2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Evaluation of Tactile Hardness Presentation Using an Airborne Ultrasound Haptic Display

Taiga Bando[1], Sota Iwabuchi[1], Shun Suzuki[1], Yasutoshi Makino[1] and Hiroyuki Shinoda[1]

I. Introduction

The Airborne Ultrasound Tactile Display (AUTD) [1] generates mid-air tactile sensations using focused ultrasound radiation force. Unlike conventional methods, it is completely contactless, enabling the creation of three-dimensional tactile fields without requiring users to wear devices.

Because the force generated is weak (a few grams-force), various modulation techniques such as Amplitude Modulation (AM) [2], Lateral Modulation (LM) [3], and Spatiotemporal Modulation (STM) [4] have been proposed to enhance perceptual intensity. More recently, oscillating the focal point at low frequencies has also been shown to produce pseudo-pressure sensations [5].

While most prior studies evaluated vertical pressing against the focus, this study examines tactile sensations evoked by lateral hand movement over a static focal point. Such a focus applies vertical force without friction, and as the hand moves sideways, a vertical softness is perceived, resembling the experience of rolling a ball across a soft surface.

We assess this sensation by comparing it to real-world objects, and find that the stimulus most closely resembles rolling a hard steel ball on a sponge-like base.

II. Experiment

In this experiment, we evaluated which of the prepared physical models most closely resembled the tactile sensation presented by the AUTD.

A. Experimental Setup

An overview of the experimental setup is shown in Fig. 1. The system employed twelve AUTD devices (AUTD3 [1]), which were arranged such that the end units faced inward toward the center, as illustrated in the figure.

B. Prepared Models

In this experiment, four types of physical models were prepared.

1) Sponge base + Sponge ball (a soft ball on a soft base)
2) Sponge base + Steel ball (a hard ball on a soft base)
3) Polyester board + Sponge ball (a soft ball on a hard base)
4) Polyester board + Steel ball (a hard ball on a hard base)

[1]Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa-shi, Chiba, Japan
bando@hapis.k.u-tokyo.ac.jp

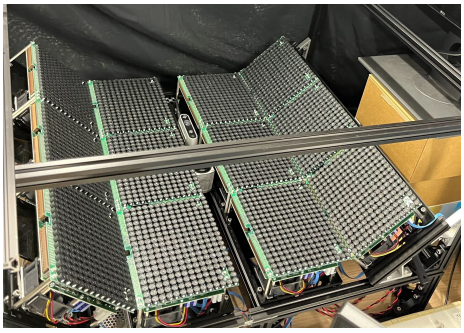

Fig. 1. AUTD

C. Experimental Method

1) Tactile Stimulation Method: In this study, a focal point was generated using the AUTD, and users were instructed to perform a horizontal stroking motion with their palm over the focal point. Fig. 2 illustrates the interaction method. Participants held their hand above the tactile display and moved it horizontally while maintaining a constant height.

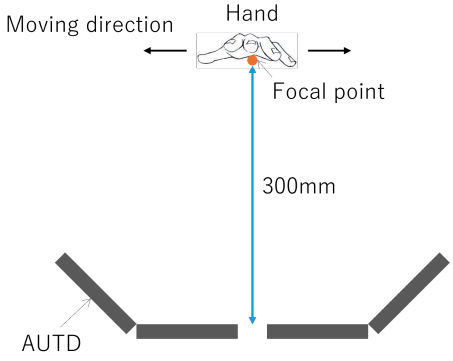

Fig. 2. Experimental setup

2) Experimental Procedure: Participants followed the procedure outlined below:

1) The participant positioned their right hand above the AUTD device.
2) They moved their hand horizontally to perceive the tactile sensation of the static focal point. This action could be repeated freely as many times as needed before making a judgment.
3) Using the same hand, they touched the physical reference model and evaluated the similarity of the sensation.

This process was repeated for the four model conditions. Participants were instructed to assess the presented stimuli

based on their perceived hardness. At that time, participants were instructed to disregard differences in perceived texture, temperature, or other sensory cues, and to evaluate only the similarity in perceived hardness. Participants rated the similarity on a 7-point Likert scale, where 1 indicated "completely different" and 7 indicated "very similar." To eliminate the influence of audible noise generated by the AUTD during tactile presentation, participants wore headphones throughout the experiment, through which white noise was played. 8 participants (6 males and 2 females) in their twenties took part in the study.

III. Results

The experimental results are shown in Fig. 3. The average score for each condition was as follows: 4.25 for the Sponge base + Sponge ball, 5.625 for the Sponge base + Steel ball, 4 for the Polyester board + Sponge ball, and 4.875 for the Polyester board + Steel ball.

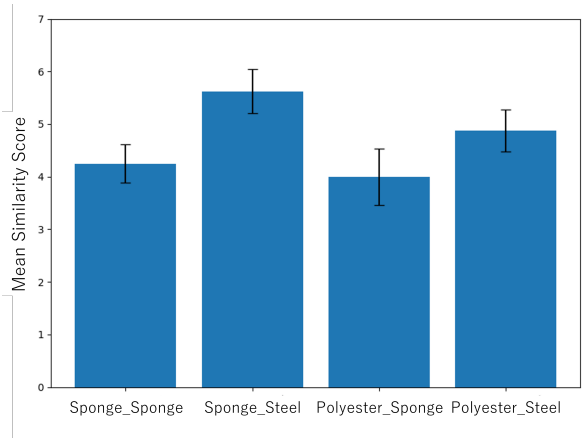

Fig. 3. Mean Evaluation Scores with Standard Errors

IV. Discussion

The results of this study demonstrate that participants were able to differentiate among tactile stimuli generated by an airborne ultrasound tactile display (AUTD) based on perceived similarity to physical models of varying hardness. A repeated measures ANOVA revealed a statistically significant difference in similarity ratings across the four conditions ($F(3,21) = 3.86$, $p = 0.024$), indicating that the perceived tactile impression varied systematically depending on the combination of base and sphere materials.

Notably, the "Sponge base + Steel ball" condition received the highest average rating, suggesting that the mid-air tactile stimulus most closely resembled the sensation of a hard object resting on a soft foundation. This result supports the hypothesis that users perceive the AUTD stimulus not as the material of the sphere itself, but as a composite tactile impression shaped by both the apparent hardness and the mechanical interaction between layers, such as a rigid object pressing into a soft base.

While these findings validate the use of AUTD for simulating relative hardness, qualitative feedback revealed that some participants experienced subtle sensations unrelated to material properties, such as faint airflow around the ultrasound focal point or the absence of thermal cues. Although these factors were not the primary focus of this study, they may have influenced tactile perception and highlight the complexity of evaluating mid-air haptic experiences.

To ensure robust and reliable assessments in future experiments, it is essential to minimize unintended sensory cues, standardize participant instructions, and clearly define the evaluation criteria. In addition, adopting multidimensional evaluation frameworks that incorporate aspects such as perceived temperature, texture, or dynamic response could offer a more comprehensive understanding of mid-air tactile perception.

V. Conclusion

This study showed that participants could distinguish between mid-air tactile stimuli generated by an AUTD and physical models of varying hardness. A repeated measures ANOVA confirmed a significant effect of condition ($F(3,21) = 3.86$, $p = 0.024$), with the "Sponge base + Steel ball" condition receiving the highest similarity ratings.

These results suggest that the AUTD stimulus is perceived not as a material itself, but as a composite impression, similar to a hard object pressing into a soft base. Some participants also reported faint airflow and lack of temperature, which may have subtly influenced perception.

To improve future evaluations, minimizing unintended cues and clearly defining evaluation criteria will be essential. Expanding assessment to include temperature, texture, and other perceptual dimensions could further enhance understanding of mid-air haptics.

Acknowledgement

We acknowledge the use of ChatGPT (OpenAI, 2025) for assistance with text refinement and organization during the preparation of this manuscript. While all final content and interpretations remain the responsibility of the authors, the tool was helpful in enhancing the clarity and fluency of the writing.

References

[1] Shun Suzuki, Seki Inoue, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Autd3: Scalable airborne ultrasound tactile display. *IEEE Transactions on Haptics*, 14(4):740–749, 2021.

[2] Takayuki Hoshi, Masafumi Takahashi, Takayuki Iwamoto, and Hiroyuki Shinoda. Noncontact tactile display based on radiation pressure of airborne ultrasound. *IEEE Transactions on Haptics*, 3(3):155–165, 2010.

[3] Ryoko Takahashi, Keisuke Hasegawa, and Hiroyuki Shinoda. Tactile stimulation by repetitive lateral movement of midair ultrasound focus. *IEEE transactions on haptics*, 13(2):334–342, 2019.

[4] William Frier, Damien Ablart, Jamie Chilles, Benjamin Long, Marcello Giordano, Marianna Obrist, and Sriram Subramanian. Using spatiotemporal modulation to draw tactile patterns in mid-air. In *Haptics: Science, Technology, and Applications: 11th International Conference, EuroHaptics 2018, Pisa, Italy, June 13-16, 2018, Proceedings, Part I 11*, pages 270–281. Springer, 2018.

[5] Tao Morisaki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. Noncontact haptic rendering of static contact with convex surface using circular movement of ultrasound focus on a finger pad. *IEEE Transactions on Haptics*, 17(3):334–345, 2024.