjects wore glasses and headphones securely to avoid focused ultrasound waves accidentally hitting their eyes and ears (Fig. 4). In addition, to avoid heating effects, the experiments were designed to prevent the lips from being exposed to prolonged intense ultrasound exposure. Furthermore, it was pre-determined that if a subject appeared or reported to be unwell, the experiments would be stopped immediately. However, no subjects reported any ill effects.

In the practical application of ultrasonic tactile stimulation to lips, the safety of the body needs to be carefully considered. Nelson et al. [19] mentioned the upper limit of ultrasound exposure to the eyes (17 mW/cm^2). This value was not exceeded in this study, considering the maximum output of the entire device and the absorption rate of ultrasound to the skin. Battista et al. [20] showed that audible noise from ultrasound focus presentation had no significant effect on the auditory system, although they did not test the case where the focus was directly presented on the ears. The future systems should be designed to suppress irradiation to the auditory organs in particular.

IV. ACOUSTIC SIMULATION

We compared the theoretical values of acoustic radiation pressure between the four locations to investigate where the focused ultrasound presentation was effective. We also examined the effect of the angle of the lips.

A. Simulation Setup

The acoustic simulations were implemented based on the boundary element method using the scattering model described by Matsubayashi et al. [21]. The arrangement of the ultrasonic transducers in the simulations was the same as that of the device configuration in the subject experiments (Fig. 4).

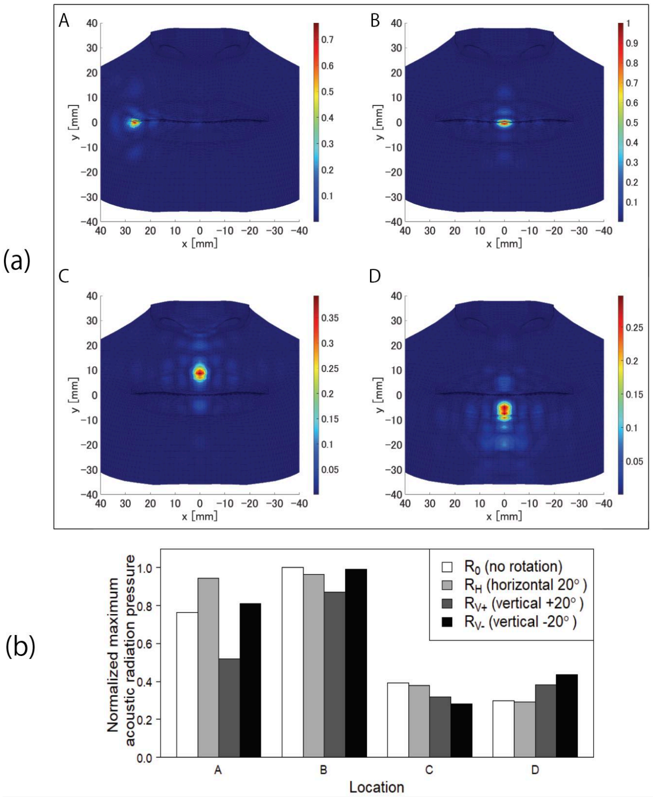

Fig. 3. (a) Simulation results of acoustic radiation pressure distribution at each location under R_0. (b) Comparison of maximum values at each location under each tilting condition.

A 3D model of the lips (Fig. 2 (a)) was used in the simulations. The facial areas that were less relevant to the ultrasound presentation to the lips were removed from this model. The simulations were set up so that the ultrasonic waves were completely reflected by the model surface, since 99.9 percent of the incident airborne ultrasound power is reflected on the skin surface [13].

B. Presentation Conditions

We calculated the acoustic radiation pressure on the target locations A-D of the lips for four different tilting conditions. Fig. 2 (b) shows each condition of the model as seen from the transducers. The initial lip model R_0 was tilted horizontally by 20 degrees (R_H), vertically forward by 20 degrees (R_{V+}), and vertically backward by 20 degrees(R_{V-}). For the horizontally tilting condition, only R_H was used due to the symmetry of the model. Under all the conditions, the model was placed so that location B was 250 mm in the frontal direction from the center of the transducers.

C. Results

The distributions of the acoustic radiation pressure in the presentation to each location under R_0 are shown in Fig. 3 (a), and the maximum values at each location under each tilting condition are shown in Fig. 3 (b). All the radiation pressure values were normalized by dividing them by the maximum value at the presentation to location B under R_0.

From Fig. 3 (a), it was confirmed under R_0 that the pressure-concentrated region at locations A and B (about 20 mm^2, location B had two separated regions) was much smaller than that at locations C and D (about 50 mm^2). We defined ”the pressure-concentrated region” as the set of regions that had radiation pressure values greater than 40 percent of the peak value in each simulation. In the simulation figures, the pressure-concentrated region corresponds to the region surrounding the light green area. Similar distributions were observed under other tilting conditions.

From Fig. 3 (b), it was found under all the conditions that the maximum values of acoustic radiation pressure at locations A and B were much larger (up to 3.53 times) than those at locations C and D. Only at location A, the maximum value changed significantly depending on the tilting condition.

D. Discussion

It was theoretically confirmed that a larger acoustic radiation pressure was generated when focused ultrasound was presented in the valley-shaped areas (locations A and B) compared to the flat areas (locations C and D). In addition, ultrasonic presentation to the valley-shaped areas focused the pressure on a narrower area than that to the flat areas. These are considered to be owing to the multiple reflections of ultrasound waves in the valley-shaped structure between the lips, which led to an increase and concentration of the acoustic radiation pressure.

Under R_0, the maximum value at location B was considerably larger than that at location A, while under R_H, the maximum values at locations A and B were almost equal. This is mainly due to the effect of the angle between the incident direction of the ultrasonic wave and the valley-shaped region. When the valley-shaped region is perpendicular to the direction of ultrasonic wave incidence, the wave is likely to be reflected toward the valley bottom, which leads to multiple reflections. As the region rotates horizontally and becomes more oblique to the incident wave, the reflected wave is likely to be reflected to the outside of the lips and not directed to the valley bottom. Under R_0, the region around location A was highly tilted (about 45 degrees) to the device plane, so the radiation pressure was clearly higher at location B than at location A. On the other hand, in R_H, both the valley-shaped regions around locations A and B were tilted to the same degree (about 20 degrees in absolute value) to the device plane, which is considered to have resulted in the approximately same radiation pressure values.

V. Experiment 1: Tactile Detection Threshold for Modulation Conditions

Experiment 1 compared the tactile detection thresholds between the modulation types and between the modulation frequencies.

A. Presentation Conditions

Based on the results of the acoustic simulations, locations A and B were selected as the effective locations for tactile

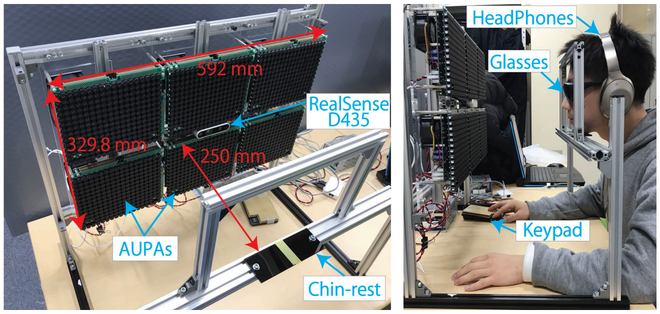

Fig. 4. Device configuration of subject experiments.

presentation. AM and LM_C (radius 2 mm) were chosen as the modulation types, and 5 Hz, 40 Hz, and 200 Hz as the modulation frequencies. To simplify the experimental process, the experiment was limited only to the basic case where the AUPAs were right in front of the face (R_0 in Section IV).

B. Procedure

12 subjects (two females and ten males aged 23-29 years) participated in this experiment. Ultrasound waves were focused on the lips with each subject's face fixed on a chin rest so that the lips were at 250 mm from the system (Fig. 4). A single ultrasonic focal point was presented at each target location. For simplicity, this study was limited to the cases of dry closed lips. The subjects wore noise-canceling headphones with pink noise playing during the ultrasound presentation, so that the driving sound generated by the AUPAs was not audible to them. The experiment was conducted with nothing on the subjects' lips. For each presentation, the experimenter manually adjusted the focus position. Instructions to the subjects during the experiment were given using a voice output from the headphones. The subjects placed their right hands on the numeric keypad.

The staircase method was adopted to measure the absolute thresholds for the tactile sensation. We defined the output intensity based on the maximum instantaneous output radiation pressure, and varied it between 255 levels in the experiment. In both the ascending and descending series, the output intensity was changed by one level every 200 ms. In this study, the time taken for each step was set to be short as 200 ms so that the subjects could maintain their concentration throughout the experiment. Starting from the minimum value, the output intensity was gradually increased. When the subject first detected the tactile sensation, the subject pressed the keypad, and the intensity value at that time (t1) was recorded. Then, in reverse, the output intensity was gradually decreased from t1. Later, when the subject no longer felt the tactile sensation, the subject pressed the keypad again, and the intensity value (t2) was recorded. The output change direction was then reversed again and started from t2. This process was repeated in one presentation, and this presentation was terminated when six transitions (t1-t6) occurred. The average value of these transitions was considered as the absolute threshold in the presentation. If the output intensity reached the minimum or maximum value during the presentation, the presentation was terminated at that point, and the measurement data were treated as outliers.

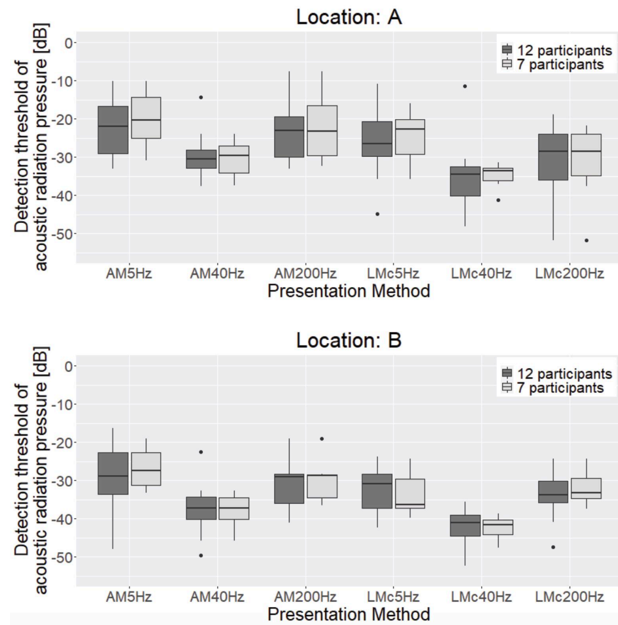

Fig. 5. Comparison of tactile thresholds between the six presentation methods at the two locations in Experiment 1.

C. Results

The results are shown in Fig. 5. The stimulation intensity is defined as the maximum instantaneous acoustic radiation pressure in each presentation method. The 0 dB corresponds to the highest stimulation intensity produced by the setup shown in Fig. 4. It was equivalent to 27.8 mN (2.83 gf) in radiation force when measured with an electronic scale (SHINKO DENSHI ViBRA AJ II). Note that the applied pressure on the skin is affected by the acoustic streaming created by the ultrasound beam. In this study, we represent the stimulation intensity by the theoretical value of the maximum instantaneous radiation pressure calculated from the emitted ultrasound.

In the presentation to location A, two subjects (one female and one male) reached the maximum value at AM 5 Hz. In addition, one female subject reached the minimum at LM_C 200 Hz. In the presentation to location B, one male subject reached the minimum at AM 40 Hz and one male subject at LM_C 5 Hz, and two subjects (one female and one male) at LM_C 40 Hz. To take care of statistical bias, both the data of the 12 subjects (D^{b}) after excluding only these outlier data and the data of the 7 subjects (D^{wb}) after excluding the subjects who produced one or more outlier data (5 subjects) are shown in the figure. In Experiment 1, the same statistical analysis was performed for D^{b} and D^{wb}. In the below analysis of D^{b} and D^{wb}, the corresponding p-values were respectively denoted as p^{b} and p^{wb}. In summary, we obtained the same conclusions from D^{b} and D^{wb} regarding the statistical significance of each factor (modulation type,

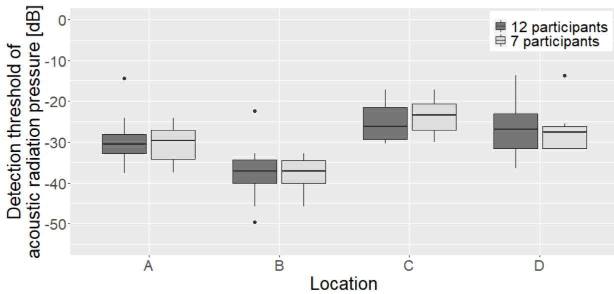

Fig. 6. Comparison of tactile thresholds for AM 40 Hz at the four locations in Experiment 2.

modulation frequency).

The Shapiro-Wilk test was conducted for each presentation method at both the locations, and all the data were found to follow a normal distribution ($p^{\mathrm{b}} \geq 0.05, p^{\mathrm{wb}} \geq 0.05$). Bartlett's test showed that the equality of variances between the groups was met at each location ($p^{\mathrm{b}} \geq 0.05$, $p^{\mathrm{wb}} \geq 0.05$ for both the locations). Two-way ANOVA and multiple comparisons using the Tukey-Kramer test were performed in both the locations with the modulation type and the modulation frequency as the factors. No interaction was found in either of the locations ($p^{\mathrm{b}} \geq 0.05$, $p^{\mathrm{wb}} \geq 0.05$ for both the locations). For location A, there was a significant difference in both the factors ($p^{\mathrm{b}} < 0.05$, $p^{\mathrm{wb}} < 0.05$ for both the factors). With respect to the modulation frequency, there was a significant difference in 5 Hz-40 Hz ($p^{\mathrm{b}} = 4.88 \times 10^{-3}, p^{\mathrm{wb}} = 2.03 \times 10^{-3}$). No significant difference was found between 40 Hz-200 Hz ($p^{\mathrm{b}} = 0.130, p^{\mathrm{wb}} = 0.101$). In location B, there was a significant difference in both the factors ($p^{\mathrm{b}} < 0.05$, $p^{\mathrm{wb}} < 0.05$ for both the factors). As for the modulation frequency, there was a significant difference in 5 Hz-40 Hz ($p^{\mathrm{b}} = 2.43 \times 10^{-4}, p^{\mathrm{wb}} = 1.50 \times 10^{-5}$) and 40 Hz-200 Hz ($p^{\mathrm{b}} = 1.69 \times 10^{-3}, p^{\mathrm{wb}} = 6.07 \times 10^{-5}$).

VI. EXPERIMENT 2: TACTILE DETECTION THRESHOLD FOR LOCATION CONDITIONS

Experiment 2 compared the tactile detection thresholds between the locations to determine where the focused ultrasound presentation was effective. This experiment also aimed to investigate whether the results of the ultrasound presentation to the actual lips were consistent with the simulation results. The subjects, procedure, and apparatus were the same as those in Experiment 1.

A. *Presentation Conditions*

All the target locations (A-D) were selected. In order to focus on comparisons between location conditions, only AM 40 Hz was chosen as the modulation type. For comparison, we used the threshold data for locations A and B measured in Experiment 1. Therefore, only the thresholds in locations C and D were measured in this experiment. As in Experiment 1, the AUPAs were placed right in front of the face.

B. *Results*

The results are presented in Fig. 6. One male subject reached the minimum value in the presentation to location B. As in Experiment 1, we analyzed D^{b} and D^{wb}, and described the results with corresponding p-values p^{b} and p^{wb}. Similar conclusions were obtained from D^{b} and D^{wb}, although the statistical methods were different.

First, we describe the analysis of D^{b}. The Shapiro-Wilk test was performed on the measured data at each location, and it was found that all the groups followed a normal distribution ($p^{\mathrm{b}} \geq 0.05$). Bartlett's test showed that the equality of variances between the groups was met ($p^{\mathrm{b}} \geq 0.05$). We performed a one-way ANOVA with the location as the factor, and the result showed a significant difference ($p^{\mathrm{b}} < 0.05$). Multiple comparisons between the locations using the Tukey-Kramer test showed significant differences in A-B ($p^{\mathrm{b}} = 3.34 \times 10^{-2}$), B-C ($p^{\mathrm{b}} = 2.37 \times 10^{-4}$), and B-D ($p^{\mathrm{b}} = 5.59 \times 10^{-4}$). Location A was not significantly different from locations C and D ($p^{\mathrm{b}} = 0.306$ for A-C, $p^{\mathrm{b}} = 0.457$ for A-D).

Next, we describe the analysis of D^{wb}. The Shapiro-Wilk test was performed on the measured data at each location, and it was found that one of the four groups did not follow a normal distribution. The Wilcoxon signed-rank test showed that the threshold for location B was significantly lower than that for locations A, C, and D ($p^{\mathrm{wb}} < 0.05$ for all the locations). Also, the Wilcoxon signed-rank test showed that the threshold for location A was not significantly different from that for locations C and D ($p^{\mathrm{wb}} \geq 0.05$ for both the locations).

VII. DISCUSSION OF THE EXPERIMENTS

From Experiment 1, it was confirmed that in the ultrasonic tactile presentation to the lips, the presentation by $\mathrm{LM_C}$ in terms of modulation type and 40 Hz in terms of modulation frequency was distinctly more detectable. Regarding the modulation type, $\mathrm{LM_C}$ was more easily detected than AM, which was similar to the results for palms and forearms [16]. This is probably because more mechanoreceptors are stimulated simultaneously by moving the ultrasound focus. For the modulation frequency, the presentation at 40 Hz was easier to detect than at 5 Hz and 200 Hz, as expected in Section II-A. It would be because lips, unlike hands and arms, do not have Pacini corpuscles, and the Meissner corpuscles provide the minimum threshold for tactile perception.

The results of Experiment 2 were in general agreement with the results of the acoustic simulations. The threshold at location B was lower than that of all other locations. However, contrary to what was expected from the acoustic simulations, the threshold at location A was not significantly different from that at locations C and D. This could be because the tactile sensitivity could vary depending on the location, and the shape of the 3D model of lips was different from that of human lips. From the simulation results, it is possible that the threshold at location A would be lower when the experiment is conducted with the face horizontally rotated to the device.

Compared to the threshold measurement of palms [16], Experiment 1 (D^{b}) showed that the lips could have a lower tactile threshold than the palms in airborne ultrasound presentation. Four AUPAs were used for the measurements in the palms, while six AUPAs were used in this study. The maximum instantaneous radiation force for the four units was 25.1 mN (2.56 gf), measured in the same way (see Section V-C) as for the six units (27.8 mN (2.83 gf)). Therefore, it is reasonable to compare the measured data at the lips with those at the palms, which are shifted downward by 0.87 dB. According to this, the tactile detection threshold of $\mathrm{LM_C}$ 40 Hz (radius 2 mm) at the center of the valley-shaped area (location B) of the lips was lower by 3 dB than that of $\mathrm{LM_C}$ 200 Hz (radius 1 mm, 3 mm) at the palms. This result suggests that, for example, when considering a warning system using focused ultrasound, the presentation of focused ultrasound to lips can be more effective than that to palms if the appropriate presentation method is chosen.

The results of these experiments demonstrate the feasibility of a non-contact tactile presentation system for lips. This system can be robust because the experimental results were reasonably stable regardless of the individual differences in lip shape. Although there are some limitations of the current devices, such as the size of the device and the distance over which it can present, non-contact tactile presentation to lips is potentially applicable to various fields in the future, such as notifications, alerting, and virtual reality.

Note that the experiments in this study were limited to the cases of dry closed lips. Future research should consider presenting them in a variety of situations, such as presentation from the side of the face, to opened lips, and even to moving lips. It should also be investigated whether tactile perception is affected by the wetness of lips.

VIII. CONCLUSION

In this study, we investigated the tactile properties of the lips in airborne focused ultrasound presentation. To the best of our knowledge, this study is the first report on the tactile perception characteristics of lips in non-contact tactile stimulation. From acoustic simulations and two subject experiments, it was confirmed that the lowest tactile thresholds were achieved at the valley-shaped area of the lips in terms of location, $\mathrm{LM_C}$ in terms of modulation type, and 40 Hz in terms of modulation frequency. Furthermore, the tactile detection threshold of $\mathrm{LM_C}$ 40 Hz (radius 2 mm) at the valley-shaped area of the lips could be lower by 3 dB than that of $\mathrm{LM_C}$ 200 Hz (radius 1 mm, 3 mm) at the palms.

The results of this study indicate the feasibility of a non-contact tactile presentation system for lips. Although there are some limitations in the current devices, non-contact tactile presentation to lips using airborne ultrasound is potentially applicable to various fields in the future, such as notifications, alerting, and virtual reality.

REFERENCES

[1] S. M. Barlow, “Mechanical Frequency Detection Thresholds in the Human Face,” *Experimental neurology*, vol. 96, no. 2, pp. 253–261, 1987.

[2] M. Z. Siemionow, B. B. Gharb, and A. Rampazzo, “The Face as a Sensory Organ,” in *The Know-How of Face Transplantation*. Springer, 2011, pp. 11–23.

[3] Y. Sato and R. Ueoka, “Investigating Haptic Perception of and Physiological Responses to Air Vortex Rings on a User’s Cheek,” in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 2017, pp. 3083–3094.

[4] H. Gil, H. Son, J. R. Kim, and I. Oakley, “Whiskers: Exploring the Use of Ultrasonic Haptic Cues on the Face,” in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 2018, pp. 1–13.

[5] S. Mizutani, M. Fujiwara, Y. Makino, and H. Shinoda, “Thresholds of Haptic and Auditory Perception in Midair Facial Stimulation,” in *2019 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE)*. IEEE, 2019, pp. 1–6.

[6] S. Weinstein, “Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part, Sex and Laterality,” *The skin senses*, 1968.

[7] N. Ranasinghe, P. Jain, N. Thi Ngoc Tram, K. C. R. Koh, D. Tolley, S. Karwita, L. Lien-Ya, Y. Liangkun, K. Shamaiah, C. Eason Wai Tung, *et al.*, “Season Traveller: Multisensory Narration for Enhancing the Virtual Reality Experience,” in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 2018, pp. 1–13.

[8] A. Wilberz, D. Leschtschow, C. Trepkowski, J. Maiero, E. Kruijff, and B. Riecke, “FaceHaptics: Robot Arm based Versatile Facial Haptics for Immersive Environments,” in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–14.

[9] I. Rakkolainen, E. Freeman, A. Sand, R. Raisamo, and S. Brewster, “A Survey of Mid-Air Ultrasound Haptics and Its Applications,” *IEEE Transactions on Haptics*, 2020.

[10] M. Nordin and K.-E. Hagbarth, “Mechanoreceptive units in the human infra-orbital nerve,” *Acta Physiologica Scandinavica*, vol. 135, no. 2, pp. 149–161, 1989.

[11] M. Trulsson and G. K. Essick, “Sensations Evoked by Microstimulation of Single Mechanoreceptive Afferents Innervating the Human Face and Mouth,” *Journal of neurophysiology*, vol. 103, no. 4, pp. 1741–1747, 2010.

[12] T. Iwamoto, M. Tatezono, and H. Shinoda, “Non-contact Method for Producing Tactile Sensation Using Airborne Ultrasound,” in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2008, pp. 504–513.

[13] T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda, “Noncontact Tactile Display Based on Radiation Pressure of Airborne Ultrasound,” *IEEE Transactions on Haptics*, vol. 3, no. 3, pp. 155–165, 2010.

[14] T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, “UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces,” in *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*, 2013, pp. 505–514.

[15] R. Takahashi, K. Hasegawa, and H. Shinoda, “Lateral Modulation of Midair Ultrasound Focus for Intensified Vibrotactile Stimuli,” in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2018, pp. 276–288.

[16] ——, “Tactile Stimulation by Repetitive Lateral Movement of Midair Ultrasound Focus,” *IEEE Transactions on Haptics*, vol. 13, no. 2, pp. 334–342, 2020.

[17] W. Frier, D. Ablart, J. Chilles, B. Long, M. Giordano, M. Obrist, and S. Subramanian, “Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-air,” in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2018, pp. 270–281.

[18] S. Suzuki, S. Inoue, M. Fujiwara, Y. Makino, and H. Shinoda, “AUTD3: Scalable Airborne Ultrasound Tactile Display,” *IEEE Transactions on Haptics*, 2021.

[19] T. R. Nelson, J. B. Fowlkes, J. S. Abramowicz, and C. C. Church, “Ultrasound Biosafety Considerations for the Practicing Sonographer and Sonologist,” 2009.

[20] A. Di Battista, “The effect of 40 kHz ultrasonic noise exposure on human hearing,” *Proc. 23rd Int. Cong. Acoustics*, pp. 4783–4788, 2019.

[21] A. Matsubayashi, Y. Makino, and H. Shinoda, “Rendering Ultrasound Pressure Distribution on Hand Surface in Real-Time,” in *Haptics: Science, Technology, Applications*. Springer International Publishing, 2020, pp. 407–415.