All-in-One Haptic Thimble for Vibration, Pressure, and Thermal Feedback: Investigating the Impact of Vibration Frequency on Thermal Perception

Mohammad Shadman Hashem
Computer Science & Engineering
Kyunghee University
Yongin-si, Gyeonggi-do, South Korea
ayon7019@khu.ac.kr

Ahsan Raza
Computer Science & Engineering
Kyunghee University
Yongin-si, Gyeonggi-do, South Korea
ahsanraza@khu.ac.kr

Seokhee Jeon*
Computer Science & Engineering
Kyunghee University
Yongin-si, Gyeonggi-do, South Korea
jeon@khu.ac.kr

***Abstract*—This paper presents a novel multimodal fingertip actuator that provides simultaneous pressure, vibration, and thermal feedback for enhanced haptic experiences in virtual reality (VR). The actuator integrates a dual-layer silicone structure for tactile feedback with thermal fabric elements, ensuring lightweight, flexible, and ergonomic usability. Pneumatic actuation delivers precise pressure and vibration responses, while a PID-controlled heating mechanism enables realistic thermal sensations. Systematic characterization demonstrates effective force, frequency, and thermal response dynamics. A case study explores the influence of vibration frequency on thermal perception, revealing that perceived thermal intensity remains unaffected by vibration, whereas comfort levels vary with temperature. Additionally, a user experience evaluation confirms the actuator's capability to enhance immersion and realism in VR applications, with findings showing a significant improvement in user experience when thermal feedback is incorporated. This multimodal actuator offers promising applications in VR training, medical simulations, and haptic interfaces, bridging the gap between physical and virtual environments.**

***Index Terms*—Multi-mode haptic feedback, pneumatic actuation, silicon actuator, hot thermal fabric.**

I. Introduction

Virtual reality (VR) replicates real-life experiences by accurately reproducing physical signals using multimodal displays [1]. Over the past few decades, computer graphics and sound synthesis advancements have successfully achieved high performance in generating visual and auditory signals. However, accurately reproducing haptic signals remains a challenge [2]. One of the main reasons is the multimodal nature of haptic feedback, which consists of multiple distinctive signals, including tactile sensations such as pressure, vibration, temperature, and friction, as well as kinesthetic sensations such as force and torque [3].

A comprehensive haptic system should provide all these sensations with the corresponding signals for enhanced immersion. Achieving this requires a high-performance multimodal actuator that displays these signals distinctly and simultaneously without compromising usability [4]. Conventional approaches often rely on integrating multiple actuators, each responsible for different haptic signals. For example, Gallo et al. developed a flexible haptic interface capable of rendering tactile and thermal stimuli using two actuators [5]. Their system combined a hybrid electromagnetic-pneumatic actuator for tactile sensations and a Peltier module for thermal feedback. However, the use of multiple actuators often increases weight and size, limiting usability, particularly when wearability is a priority.

To address these challenges in practical applications, especially in virtual reality (VR) settings, the use of wearable haptic devices has gained significant attention. Wearable haptic devices are recognized for delivering tactile feedback directly to the user's body, enhancing the sense of immersion in virtual environments. They offer portability and ease of use, enabling users to experience realistic sensations without being constrained by stationary equipment [6]–[8]. Nevertheless, integrating multiple actuators into wearable systems often compromises their portability, motivating the need for compact, multimodal actuator designs.

Recent research has explored the development of multimodal haptic actuators capable of generating multiple haptic signals with a single actuator, offering a promising solution to these challenges. Several studies have demonstrated the potential of such actuators. For instance, a pneumatically controlled soft actuator was designed to provide high-frequency vibrotactile and pressure feedback using a single mechanism [9], [10]. Furthermore, these actuators offer several advantages, including lightweight construction, flexibility, high strain density, and ease of fabrication, allowing customization in shape and functionality [11], [12]. Although the initial design only provided one type of feedback at a time using a single air bladder, subsequent developments led to a dual-layer pneumatic actuator capable of providing pressure and vibration feedback simultaneously [13]. However, these designs are primarily limited to mechanical feedback and are incapable of rendering thermal sensations, which restricts their ability to

This research was supported by the MSIT(Ministry of Science and ICT), Korea, in part under the ITRC(Information Technology Research Center) support program(IITP-2025-RS-2022-00156354), and in part under the Mid-Researcher Program (2022R1A2C1008483) supervised by the NRF Korea.

* Corresponding Author

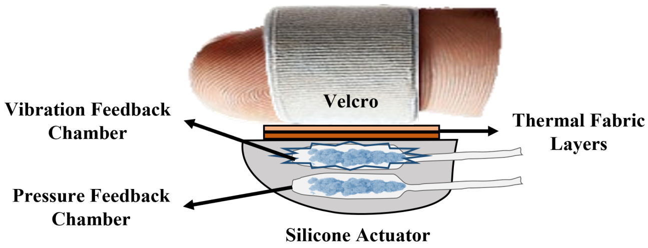

Fig. 1. Schematic diagram of the fingertip actuator.

fully replicate realistic multimodal haptic experiences.

This paper extends the concept of multimodal actuators by presenting a dual-layer silicone actuator capable of generating vibration, impact, pressure, and thermal feedback. To achieve this, two thermal fabric elements with Velcro are integrated with the silicone actuator, enabling the simultaneous delivery of all four feedback modalities. This actuator holds strong potential for safety training, medical education, and rehabilitation by enhancing the realism of virtual training environments. For instance, it can simulate handling hot objects in industrial settings or teach children about common household risks. In medical training, it can replicate the thermal properties, textures, and stiffness of internal organs to improve the effectiveness of surgical simulations.

II. Actuator Design and Fabrication

The proposed system delivers thermal and tactile sensations simultaneously using a single wearable actuator. It provides hot thermal feedback through dual-layer thermal fabric, while pressure and vibration feedback are provided via silicone air chambers. This section presents the design and fabrication process of the actuator.

A. Actuator Design

We present a flexible, lightweight silicone actuator with dual air chambers for providing pressure and vibration feedback. It also includes thermal fabric elements that evenly distribute heat across the fingertip, allowing multimodal haptic feedback in a single device. As shown in Figure 1, the actuator delivers pressure, vibration, and thermal feedback independently or in combination. Its compact and ergonomic design minimizes interference with natural hand movements during VR interactions. The outer silicone wall is non-stretchable to maintain structural integrity, while the inner wall is stretchable to convey tactile sensations precisely. Each chamber connects to a compressed air source via pneumatic tubes and valves for precise control of air volume and pressure.

The silicone actuator is glued with Velcro and two pieces of thermal fabric. The bottom piece of the thermal fabric is spirally stitched with conductive yarn to create precise actuation points for thermal feedback. Another removable piece of the same thermal fabric is added to the top of the bottom piece to ensure evenly distributed heat across the fingertip's surface. Notably, only the edges of the Velcro are attached to the silicone layer and the thermal fabric to avoid interference with the thermal feedback distribution throughout the fabric. The Velcro is securely glued to the silicone layer using silicone adhesive to ensure stability without affecting heat transmission. It allows for adjustments to accommodate different finger sizes.

B. Material Selection and Molding Process

Ecoflex-0030 silicone material was used to mold the silicone layers of our proposed actuator. This flexible and resilient material has the property of 90% elongation at break, and 10 psi modulus of elasticity at 100% elongation [9]. The silicone layer development was carried out using a thorough molding process, as shown in Figure 2 (a). A 3D-printed mold was required to provide the desired shape of the final product. The mold was made of acrylonitrile butadiene styrene (ABS) material. The Ecoflex-0030 material was then poured into the mold and allowed to solidify until it reached a solid state. The material was selected because of its high flexibility, allowing effective tactile feedback through the air chambers.

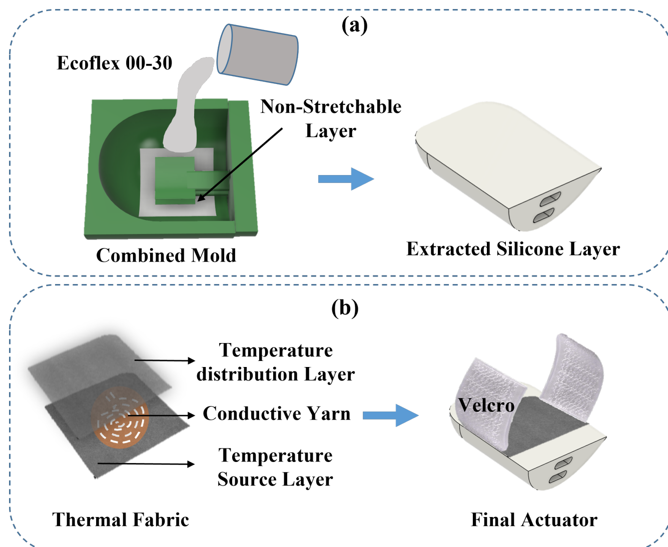

Fig. 2. Mold design and manufacturing process of the final actuator.

EeonTex thermal fabric (Eeontex-NW170-PI-20) was selected for hot thermal feedback. It is flexible, lightweight, and has excellent thermal controllability [14]. This fabric is comprised of polyester and nylon microfibers coated with a conductive polymer, enabling precise thermal sensation generation. As shown in Figure 2 (b), the bottom piece of the fabric is spirally stitched with conductive yarn to create accurate thermal effects. In addition, a removable piece of the same thermal fabric is attached to ensure an even heat distribution across the surface of the fingertip. To finalize the assembly, this thermal fabric is affixed to the silicone layer and Velcro, securing the actuator to the fingertip. As the thermal conductivity of the silicone is relatively low, it does not significantly hinder the dissipation of heat from the thermal fabric, making it a suitable choice for our design.

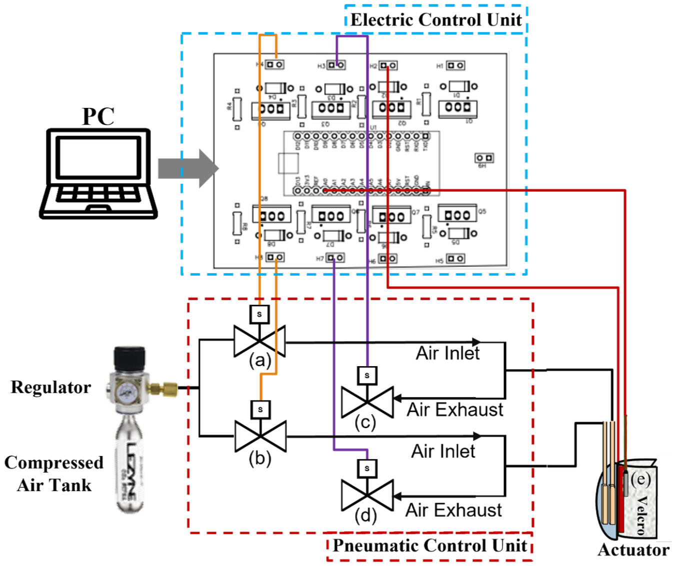

Fig. 3. Proposed system configuration. Inlet solenoid valves (a) and (b); Exhaust solenoid valves (c) and (d); Thermistor (e)

III. System Configuration

The main control mechanism combines pneumatic actuation for tactile feedback and electrical heating for thermal sensation. The airflow is precisely regulated to inflate and deflate the silicone air chambers, while a PID control system with a thermistor manages the temperature of the fingertip. As shown in Figure 3, each air chamber is connected to a pneumatic tube and two air solenoid valves: one for inflow using a positive solenoid valve and one for outflow via a negative solenoid valve. This configuration enables controlled circulation of compressed air for pressure and vibration feedback.

In particular, four digitally-controlled solenoid valves (SC0526GC; Skoocom Technology Co. Ltd.) were used to control the airflow inside the silicone air chambers. Two of the air solenoid valves are positive valves, which let air into the silicone chambers, while the other two are negative valves, allowing air to be released from the chambers. These valves were used to strategically control the pressure and vibration feedback of the proposed actuator [10]. Static pressure is generated by opening the positive valve to let air enter the chamber and then closing it to trap the air, while the negative valve remains closed throughout to maintain the pressure. Vibration feedback is created by quickly opening and closing another set of positive and negative valves in sequence.

Eeontex hot thermal fabric (Adafruit) was used to render the thermal feedback. A thermistor (223Fu3122-07U015, Mouser Electronics) was attached to the top of the thermal point or location created with conductive yarn, enabling control of the closed-loop PID control system. The proportional (Kp), integral (Ki), and derivative (Kd) gains were set to 10, 0.5, and 1, respectively. The system reached a human-perceivable hot temperature within 2–3 seconds with these parameters.

An Arduino Uno microcontroller ensured smooth communication between the computer and the actuator. Through the Arduino, digital and analog output commands were sent to the transistor circuit, enabling serial communication and receiving the analog input data from the thermistor. We incorporated diodes (1N4007) into the circuitry to guarantee the steady operation of these solenoid valves and thermal fabric and minimize transient voltage issues. These orders were used to control the operation of the air solenoid valves and thermal fabric, which in turn produced both tactile and thermal feedback sensations.

IV. Characterization of the Actuator

A series of systematic measurement experiments was conducted to characterize the actuator. It starts with the analysis of its thermal response dynamics, followed by quantitative evaluations of its pressure generation capabilities and vibration performance characteristics.

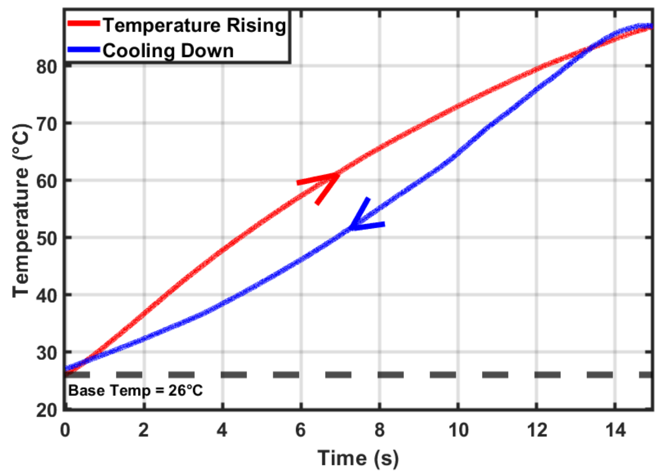

Fig. 4. Temperature measurement over time.

A. Temperature Response for Thermal Feedback

Figure 4 shows the temperature transition of the thermal fabric over a 15-second measurement period. The temperature was monitored using a thermistor (223Fu3122-07U015, Mouser Electronics), with the ambient room temperature maintained at 26°C to provide a consistent baseline. At an analog input voltage of 255, the thermal fabric reached a peak temperature of 87°C after 15 seconds and took an additional 15 seconds to cool back down to baseline once the input voltage was turned off. However, by using a thermistor-based closed-loop system, such as a PID controller, the temperature can be precisely regulated to remain below the human pain threshold, typically under 45°C, ensuring safe operation during use.

B. Force Response for Pressure Feedback

Figure 5 illustrates the relationship between force magnitude and the valve opening duration. A force sensor (Wenzhou SF20) was placed above the actuation chamber of the actuator. This sensor has a force-sensing resolution of 0.01 Newton. Data was recorded at pressure levels of 10 psi by adjusting the pressure regulator. Each pressure level was measured by

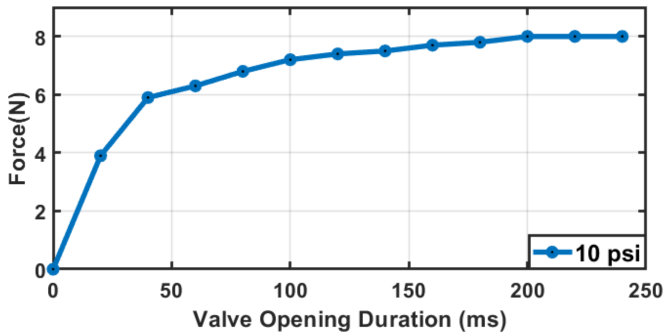

Fig. 5. Force measurement at 10 psi with respect to the valve opening time.

adjusting the duration of the solenoid valve opening in 20-ms increments, from 0 ms to 240 ms. This measurement procedure was repeated 3 times, and the data points were averaged for each step size. The trend peaks at 8 N with a valve opening delay of 200 ms at 10 psi, indicating that saturation occurs at this point.

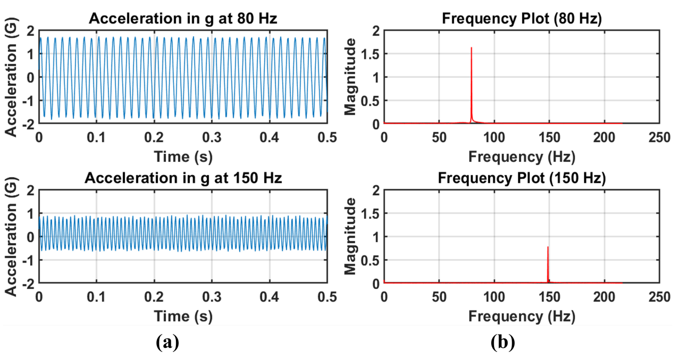

Fig. 6. Examples of vibration measurements in time domain (a) and in frequency domain (b).

C. Acceleration Response for Vibration Feedback

Figures 6(a) and 6(b) show vibration signals under various conditions in the time and frequency domains, respectively. An accelerometer (GY-61) was mounted on the upper air chamber of the silicone actuator. A data collection unit (NI-DAQ 6009) recorded the acceleration data, while MATLAB was used to store the data on the PC. The actuator's ability to provide vibrotactile feedback was evaluated across five frequencies, ranging from 1 Hz to 200 Hz. The maximum amplitude was observed at 80 Hz, with an acceleration of 1.7 g.

V. User Perception and Experience Evaluation

This section demonstrates the actuator's potential through two investigations: a case study evaluating user perception under simultaneous multimodal feedback and a user experience study conducted in a VR environment to assess perceived immersion and realism. During both studies, A total of ten participants (8 male, 2 female; average age 29) participated. Seven had no prior experience with haptic rendering, while three had general knowledge. None reported any conditions affecting hand sensation. All participants provided written informed consent.

A. Case Study 1: Effect of vibration at different frequencies on thermal perception

We indirectly demonstrate the potential of our multimodal actuator through a case study on perception. The study examines the effect of simultaneous multimodal tactile feedback on perception using our system [15]. Specifically, it explores how the frequency of simultaneously delivered vibration feedback influences the perception of temperature. We note that such experiments can be conducted more effectively with multimodal actuators like ours.

1) Previous Work: The integration of thermal and vibrotactile feedback has received growing attention in haptic technology due to its ability to enrich the sensory experience. As a result, researchers have explored how these modalities interact and influence perception, which is critical for designing effective multimodal haptic systems.

Initial studies focused on how vibration affects thermal perception. Thermal perception is influenced by factors such as vibration, temperature intensity, rate of change, and surface properties. Research shows that vibration can increase the cold sensitivity but has little effect on the perception of warmth, especially shortly after exposure [16]. Intermittent and continuous vibrations affect vibrotactile thresholds, although thermal perception generally remains stable [17].

In addition, contact conditions, such as surface texture and pressure, also influence thermal perception. Higher contact pressure improves heat transfer and thermal sensation, while rougher surfaces reduce it by creating air gaps [18]. Rough surfaces can also improve thermal comfort and tactile discrimination at elevated temperatures [19].

The contact force also affects the thermal perception. The stronger force intensifies the sensations of heat and cold [20]. Dynamic effects, such as thermal motion illusions, show that directional tactile cues can enhance thermal motion perception, especially with optimal actuator placement and extreme temperatures [21]. Multimodal systems such as the ThermicVib glove, which combines LRAs and FTEDs, improve spatial and dynamic thermal feedback in VR [22]. Other studies found that high-frequency vibration can interfere with the recognition of thermal patterns, especially cooling, highlighting complex thermo-tactile interactions [23].

In contrast, temperature can influence tactile perception. Non-noxious heat has been shown to improve tactile sensitivity and reduce vibration-induced impairment, with effects depending on the duration of preconditioning and thermal context [24]–[26].

2) Study Design: While previous studies have shown that vibration can influence thermal sensitivity and vice versa, the effect of varying vibration frequencies on simultaneous thermal and vibrotactile feedback remains unexplored. To address this gap, this study examines how different vibration frequencies (1 Hz, 10 Hz, 50 Hz, and 100 Hz) impact the perception of two temperature levels (34 °C and 43 °C). Frequencies above 100 Hz were excluded due to a significant drop in vibration amplitude caused by actuator limitations, which reduced the perceptual impact of vibration on thermal feedback [27], [28]. Therefore, 1–100 Hz was selected as the effective range for reliable and perceivable vibrotactile stimulation. This work advances multimodal haptic system design for broader applications.

3) Experimental Setup and Procedure: The experiment employed the proposed silicone actuator integrated with thermal fabric to deliver simultaneous thermal and vibrotactile feedback. Vibratory stimuli were applied at four frequencies (1 Hz, 20 Hz, 50 Hz, 100 Hz), while thermal feedback was provided at two levels: 34°C (low intensity) and 43°C (high intensity). The thermal fabric maintained the target temperature until participants provided their responses.

Participants were seated in a controlled environment (26°C, 40% humidity) and wore the actuator on their index finger. For each trial, the actuator was activated until the thermal fabric reached the set temperature. Participants then rated their perception of thermal intensity and comfort using open-ended scales, where higher scores reflected greater intensity or comfort.

The experiment included five thermal-tactile conditions (thermal only and thermal with each vibration frequency), repeated across three trials per condition, for both temperature levels, resulting in 30 trials per participant. A within-subjects design ensured that all participants experienced every condition. Trials were randomized to mitigate order effects, and rest breaks were provided to minimize sensory adaptation. This setup enabled a thorough assessment of how vibration frequency influences thermal perception.

4) Results and Discussion: The experimental data collected from the participants showed variability in their rating scales for both the thermal intensity and the level of comfort. To standardize the data for meaningful comparisons, we employed a normalization approach inspired by the mean deviation method [27], [28]. For each participant, we calculated the subjective geometric mean (GM_s) of their ratings across all conditions. The overall geometric mean (GM_g) was derived by aggregating these GM_s values between participants. The normalization factor was then calculated as $GM_{norm} = GM_g/GM_s$, ensuring consistency in the rating scales and minimizing differences between individuals.

The analysis revealed that the participants could significantly differentiate between the two thermal levels (34°C versus 43°C) at all vibration frequencies tested (0 Hz, 1 Hz, 20 Hz, 50 Hz, and 100 Hz), as shown in Figure 7(a). Statistical analysis indicated a high level of significance ($p < 0.01$) in the perceived magnitude of thermal intensity between the two temperature levels. However, the vibration frequency had no significant effect on the perceived magnitude of thermal intensity ($p > 0.05$). This suggests that the perception of thermal intensity within the 34°C to 43°C range is primarily governed by the absolute temperature, with low-frequency vibrations (1–100 Hz) exerting negligible influence on participants' thermal ratings within this range.

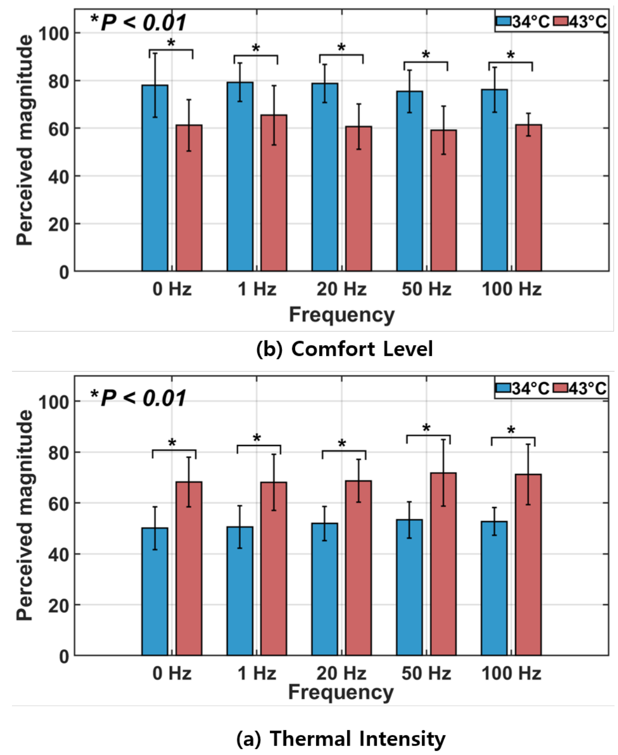

Fig. 7. Perceived magnitude of (a) thermal intensity and (b) comfort level. Significant differences are marked with p <0.01.

Similarly, the perceived magnitude of the comfort level demonstrated a significant differentiation between the two thermal levels at all vibration frequencies ($p < 0.01$), as illustrated in Figure 7(b). Participants consistently rated the 34°C condition as more comfortable than the 43°C condition, regardless of the vibration frequency. No significant interaction effect between temperature and vibration frequency was observed ($p > 0.05$). The results indicate that comfort levels were only influenced by thermal conditions, with vibration frequency having minimal effect on participant comfort ratings.

Qualitative feedback from participants aligned with these findings. They consistently reported that the thermal stimuli were clear and distinguishable, with vibration frequencies perceived as secondary to the thermal sensation. No noticeable interaction between vibration and thermal perception was described, further supporting the conclusion that vibration did not alter the perceived magnitude of thermal intensity or comfort level in this experimental setup.

B. Case Study 2: User Experience Evaluation

To demonstrate the effectiveness of the rendered feedback using our proposed actuator, a virtual scenario featuring a bowl of liquid placed on a stove with fire was developed using Unity Game Engine (version 2021.3.11f1). This setup enabled users to simultaneously experience contact pressure, vibration, and thermal feedback, highlighting the actuator's multi-functional capabilities. In the virtual environment, user hand movements were tracked using a Leap Motion sensor for seamless interaction.

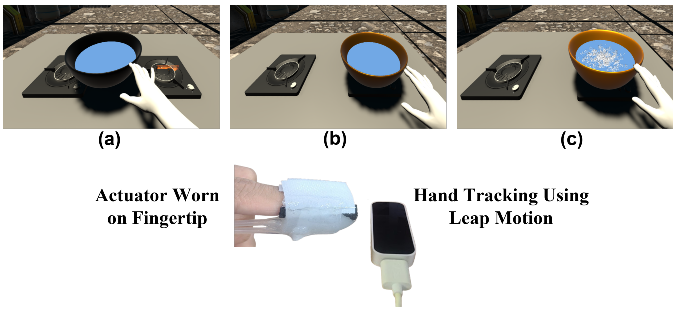

Fig. 8. Finger tracking and application used in the study. Three different interaction scenarios are implemented: (a) Contact pressure feedback only, (b) Simultaneous pressure and thermal feedback, (c) Simultaneous pressure, thermal, and vibration feedback.

Figure 8 illustrates the rendering hardware and the virtual scenarios. In the VR scenario, users initially touch a bowl filled with liquid at a normal temperature, experiencing only contact pressure feedback. When the bowl is placed on a stove and the heat is turned on, the bowl changes color and begins to heat up. At this stage, users experience both contact pressure and thermal feedback simultaneously. As the liquid starts to boil, users perceive simultaneous pressure, thermal, and vibration feedback. The time it takes for the liquid to begin boiling varies depending on the type of liquid.

1) Experimental Setup and Procedure: A perceptual user study was conducted to observe the perceived immersion (How engaged did the user feel with the virtual environment while interacting with the haptic feedback?) and overall realism (How similar did the overall interaction feel compared to a real-world situation?) of our rendered feedback in the VR environment. We compared the tactile feedback (pressure and vibration) with and without thermal feedback. In the user study, participants rated their perceived immersion and overall realism for each type of feedback (Tactile Feedback and Tactile plus Thermal Feedback) after experiencing the VR scenario, using a visual analog scale ranging from 0 to 100. On this scale, 0 indicated ”not immersive at all” or ”not realistic at all,” and 100 indicated ”extremely immersive” or ”highly realistic.” Participants were informed of this scale’s definition prior to providing their responses.

2) Result and Discussion: As illustrated in Figure 9, the mean scores for the tactile plus thermal feedback condition, evaluated based on the two metrics perceived immersion and overall Realism, are 86.63% and 89.38%, respectively. To analyze the data statistically, we performed a one-way ANOVA with repeated measures. Post hoc comparisons using the Tukey test revealed significant differences ($p < 0.001$) between tactile plus thermal feedback and tactile feedback only for the two metrics (perceived immersion and overall realism). These results demonstrate a significant improvement compared to the scores observed in the tactile-only feedback condition, highlighting the enhanced effectiveness of the multimodal feedback

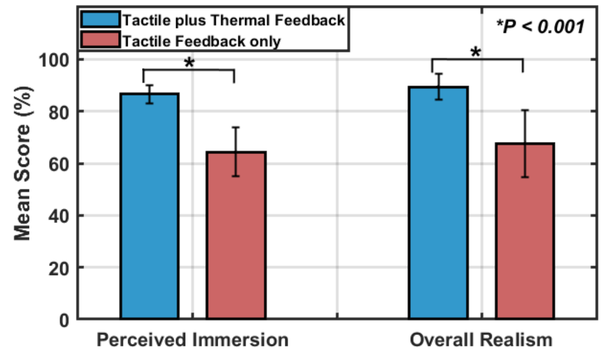

Fig. 9. Mean score and standard deviation of user study.

system. The inclusion of thermal feedback not only amplifies the user’s sense of immersion but also contributes to an overall higher realism level, as evidenced by the consistently superior mean scores across both metrics.

VI. Conclusion and Limitation

This paper presents a silicone-based fingertip actuator integrated with hot thermal fabrics designed to provide realistic tactile and thermal sensations. The actuator delivers pressure, vibration, and thermal feedback simultaneously, using a combination of a dual-layer silicone actuator and thermal fabrics. The operation relies on pneumatic actuation and PID control mechanisms, allowing users to experience subtle tactile sensations and temperature variations that mimic real-world interactions.

The actuator is designed to be adaptable, accommodating various finger sizes with a Velcro mechanism and featuring adjustable air chambers to control feedback intensity. Additionally, thermal modulation was tested to enhance the realism of interactions with virtual objects at different temperatures, successfully demonstrated on a virtual hot bowl of liquid.

However, the actuator is currently limited to generating only hot thermal sensations and requires a noticeable amount of time to reach the target temperature due to the thermal fabric’s heating dynamics. In addition, we observed that the performance of the thermal fabric may degrade over time due to continuous contact with human skin. To address long-term wearability and facilitate integration with other haptic devices, we developed a dual-layer thermal fabric system. In this design, the top layer, which comes into direct contact with the skin, can be easily removed and replaced without affecting the actuator’s overall performance.

Despite these limitations, the actuator remains a valuable tool for haptic feedback applications because of its lightweight, flexible structure and ergonomic design, which minimize interference with natural finger movements and allow for seamless integration into virtual environments. These features make it particularly well-suited for immersive haptic systems and virtual reality applications.

REFERENCES

[1] Pietro Cipresso, Irene Alice Chicchi Giglioli, Mariano Alcañiz Raya, and Giuseppe Riva. The past, present, and future of virtual and augmented reality research: a network and cluster analysis of the literature. *Frontiers in psychology*, 9:309500, 2018.

[2] RK Venkatesan, Domna Banakou, and Mel Slater. Haptic feedback in a virtual crowd scenario improves the emotional response. *Frontiers in Virtual Reality*, 4:1242587, 2023.

[3] Heather Culbertson, Samuel B Schorr, and Allison M Okamura. Haptics: The present and future of artificial touch sensation. *Annual Review of Control, Robotics, and Autonomous Systems*, 1:385–409, 2018.

[4] Mingyu Kang, Cheol-Gu Gang, Sang-Kyu Ryu, Hyeon-Ju Kim, Da-Yeon Jeon, and Soonjae Pyo. Haptic interface with multimodal tactile sensing and feedback for human–robot interaction. *Micro and Nano Systems Letters*, 12(1):9, 2024.

[5] Simon Gallo, Choonghyun Son, Hyunjoo Jenny Lee, Hannes Bleuler, and Il-Joo Cho. A flexible multimodal tactile display for delivering shape and material information. *Sensors and Actuators A: Physical*, 236:180–189, 2015.

[6] Zhong-Yi Zhang, Hong-Xian Chen, Shih-Hao Wang, and Hsin-Ruey Tsai. Elaxo: Rendering versatile resistive force feedback for fingers grasping and twisting. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*, pages 1–14, 2022.

[7] Hirotoshi Kosawa and Satoshi Konishi. Wearable hand motion capture device. In *2018 IEEE CPMT Symposium Japan (ICSJ)*, pages 129–130, 2018.

[8] Hesen Dai, Chen Yiming, Wang Mingkun, Dong Sun, and Hongyi Lin. Design of multi-channel tactile feedback digital glove for virtual reality. *IEEE Sensors Letters*, 2024.

[9] Aishwari Talhan, Hwangil Kim, and Seokhee Jeon. Tactile ring: Multi-mode finger-worn soft actuator for rich haptic feedback. *IEEE Access*, 8:957–966, 2019.

[10] Ahsan Raza, Waseem Hassan, and Seokhee Jeon. Pneumatically controlled wearable tactile actuator for multi-modal haptic feedback. *IEEE Access*, 2024.

[11] Daisuke Sasaki, Toshiro Noritsugu, and Masahiro Takaiwa. Development of active support splint driven by pneumatic soft actuator (assist). In *Proceedings of the 2005 IEEE international conference on robotics and automation*, pages 520–525. IEEE, 2005.

[12] Aslan Miriyev, Kenneth Stack, and Hod Lipson. Soft material for soft actuators. *Nature communications*, 8(1):596, 2017.

[13] Mohammad Shadman Hashem, Joolekha Bibi Joolee, Waseem Hassan, and Seokhee Jeon. Soft pneumatic fingertip actuator incorporating a dual air chamber to generate multi-mode simultaneous tactile feedback. *Applied Sciences*, 12(1):175, 2021.

[14] Eontex Thermal Fabric. Eontex high-conductivity heater fabric-nw170-pi-20,. https://www.adafruit.com/product/3670,/, 2018. Available online; accessed 5 September 2018.

[15] Lynette A Jones and Hsin-Ni Ho. Tactile–thermal interactions: Cooperation and competition. *IEEE Transactions on Haptics*, 2025.

[16] Lage Burström, Ronnie Lundström, Fredrik Sjödin, Asta Lindmark, Markus Lindkvist, Mats Hagberg, and Tohr Nilsson. Acute effects of vibration on thermal perception thresholds. *International archives of occupational and environmental health*, 81:603–611, 2008.

[17] Lage Burström, Mats Hagberg, Ronnie Lundström, and Tohr Nilsson. Influence of vibration exposure on tactile and thermal perception thresholds. *Occupational medicine*, 59(3):174–179, 2009.

[18] Jessica Galie, Hsin-Ni Ho, and Lynette A Jones. Influence of contact conditions on thermal responses of the hand. In *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 587–592. IEEE, 2009.

[19] Han Zhang and Alan Hedge. The effect of surface texture on thermal sensation and comfort. In *International Electronic Packaging Technical Conference and Exhibition*, volume 58097, page V001T01A026. American Society of Mechanical Engineers, 2017.

[20] Danilo Troisi, Jeanne Hecquard, Ferran Argelaguet, Justine Saint-Aubert, Marc Macé, Anatole Lécuyer, Claudio Pacchierotti, and Monica Malvezzi. Studying the influence of contact force on thermal perception at the fingertip. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, pages 154–161. Springer, 2024.

[21] Yatharth Singhal, Daniel Honrales, Haokun Wang, and Jin Ryong Kim. Thermal in motion: Designing thermal flow illusions with tactile and thermal interaction. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*, pages 1–13, 2024.

[22] Hyung Ii Yi, Hojeong Lee, and Sang Ho Yoon. Thermicvib: Enabling dynamic thermal sensation with multimodal haptic glove for thermal-responsive interaction. In *2024 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 614–623. IEEE, 2024.

[23] Anshul Singhal and Lynette A Jones. Perceptual interactions in thermo-tactile displays. In *2017 IEEE World Haptics Conference (WHC)*, pages 90–95. IEEE, 2017.

[24] Zheng Zhang, Eric M Francisco, Jameson K Holden, Robert G Dennis, and Mark Tommerdahl. The impact of non-noxious heat on tactile information processing. *Brain research*, 1302:97–105, 2009.

[25] Joseph C Stevens. Temperature can sharpen tactile acuity. *Perception & psychophysics*, 31(6):577–580, 1982.

[26] Barry G Green. The effect of skin temperature on vibrotactile sensitivity. *Perception & Psychophysics*, 21:243–248, 1977.

[27] Ahsan Raza, Waseem Hassan, Tatyana Ogay, Inwook Hwang, and Seokhee Jeon. Perceptually correct haptic rendering in mid-air using ultrasound phased array. *IEEE Transactions on Industrial Electronics*, 67(1):736–745, 2019.

[28] Anne M Murray, Roberta L Klatzky, and Pradeep K Khosla. Psychophysical characterization and testbed validation of a wearable vibrotactile glove for telemanipulation. *Presence: Teleoperators & Virtual Environments*, 12(2):156–182, 2003.