Flip-Pelt: Motor-Driven Peltier Elements for Rapid Thermal Stimulation and Congruent Pressure Feedback in Virtual Reality

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Figure 1: The Flip-Pelt system showcases a motor-driven peltier element concept, utilizing the dual-sided functionality of pre-heated or cooled elements and enabling rapid thermal transitions with a 450ms motor operation speed. Moreover, this design simulates the stiffness of contact materials through congruent pressure feedback alongside thermal sensations.

ABSTRACT

This study introduces "Flip-Pelt," a motor-driven peltier device designed to provide rapid thermal stimulation and congruent pressure feedback in virtual reality (VR) environments. Our system incorporates eight motor-driven peltier elements, allowing for the flipping of preheated or cooled elements to the opposite side. In evaluating the Flip-Pelt device, we assess user ability to distinguish between heat/cold sources by their patterns and stiffness, and its impact on enhancing haptic experiences in VR content that involves contact with various thermal sources. Our findings demonstrate that rapid thermal stimulation and congruent pressure feedback provided by Flip-Pelt enhance the recognition accuracy of thermal patterns and the stiffness of virtual objects. These features also improve haptic experiences in VR scenarios through their temporal congruency between tactile and thermal stimuli. Additionally, we discuss the scalability of the Flip-Pelt system to other body parts by proposing design prototypes.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; Virtual reality.

KEYWORDS

Multimodal Haptics, Thermal Feedback, Virtual Reality

ACM Reference Format:
Seongjun Kang, Gwangbin Kim, Seokhyun Hwang, Jeongju Park, Ahmed Elsharkawy, and SeungJun Kim. 2024. Flip-Pelt: Motor-Driven Peltier Elements for Rapid Thermal Stimulation and Congruent Pressure Feedback in Virtual Reality. In *The 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24), October 13–16, 2024, Pittsburgh, PA, USA.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3654777.3676363

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UIST '24, October 13–16, 2024, Pittsburgh, PA, USA

ACM ISBN 979-8-4007-0628-8/24/10
https://doi.org/10.1145/3654777.3676363

1 INTRODUCTION

Our perception of objects and environments results from the integration of information across our multisensory channels [7]. In virtual reality (VR) environments, multisensory stimuli enhance user presence and create a realistic experience [21]. This enhanced presence and realism can be achieved through the spatial and temporal congruence of multisensory stimuli [23, 46, 47], with congruent pairs leading to stronger perceptual binding [90]. In response, interactive technologies and interfaces have been developed to offer sensations congruent with the visual information provided by head-mounted displays (HMDs). Haptic feedback, such as vibrations [36, 41, 42, 44, 52, 71], pressure [8, 13, 45], texture [28, 79], electrotactile [18, 37–39, 92] and temperature [29, 56, 69, 100], were used to provide bodily sensations that align with visual experience. Among these sensations, temperature feedback contributes to user immersion in VR by providing overall atmosphere and event-specific sensations.

Temperature feedback shapes the perception of environmental conditions, such as weather [9] and subtly modulates the emotional perception of scenes by altering valence and arousal [1, 97]. It can also provide an event-specific sensation of virtual objects' temperature, helping to identify objects during interaction [81] and enhancing user engagement [29]. Despite the duality of its role, thermal feedback has been geared more toward presenting ambient information or creating an atmosphere through environmental temperature cues [57]. By contrast, human perception when interacting with objects is the result of visual, thermal, and tactile experiences. For example, visual, thermal, and pressure information is processed and integrated when sensing the touch and grasp of objects. The concurrent presentation of thermal and tactile cues in VR influences the user's perception of stimuli from each feedback method [81]. However, providing thermal feedback that adapts to interactions such as touching objects with specific temperature configurations remains challenging because of the required level of temporal congruency between the touch and temperature sensations.

Modern approaches for thermal haptic feedback in VR employ peltier elements [2, 59, 69, 74, 96, 100] or fluid mediums [6, 29, 29, 31, 55, 56, 75] as sources of warmth and coolness feedback. While the either method can attain spatial congruency in thermal-pressure sensation with their co-located hardware design, it has limited temporal congruency owing to the response times for the feedback to be delivered to users. Although the temperature of peltier elements can be regulated by the applied current, their time-temperature characteristics feature seconds-level response times to reach target warmth or coolness. While fluid-based methods have faster response times by using preheated or cooled mediums, they still require time for the fluids to be delivered from the chamber to the target stimulus area. The response time required for thermal feedback can result in reduced temporal congruency between visual, pressure, and thermal experiences, specifically in scenarios requiring frequent physical contact with objects (e.g., feeling the temperature of a hot pan a few seconds after grasping it). Thus, temporal congruency between thermal and pressure feedback is required to leverage multisensory integration to provide the sensation of interacting with objects, enhancing stimulus recognition, and immersion in VR.

To address these issues, we present Flip-Pelt, a co-located thermal and pressure haptic device for rapid thermal feedback using servo motors to flip and press the cool and warm sides of the peltier elements. We report on the design and implementation of our system, the thermal characteristics of the device, and the user experience with the device. In a two-fold user study, we tested users' proficiency in recognizing stimuli with different shapes and stiffnesses and examined how rapid thermal stimuli and pressure feedback affect the user experience in terms of their haptic experience by providing congruency between multimodal sensations.

2 RELATED WORK

2.1 Thermal and Pressure Feedback in VR

As we use our haptic sensory modalities to interact with objects, we integrate visual and haptic information to form a unified understanding of the object. People perceive objects by integrating visual and haptic information into a shared multisensory representation, with a common neural substrate involved for both [54]. Co-location of haptic and visual feedback improves user task performance [65] and immersion in VR [12]. Similarly, within haptic modalities, multisensory involvement of distinct receptors in the skin forms haptic sensation [25, 94]. In response, devices have been designed to provide multimodal haptic stimuli. For instance, the work by Zhu et al. was designed to provide the sensation of compression, skin stretch, and vibration using sleeves [102]. Likewise, devices to provide different kinds of haptic stimuli were suggested to benefit from multisensory involvement [13, 72, 99]. These multisensory stimuli improve the perceptual distinguishability of haptic cues [16, 85], user task performance [64], as well as usability and expressiveness [102].

Human perception of an object is not limited to its size, location, and contact, but also includes the sensed material properties when touching it. For instance, the perception derived from grasping an object includes its shape, warmth, and elasticity. Together with visual information, the perception of an object's properties is governed by the integration of multiple haptic cues, including compliance related to indentation depth and contact area [4, 14, 53] and heat exchange between the skin and the object [35, 87]. The heat exchange and compliance are intertwined; the contact area and the temperature difference between the skin and the object, along with the object's compliance, all influence heat exchange [35]. Due to the intertwined nature of both sensations, our perception precision of tactile information increases with thermal feedback, especially at a greater difference from skin temperature [19].

Despite their role in human perception of an object's properties, only a few studies explore the simultaneous provision of temperature and pressure feedback, mainly due to the difference in responsiveness of each actuation. While tactile stimuli feature rapid transmission, peltier elements for thermal feedback exhibit response times of a few seconds unsuitable for rapid interaction. Instead, pneumatic methods with prewarmed or cooled fluid medium from chambers were used to simulate grasping warm or cool objects [6]. Similar approaches with water tubes at different temperatures were used to stimulate both pressure and temperature on the forearm [24, 56], or silicone bubbles using chambers for the modular delivery of thermal and pressure sensations across various body parts

[100]. While these methods provide faster thermal feedback than peliter elements, the response time required for fluids to travel from the chamber could be improved for more frequent interactions.

Given the integrated perception of haptic information, spatially aligned provision of pressure and temperature cues can provide a realistic haptic experience for object interactions. However, conventional peltier element-based devices assume default contact on skin to compensate for its late responsiveness and thus were mostly accompanied by time-synchronized tactile feedback without positional synchronization. Recent work by Mazursky et al. [60] used flexible conductors with peltier elements to provide passive haptics for grasping experiences with thermal feedback. This work aligns more closely with the actual object interaction by positioning a peltier-connected device near the hand for potential passive haptic encounters. As demonstrated by Mazursky et al. [60], leveraging the spatial congruence between thermal and haptic feedback through peltier elements, we design the active contact of peltier elements to provide pressure feedback in a way that mirrors actual object interactions. Specifically, our Flip-Pelt system uses flipping peltier elements for thermal sensation to provide active pressure feedback, providing a co-located multisensory haptic experience.

2.2 Rapid Thermal Feedback in VR

Peltier elements have been widely explored as a method to deliver thermal feedback due to their ability to control temperature by adjusting the current's magnitude and direction. By controlling the direction of the current, peltier elements can be made either warm or cool, allowing both sided feedback in VR. Due to the compact size of peltier elements and their ability to provide warm and cool feedback without additional materials, they were integrated into electronic systems for thermal feedback to human body parts. The small possible form factor enabled their use at locations like fingertips [22] and fingernails [63], in shapes of a ring wearable on a finger [101] or a wristband-shaped thermal stimulation device [68]. Peltier elements attached to head-mounted displays [67, 69] have been used to offer directional signals and enhance immersive experiences related to the surrounding environment. The application scenarios of these devices in VR were mainly centered around gradual temperature changes [59, 63, 68, 89, 101], providing atmospheric sensations via temperature feedback for enriched multimedia experiences such as movies [59] and music [2] or simulating ambient temperatures [67, 69]. This is because peltier elements exhibit a delay in reaching target temperatures due to their constrained temperature change rate, as evidenced by reported thermal response rates of ±1 °C/s [2], ±3 °C/s [30, 69], and ±4 °C/s [59]. This thermal characteristic made them more favorable for simulating moods or atmospheres than simulating physical contact with sources of heat or cold that require rapid temperature changes.

Alternatively, fluid medium-based methods were employed for quicker presentation of object-specific thermal sensations [55, 75]. Since these methods deliver prewarmed or cooled water or air to the target area, they showed faster response time than peltier elements, allowing their uses in scenarios to present the properties of virtual objects [29]. For example, they were used to provide thermal sensations in VR on the abdomen [29], arms [29, 56], palm [6], and fingertip [31] via tube networks. Due to the prewarming and cooling, these systems generally require independent chambers for both sensations, unlike peltier elements which can provide simultaneous cooling and heating on each side. The use of fluid chambers could limit their usage to stationary settings, where people are within a reachable distance to the chamber, which should be short to maintain the desired temperature. Also, the time for the fluid to travel from the chamber to the target area is inevitable, though it is fast. Its use in frequent thermal transition scenarios where users constantly touch and detach from objects is less applicable. While these systems offer prompt transitions, they sometimes provide limited resolution stimuli due to the complexity of fluid control, mixing, and temperature regulation.

The choice between peltier and fluid-based approaches depends on their distinct characteristics and suitability for application scenarios. While peltier elements-based approaches are more applicable for mobile VR scenarios and high-resolution stimuli due to their small form factors, their response time to reach the target temperature is less suitable for human-object interaction scenarios in VR where prompt changes in temperature are abundant. Conversely, fluid-based methods, which provide rapid thermal stimulations with preheated or cooled fluid mediums transferred via network tubes, are ideal for interactive experiences but face challenges in resolution and mobility. Considering these trade-offs, Flip-Pelt leverages the strengths of both approaches, providing rapid thermal stimulations suitable for dynamic VR interactions. Drawing inspiration from the preheating and cooling strategies of fluid systems, Flip-Pelt preconditions the temperature of peltier elements and contact them for rapid thermal feedback. This method, by enabling direct contact with prewarmed or cooled peltier elements, replicates the process of physically feeling temperatures of objects in the real world and provides thermal feedback congruent to the visual experience.

3 IMPLEMENTATION

3.1 Hardware Implementaion

We developed a peltier module capable of flipping, with each element connected to a servo motor for a rotation of up to 270°. This configuration offers thermal stimuli controlled by the motor's rapid reaction, surpassing the slower response of the peltier elements (Figure 2). To ensure tight contact between the skin and the rotating peltier elements, parallel contact with rotation was designed using elastic bands and rotation pivots (a combination of bolts and Nylon insert locknuts as shown in Figure 3 (a)). For warm sensory stimulation, the elements were flipped to the warm side; for cool sensory stimulation, the elements were flipped to the cool side. The system utilizes an Arduino Nano 33 IoT for the overall control and H-bridge DC motor drivers to manage the peltier elements. NTC thin-film thermistors (MF5B 10K) attached to each element group ensured temperature monitoring, enabling integrated control mechanisms.

Due to the thermodynamics of peltier elements, when one side cools, the opposite side simultaneously becomes hotter. To manage this temperature differential and ensure that each side of the element can be adjusted to a temperature range conducive for stimulation, the device was designed with a multi-layer structure, comprising a 1mm thick aluminum plate and a 3mm thick silicone layer (Figure 3 (b)). The high thermal conductivity of aluminum was positioned on the hot side to facilitate heat dissipation from

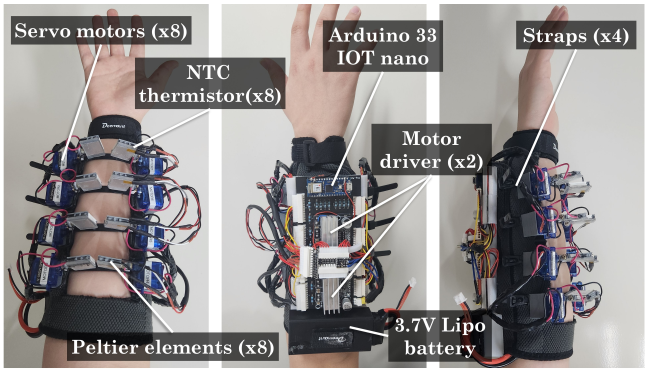

Figure 2: Hardware configuration of the Flip-Pelt device. (Left) Front view showing servo motors, temperature sensors, and peltier elements. (Center) Back view showing the battery, motor driver, and microcontroller.

the hot ceramic side of the peltier element, preventing excessive heat from moving through the np-junction semiconductor to the cooler side. The silicone layer acts as a barrier, preventing direct heat conduction from making contact with the skin for user safety. This arrangement ensures that the warm side does not become excessively hot while maintaining the cool side within a temperature range suitable for cooling sensations.

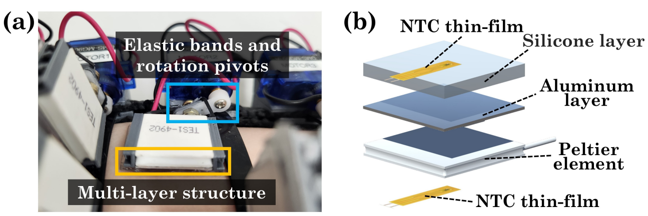

Figure 3: Detailed design of the dual-sided peltier element: (a) Utilizing elastic bands and rotation pivots, (b) Multi-layer composition.

3.2 Technical Evaluation

3.2.1 Thermal Behavior of a Dual-Sided Peltier Element. To determine the optimal input voltage for dual-sided peltier elements with multi-layer designs, we measured the time-dependent temperature changes in these elements. This involved operating TES1-4902 peltier elements, sized 20 mm × 20 mm with multi-layer structures, using voltages that ranged from 1 V to 5 V in 0.5 V increments. To ensure user safety, current of each elements are adjusted by PID controller to prevent exceeding the maximum warm side temperature of 40 °C, starting from an initial condition with the peltier element's temperature at 25 °C. Each voltage setting was tested three times, and average temperature values for the time-voltage relationships ranging from 1.5 V to 3.0 V input voltage are plotted in Figure 4.

Initially, the temperature on the cool side decreased as the temperature on the warm side of the element increased. However, after a certain period, heat conduction from the warm to cool side occurred, causing the temperature on the cool side to gradually increase until it reached the warm side temperature. The activation threshold of the TRPV3 (Transient Receptor Potential Vanilloid 3) channel, which detects warm sensations, is approximately 31 °C to 40 °C [98]. Additionally, the TRPM8 (Transient Receptor Potential Melastatin 8) channel, which is responsible for detecting cool sensations, becomes active within a temperature range of approximately 8 °C to 28 °C [61]. Therefore, we define the "warm sensation range" as the activation temperature of the TRPV3 channel and the "cool sensation range" as the activation temperature of the TRPM8 channel. The intersection of these ranges facilitates the perception of both warm and cool sensations; hence, we define this overlapping range as the "dual-sided peltier element lifetime".

At 1.5 V input, the temperature of the warm side did not reach the maximum of 40 °C within the dual-sided peltier element lifetime (M = 192.3 s, SD = 3.37 s), and it took 100 s to enter the lifetime phase. From 2.0 V input onwards, the warm side's temperature achieved the maximum temperature within the dual-sided peltier element lifetime (M = 196.1 s, SD = 4.77 s), providing sufficient thermal and cooling sensations, with the entry into the lifetime phase occurring within 56 s. At inputs of 2.5 V and 3.0 V, although similar trends to 2.0 V were observed, the dual-sided peltier element lifetime gradually decreased (2.5 V: M = 133.8 s, SD = 9.22 s; 3.0 V: M = 101.3 s, SD = 4.74 s). Therefore, to ensure the longest duration of both thermal and cooling sensations and a shorter entry time into the dual-sided peltier element lifetime phase, we determined the optimal operating input voltage for the peltier elements as 2.0V.

3.2.2 Power Consumption and Lifetime of the Flip-Pelt Device. Although the peltier element used could operate at a maximum power consumption of 7.5 W per element (5.0 V, 1.5 A), requiring 60 W in total, the Flip-Pelt prototype operates at a power consumption of 1.2 W per peltier element (2.0 V, 0.6 A), totaling 9.6 W for controlling eight elements. In our configuration, the device was powered with a 3.7 V, 2200 mAh Li-Po battery, which allowed for approximately 51 min of operation. However, as demonstrated in Section 3.2.1, the duration of reliable operation in a single session to experience warm or cool sensations is 196 s, the elements require approximately 5 min to cool down to the initial temperature of 25 °C, making them ready for reuse.

3.2.3 Flip-Pelt Device's Operating Latency. The total latency of our device is approximately 480 ms. This duration encompasses detecting contact with a virtual object in Unity3D (10 ms), sending and receiving commands between the Unity and Arduino board (20 ms), and actuating the motors (based on the maximum travel distance: 0° to 270°) to make contact with the skin (450 ms).

3.3 Software Implementation

The Flip-Pelt device functions within the VR content utilizing the Unity engine, with its software system comprising upper body tracking, contact detection with virtual objects, and virtual pressure simulation. We implemented the upper body tracking functionality using the inside-out tracking capability of the Meta Quest 3. To detect contact with virtual objects, we positioned eight collision bumpers at the peltier element locations. When a collision bumper encounters a virtual object in Unity, its predefined warm or cool

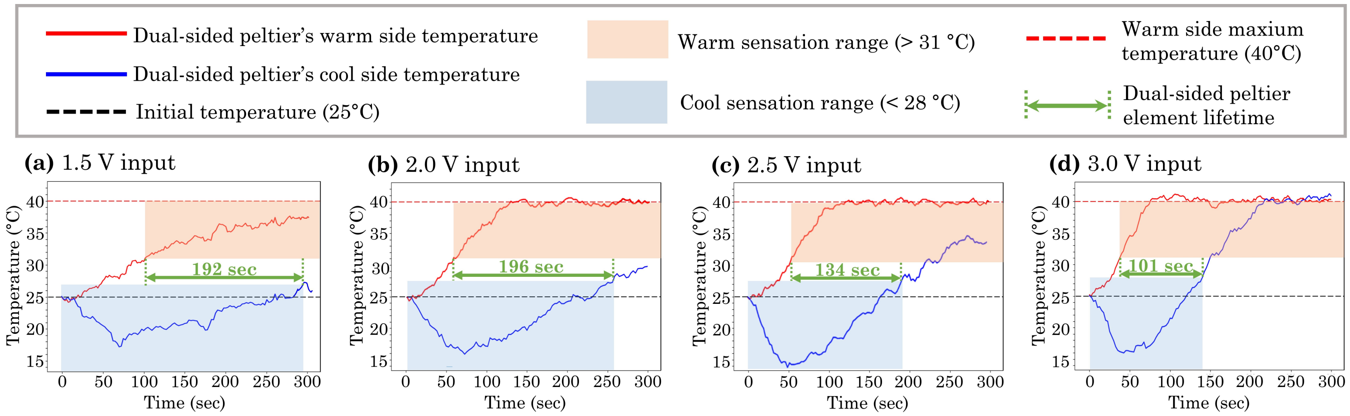

Figure 4: Measurement of time-dependent temperature and lifetime of the dual-sided peltier element (input range 1.5–3.0V)

attributes of the virtual object determine the direction in which the peltier element flips.

To simulate the pressure stimulated by flipping according to the stiffness of the contacted virtual object, we utilize the Young's modulus values measured for internal forearm deformation from previous research (14.0 ± 5.0 kPa [49], 14.38 ± 3.61 kPa [3]) along with the predefined Young's modulus of the virtual object. Subsequently, the Maxwell viscoelastic model [29] was converted into an executable code within the Unity engine to calculate the virtual pressure. This simulation can determine the depth at which the virtual object penetrates the skin (Figure 5 (b)) and convert that depth into the operating angle of the peltier element (Figure 5 (c)), personalizing the angle at which the peltier element makes contact with the skin for each wearer.

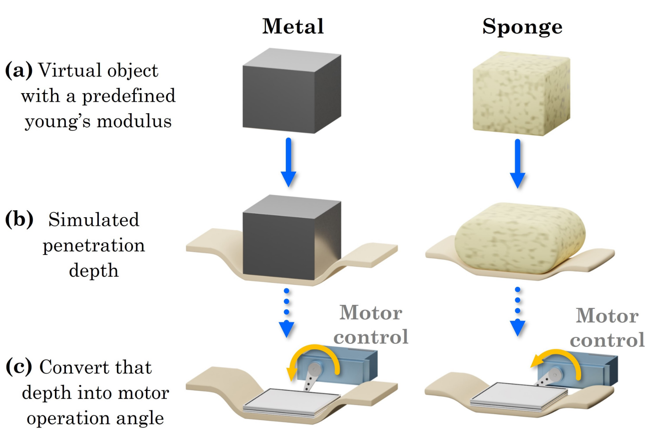

Figure 5: Virtual pressure simulation overview: (a) Virtual objects with predefined Young's modulus (e.g., Metal, Sponge), (b) Skin penetration depth calculation, (c) Servo motor angle adjustment based on calculated penetration depth.

4 STUDY 1: FLIP-PELT'S THERMAL AND PRESSURE FEEDBACK RECOGNITION TEST

The Flip-Pelt device was developed to simulate the contact between virtual sources of heat and cold. With eight modules, this device is capable of delivering stimuli with diverse patterns and stiffness. Despite their functionality, the ability of users to perceive and distinguish these stimuli as separate sensations has yet to be examined. As the device targets scenarios where temperature and stiffness are felt simultaneously, understanding how synchronized thermal and pressure stimuli improve object perception is crucial. Consequently, we evaluated the users' ability to recognize differences in stimuli patterns and stiffness, with the findings compiled in a confusion matrix, and investigated how rapid thermal stimuli synchronized with pressure feedback could enhance stimulus recognition. This leads to the formulation of the first research question:

- RQ1: Can Flip-Pelt users distinguish the stimuli patterns and stiffness levels on the forearm? If so, how do rapid thermal feedback and pressure influence their recognizability?

4.1 Comparative Conditions Design

This study utilized four conditions to compare the accuracy of the recognition for stimulus patterns and stiffness with the Flip-Pelt system. We identified (1) thermal stimulation methods and (2) the presence of pressure feedback as the variables of the user study. For thermal stimulation, two approaches were employed: the current direction control, which is commonly used in traditional peltier element-based devices [59, 69, 100], and the method of flipping peltier elements. To enable a fair comparison, we applied a maximum operating voltage of 5V to the current control method to achieve rapid temperature targets. Moreover, conditions without pressure feedback utilized the peltier elements in simple contact with the skin, primarily for heat transfer purposes [59, 69, 89], while conditions with pressure feedback provided an additional tactile sensation alongside the thermal perception [56, 100], leading to a total of four conditions (2 thermal stimulation methods × 2 pressure conditions).

As indicated in Table 1, **CurrNonPress** and **CurrPress** conditions are where thermal and cooling sensations are stimulated by controlling the current direction to the peltier elements (Figure 6(a)). **FlipNonPress** and **Flip-Pelt** conditions involve thermal sensations stimulated by utilizing servo motors to flip the peltier elements to their preset sides (Figure 6(c)). **CurrNonPress** and **FlipNonPress** conditions operate without pressure feedback (Figure 6(b)), whereas **CurrPress** and **Flip-Pelt** conditions incorporate pressure feedback (Figure 6(d)).

Table 1: Overview of comparative conditions for user study

Condition	Thermal Stimulation (Figure Ref.)	Presence of pressure (Figure Ref.)
CurrNonPress	Current direction control (Figure 6(a))	No pressure feedback (Figure 6(b))
FlipNonPress	Flipping peltier elements (Figure 6(c))	No pressure feedback (Figure 6(b))
CurrPress	Current direction control (Figure 6(a))	With pressure feedback (Figure 6(d))
Flip-Pelt	Flipping peltier elements (Figure 6(c))	With pressure feedback (Figure 6(d))

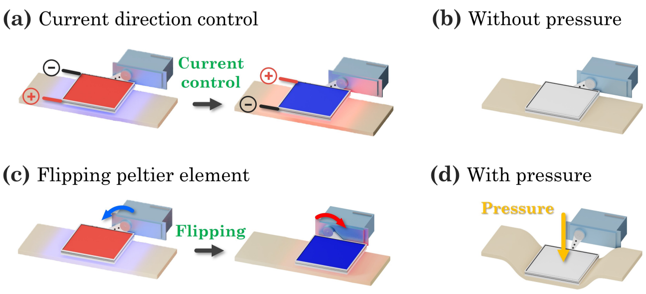

Figure 6: Operation overview of the two variables used in the user study: (a, c) Thermal stimulation methods, (b, d) Presence of pressure feedback.

4.2 Study Design

4.2.1 Stimuli Patterns and Stiffness. The focus of study 1 is to assess whether participants can distinguish temperature and pressure changes when subjected to five patterns of warm or cold objects made of materials with different stiffness, such as sponge or metal. To test across possible stimuli in objects with temperature in VR scenarios, five patterns of stimulation were chosen for evaluation. These patterns include dispersed stimuli across the forearm (Figure 7(a)), and stimuli focused on horizontal (Figure 7(b),(c)) and vertical (Figure 7 (d),(e)) sides of the matrix over the forearm. Such configurations aim to replicate potential contact scenarios between the forearm and objects in VR environments (Figure 7). Additionally, for conditions with pressure feedback, a virtual pressure simulation (in section 3.3) was used to simulate materials with different stiffness, represented as sponge (young's modulus= 20 kPa) [73] and metal (young's modulus= 200GPa) [93].

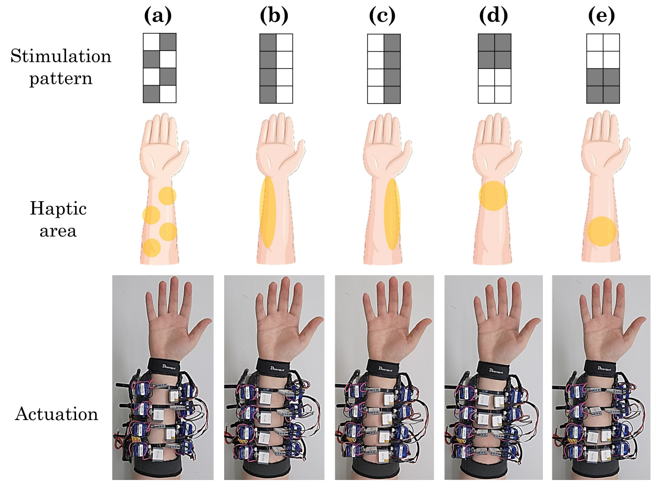

Figure 7: Haptic areas and actuation images for patterns consisting of horizontal (b-c), vertical (d-e) orientations, and dispersed stimuli (a).

4.2.2 Stimulation Recognition Task. Before the task, the motor angle for initiating skin contact was personalized for each participant to ensure an optimal interaction with the stimuli. Following this customization, participants were provided with a practice session to experience for 3 min. In the VR scene for stimulation recognition task, a stamp was positioned above the participant's forearm to provide thermal and pressure feedback, imprinting 1 cm deep for 3 s for each stimulus before removal. The stimulus recognition task involved a total of 10 combinations (5 patterns × 2 stiffness levels) of cool stimuli, followed by warm stimuli, with the order of warm and cool groups counterbalanced across participants using a within-subject design. To minimize the influence of thermal or cooling sensations from previous stimuli, every stimulus recognition task was performed after a minimum of 10 s rest after the previous session.

4.3 Results

We recruited 14 participants (7 females, 7 males, average age=23.93, SD = 1.98) for stimulation recognition task. Figure 8 illustrates the overall confusion matrix result for the stimulation patterns and stiffness recognition task.

Regarding stimulus pattern recognition, the participants across all conditions (**CurrNonPress**: M = 0.60, SD = 0.16; **FlipNonPress**: M = 0.71, SD = 0.18; **CurrPress**: M = 0.75, SD = 0.18; **Flip-Pelt**: M = 0.83, SD = 0.15) were able to identify the stimulated pattern with a probability above the chance level (with five types of patterns, the chance level is 20%). For stiffness recognition, conditions with pressure feedback (**CurrPress**: M = 0.83, SD = 0.18; **Flip-Pelt**: M = 0.84, SD = 0.17) distinguished the stimulated stiffness above the chance level. In contrast, conditions without pressure feedback (**CurrNonPress**: M = 0.53, SD = 0.08; **FlipNonPress**: M = 0.51, SD = 0.12) did not provide any clues about stiffness, resulting in chance level accuracy (with two types of stiffness, the chance level is 50%).

To further analyze the effects of the thermal stimulation method and the presence of pressure feedback, we divided the results into

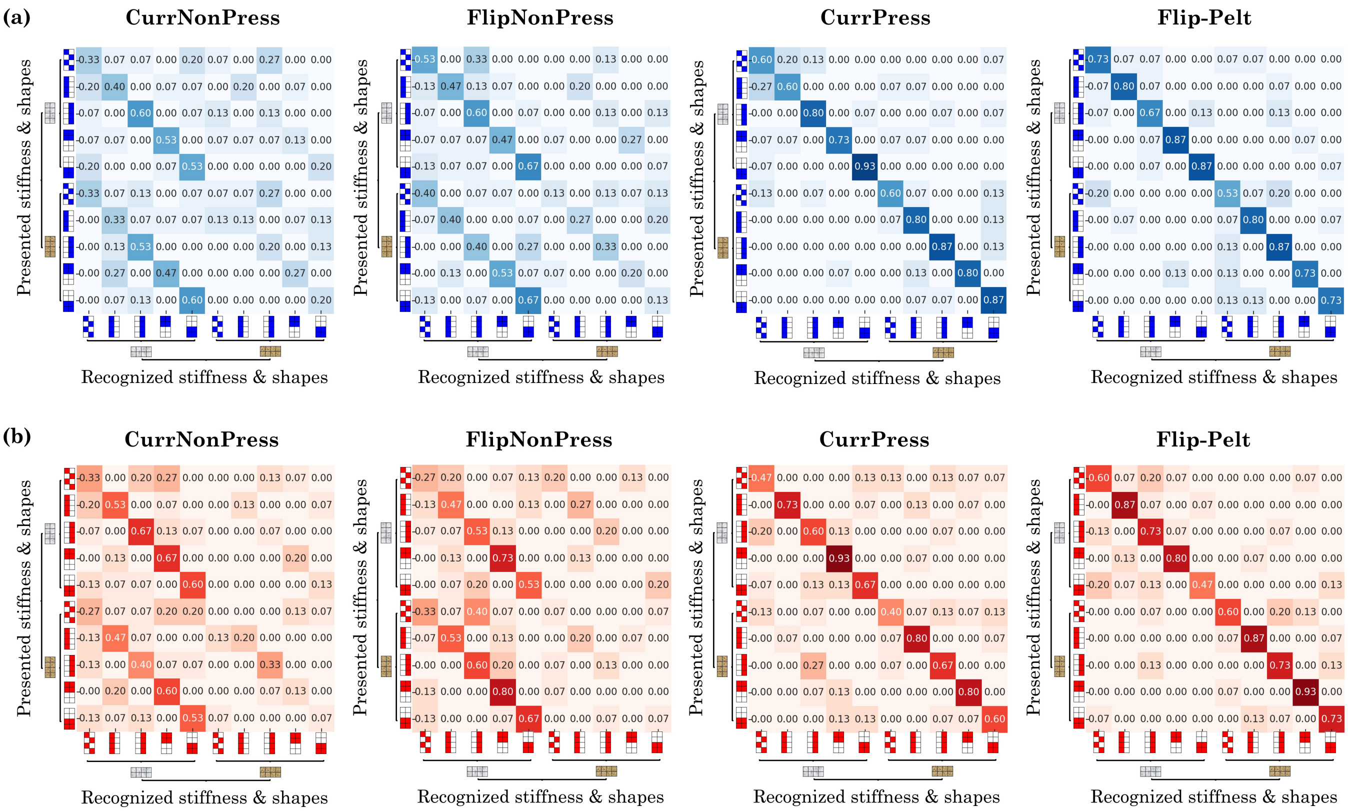

Figure 8: (a) From left to right, confusion matrices for cooling stimuli's pattern and stiffness and (b) Confusion matrices for warming stimuli's pattern and stiffness for each conditions

stimulus pattern and stimulus stiffness recognition accuracy (Figure 9). For all conditions, the absolute values of skewness and kurtosis did not exceed 3.0 and 10.0, respectively, satisfying normality [50] and conducted a two-way repeated measures ANOVA. For both cooling and warming stimuli, the thermal stimulation method (cooling: $F(2, 26) = 9.428$, $p = 0.009$; warming: $F(2, 26) = 5.025$, $p = 0.043$) and the presence of pressure feedback (cooling: $F(2, 26) = 17.063$, $p = 0.001$; warming: $F(2, 26) = 8.551$, $p = 0.012$) had significant effects on stimulus pattern recognition accuracy. However, the stiffness recognition accuracy was only affected by the presence of pressure feedback (cooling: $F(2, 26) = 165.687$, $p < 0.001$; warming: $F(2, 26) = 111.823$, $p < 0.001$). The thermal stimulation methods (cooling: $F(2, 26) = 0.197$, $p = 0.664$; warming: $F(2, 26) = 0.057$, $p = 0.816$) did not have a significant impact on stiffness recognition accuracy. No interaction effects were observed for all assessments. Therefore, no further post-hoc analysis was conducted.

The results of the two main effects indicated that for identifying the pattern of stimuli on the forearm, both the flipping peltier elements method and the presence of pressure feedback led to improved recognition accuracy. Participants showed a 15% improvement in pattern recognition ability when they were stimulated with the flipping peltier elements method for thermal feedback ($M = 0.77$, $SD = 0.18$) compared to those stimulated with current direction control ($M = 0.67$, $SD = 0.19$), and participants with pressure feedback ($M = 0.79$, $SD = 0.17$) showed a 20% improvement compared to those

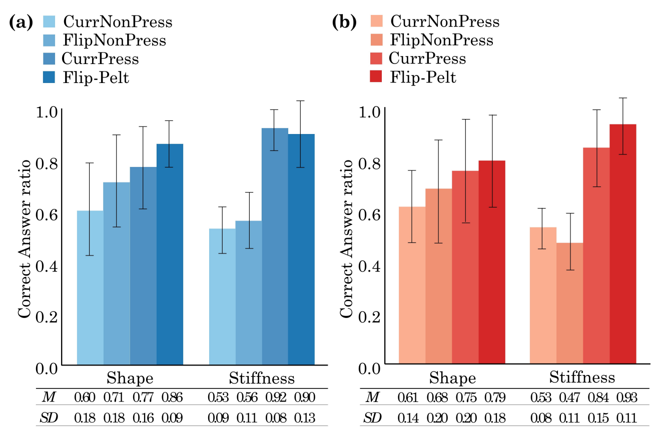

Figure 9: Bar graph showing participants' accuracy rates for each stimulus pattern and stiffness in Study 1: (a) For cooling stimuli, (b) For warming stimuli.

without pressure feedback ($M = 0.66$, $SD = 0.18$). Conversely, for identifying the stiffness of stimuli on the forearm, only the presence of pressure feedback was effective. Participants with pressure feedback ($M = 0.84$, $SD = 0.17$) showed a 33% improvement in stiffness recognition ability over those without pressure feedback ($M = 0.60$, $SD = 0.15$).

5 STUDY 2: USER EXPERIENCE EVALUATION OF FLIP-PELT IN VR DEMO

Study 1 validated the Flip-Pelt's capability for rapid thermal stimuli and pressure feedback, allowing for the recognition of stimuli with distinct patterns and stiffness. This section evaluates the haptic experience concerning thermal and pressure feedback within the VR demo scenarios, investigating how Flip-Pelt's enhancements in stimuli recognition accuracy, as assessed in Study 1, influence the user experience. This inquiry led to the focus on two more primary research questions:

- RQ2: Does the Flip-Pelt enhance the haptic experience in VR demo scenarios through its rapid thermal stimulation and congruent pressure feedback?
- RQ3: Between the Flip-Pelt's rapid thermal stimulation and pressure feedback, which contributes more to enhancing the haptic experience in VR demo scenarios?

We created two VR demo scenarios that require rapid contact with varying sensations of temperature and pressure: '*Sensory Massage*' (Figure 10) and '*Take a Shower*' (Figure 11). We employed the four comparison conditions from Study 1. Through these four conditions and two types of contents, we assessed the facets of the haptic experience, including *Autotelic*, *Expressivity*, *Immersion*, *Realism*, and *Harmony*, using the HX model survey [78].

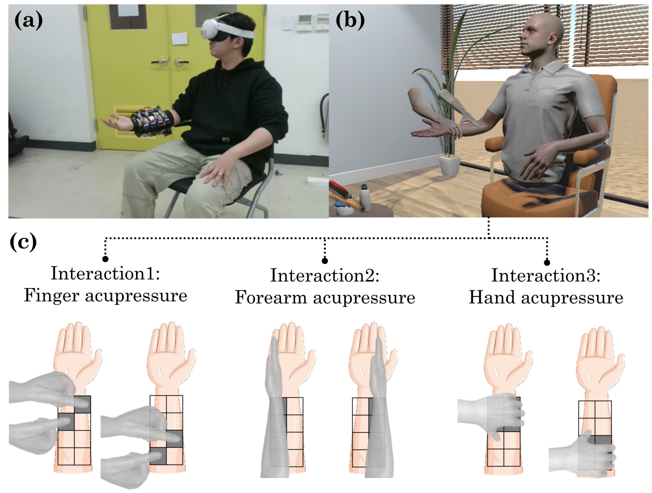

Figure 10: (a) Real user experience of the *Sensory Massage* content and a (b) Screenshot of the scene within the virtual content. (c) Three interactable experiences.

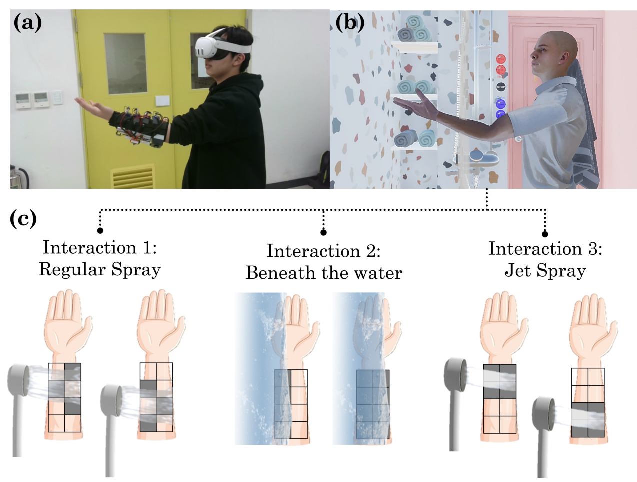

Figure 11: (a) Real user experience of the *Take a Shower* content and a (b) Screenshot of the scene within the virtual content. (c) Three interactable experiences.

5.1 VR Demo Scenarios Design

5.1.1 *Sensory Massage.*

In the first demo scenario, *Sensory Massage*, participants experience receiving a massage with thermal sensations. A massage therapist administered three types of massages: *finger acupressure*, *forearm acupressure*, and *hand acupressure* each lasting 20 s. These massage types were designed based on the stimulation patterns of Study 1 (Figure 10 (c)). The participants experienced both cool and warm stimuli in a single demo trial, with the order of warm and cool groups counterbalanced. The massage therapist's hands were visualized as pale for cool and red for warm. After experiencing *Sensory Massage* in VR with thermal and pressure feedback, the participants assessed their haptic experience using the HX model survey [78]. This procedure was equally distributed across the four conditions. The total demo scenario playtime was 3 min.

5.1.2 *Take a Shower.*

The second demo scenario, *Take a Shower*, provides an experience in which participants wash ink off from their arms under a showerhead. The participants approached the showerhead to wash their forearms using two types of water streams, *regular spray* and *jet spray*, for 20 s each. They are also tasked with pulling a plug *beneath the water* to drain the bathtub. These three stimuli are designed based on Study 1's stimulation pattern (Figure 11 (c)). The participants experienced both cool and warm water streams in a single demo trial, with the order of warm and cool groups counterbalanced. The warm water was visualized with steam to enhance the perception of warmth. After experiencing the *Take a Shower* in VR with thermal and pressure feedback, the participants assessed their haptic experience using the HX model survey [78]. This procedure was equally distributed across the four conditions. The total demo scenario playtime was 3 min.

5.2 Results

We recruited 14 participants for each of the *Sensory Massage* (7 females, 7 males, average age=23.93, *SD* = 1.98) and *Take a Shower* (7 females, 7 males, average age=23.85, *SD* = 2.07) contents. The HX model survey results for the two demo contents are shown in Figure 12. The x-axis represents the total haptic experience score and the five sub-scales of the haptic experience, whereas the y-axis shows the box-plotted haptic experience scores on a 7-point Likert scale. In all conditions, the absolute values of skewness and kurtosis did not exceed 3.0 and 10.0, respectively, satisfying normality. We performed a two-way repeated measures ANOVA to analyze the effect of the Flipping peltier elements method and pressure feedback on each haptic experience for the two different contents.

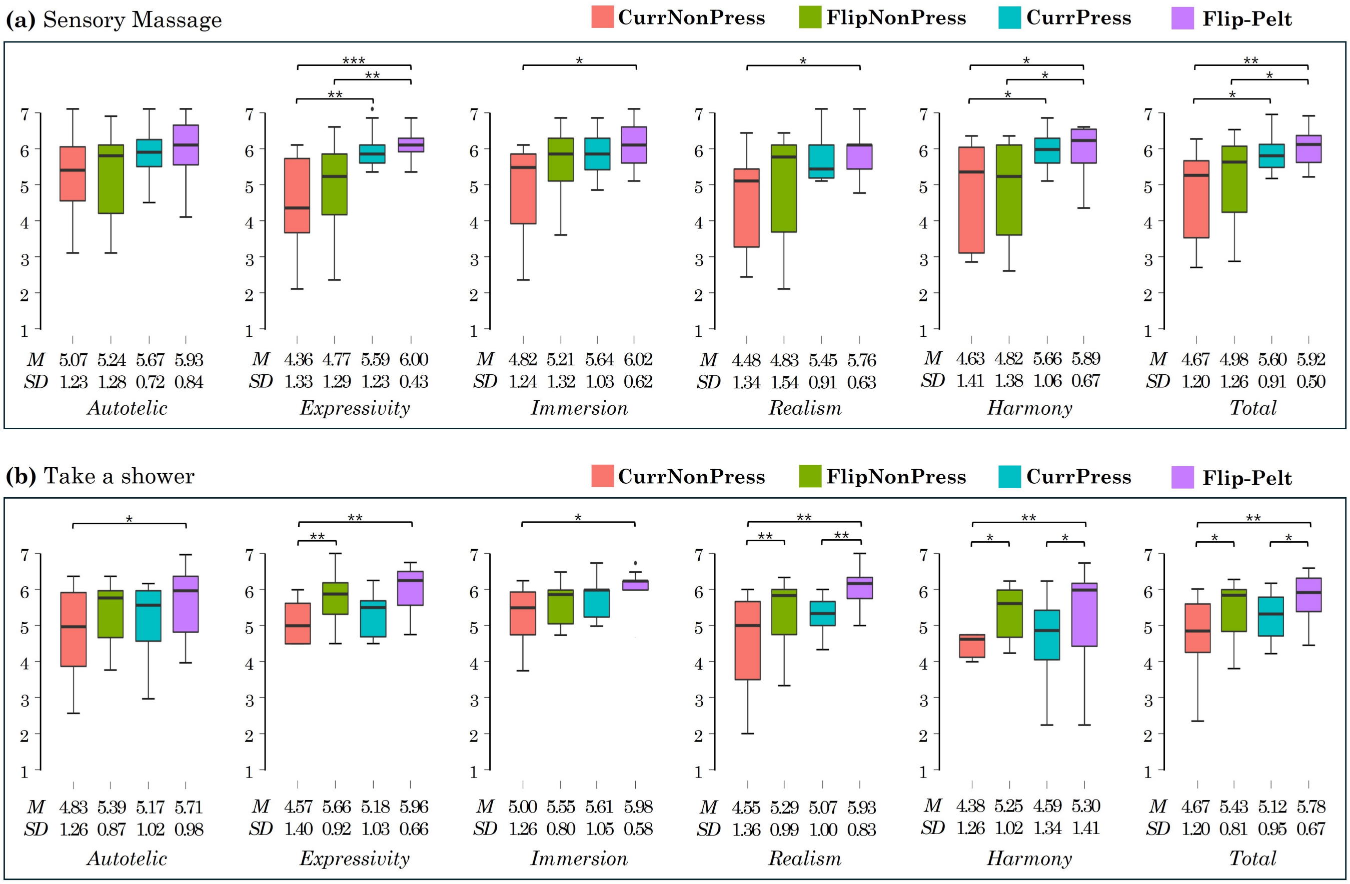

Figure 12: Box plots of the 7-point Likert scale scores for *Autotelic, Expressivity, Immersion, Realism, Harmony,* Total evaluated in Study 2: (a) Haptic experience after experiencing the *Sensory Massage* content, (b) Haptic experience after experiencing the *Take a Shower* content.

5.2.1 *Sensory Massage.*

In the massage content, both the thermal stimulation method ($F(2, 26) = 6.342$, $p = 0.026$) and the presence of pressure feedback ($F(2, 26) = 10.048$, $p = 0.007$) had a significant effect on the total haptic experience. When examining the sub-scales, the thermal stimulation method significantly influenced *Expressivity* ($F(2, 26) = 4.736$, $p = 0.049$), *Immersion* ($F(2, 26) = 5.383$, $p = 0.037$), and *Realism* ($F(2, 26) = 4.986$, $p = 0.044$). Similarly, the presence of pressure feedback significantly affected *Expressivity* ($F(2, 26) = 17.24$, $p = 0.001$), *Immersion* ($F(2, 26) = 6.632$, $p = 0.023$), *Realism* ($F(2, 26) = 6.903$, $p = 0.021$), and *Harmony* ($F(2, 26) = 11.249$, $p = 0.005$).

To compare individual conditions, we conducted a Bonferroni post-hoc test. Although no significant differences were detected using the thermal stimulation method, the presence of pressure feedback yielded statistically significant results. Specifically, the **CurrPress** showed significantly higher *Total*, *Expressivity*, and *Harmony* haptic experiences compared to **CurrNonPress** (*Total*: $t(13) = 2.988$, $p = 0.041$; *Expressivity*: $t(13) = 3.723$, $p = 0.007$; *Harmony*: $t(13) = 3.012$, $p = 0.045$). Similarly, **Flip-Pelt** demonstrated significantly higher *Total*, *Expressivity*, and *Harmony* haptic experiences compared to **FlipNonPress** (*Total*: $t(13) = 3.024$, $p = 0.041$; *Expressivity*: $t(13) = 3.723$, $p = 0.007$; *Harmony*: $t(13) = 3.116$, $p = 0.036$).

These results suggest that the flipping peltier elements method and pressure feedback contributed to higher levels of haptic expressivity (*Expressivity*), deeper immersion through high-quality sensory stimulation (*Immersion*), and a more realistic VR experience (*Realism*). However, when considering effect sizes, as defined by Cohen [11], the thermal stimulation method (*Total*: $d = 0.298$) had a small effect size (< 0.3), whereas the presence of pressure feedback (*Total*: $d = 0.928$) had a large effect size (> 0.8). This indicates that the pressure feedback plays a crucial role in enhancing the haptic experience of massage content.

5.2.2 *Take a Shower.*

In the shower content, both the thermal stimulation method ($F(2, 26) = 11.272$, $p = 0.005$) and the presence of pressure feedback ($F(2, 26) = 4.958$, $p = 0.044$) had a significant effect on the total haptic experience. When examining the sub-scales, the thermal stimulation method significantly influenced *Autotelic* ($F(2, 26) = 7.716$, $p = 0.016$), *Expressivity* ($F(2, 26) = 12.678$, $p = 0.003$), and *Realism* ($F(2, 26) = 22.368$, $p < 0.001$). Similarly, the presence of pressure feedback significantly affected *Autotelic* ($F(2, 26) = 4.801$, $p = 0.047$) and *Immersion* ($F(2, 26) = 4.692$, $p = 0.049$).

To compare individual conditions, post-hoc tests were performed using the Bonferroni correction. For the thermal stimulation method, **FlipNonPress** showed significantly higher *Total*, *Expressivity*, *Realism*, and *Harmony* haptic experiences compared to **CurrNonPress** (*Total*: $t(13) = 3.214$, $p = 0.022$; *Expressivity*: $t(13) = 3.581$, $p = 0.009$; *Realism*: $t(13) = 3.407$, $p = 0.009$; *Harmony*: $t(13) = 3.214$, $p = 0.022$). Additionally, **Flip-Pelt** showed significantly higher *Total*, *Realism*, and *Harmony* haptic experiences compared to **CurrPress** (*Total*: $t(13) = 2.760$, $p = 0.049$; *Realism*: $t(13) = 3.956$, $p = 0.003$; *Harmony*: $t(13) = 2.760$, $p = 0.049$). However, no significant differences were detected in the presence of pressure feedback.

These results suggest that the flipping peltier elements method provided a more satisfactory haptic experience (*Autotelic*) compared to the current direction control, achieved a higher level of haptic expressivity (*Expressivity*), and enabled a more realistic VR experience (*Realism*). The presence of pressure feedback contributed to a satisfying haptic experience (*Autotelic*) and enabled deeper immersion (*Immersion*). When considering effect sizes, as defined by Cohen, the thermal stimulation method (*Total*: $d = 0.862$) had a large effect size (> 0.8), while the presence of pressure feedback (*Total*: $d = 0.436$) had a medium effect size (> 0.4). This indicates that the thermal stimulation method played a key role in enhancing the haptic experience in the shower content.

6 DISCUSSION

6.1 Exploring the Research Questions

6.1.1 RQ1: Can Flip-Pelt users distinguish the stimuli patterns and stiffness levels on the forearm? If so, how do rapid thermal feedback and pressure influence their recognizability? In addressing Research Question 1, our result showed that participants under the Flip-Pelt condition exhibited proficiency in discerning various stimulus patterns and stiffness, achieving a average accuracy of 83%. The result demonstrated that users could differentiate between horizontal and vertical orientations on the forearm and identify stimuli distributed across the skin. Furthermore, the evaluation demonstrated the device's capacity to distinguish between materials of varied stiffness, thereby substantiating the Flip-Pelt system's capability in replicating a tactile sensations.

Specifically, the introduction of rapid thermal stimuli via the flipping peltier elements method facilitated a 15% enhancement in the accuracy of stimulus pattern recognition compared to conventional current direction control methodologies. While prior research has indicated variances in the accuracy of stimulus pattern recognition influenced by the type of temperature receptors activated (e.g., cold receptors and warm receptors) [69, 82], our findings showed comparable recognition accuracy to both types of temperature receptor activated. Instead, we observed that the promptness of temperature stimuli improved pattern recognition accuracy. This phenomenon is attributable to the heightened sensitivity of temperature receptors to rapid changes in temperature. Existing literature supports the observation that rapid temperature alterations elicit a more acute response from temperature receptors [26, 34, 70], thereby generating stronger neural signals [17].

Moreover, the integration of pressure feedback aided in distinguishing between materials of different stiffness with an accuracy of 84%, demonstrating that our pressure simulation strategy could be applied to motor-driven peltier elements to contribute to material stiffness differentiation. Previous methodologies simulated the stiffness of virtual objects such as force feedback by motor [80, 86], jamming techniques [20, 66], and pneumatic systems [58, 88]. The haptic experience of touching an object these systems provide could be strengthened by introducing additional sensations such as thermal feedback, especially when touching virtual objects with warm or cool temperatures. The Flip-Pelt system, by enabling the peltier elements themselves to directly exert pressure, the Flip-Pelt design facilitates the simultaneous delivery of touch and thermal sensations, enhancing the temporal congruence between tactile and thermal stimuli. This alignment has the potential to mitigate the perceptual discordance stemming from multisensory conflicts in virtual reality scenarios, thereby augmenting stimulus recognition and immersion [21].

6.1.2 RQ2: Does the Flip-Pelt enhance the haptic experience in VR demo scenarios through its rapid thermal stimulation and congruent pressure feedback? In addressing Research Question 2, within the Flip-Pelt condition, we observed improvements in the haptic experience during VR demo scenarios, with *Total* HX model survey scores increasing to 5.92 (*SD* = 0.50) for the *Sensory Massage* content and 5.78 (*SD* = 0.67) for *Take a Shower* content. These scores significantly outperformed those obtained under conventional current direction control setups and conditions without pressure feedback, highlighting the impact of Flip-Pelt's rapid thermal transitions and pressure feedback on haptic experience in VR.

As mentioned in Sections 5.1.2 and 5.1.3, the three types of massages stimulated during the *Sensory Massage* and the three shower interactions experienced in *Take a Shower* were all composed of the five patterns used in Study 1. Hence, the improved recognition accuracy from the flipping peltier elements method and pressure feedback allowed participants to discern the three massage types as unique haptic experiences, closely integrated with their respective visual cues. Similarly, for the *Take a Shower* content, the haptic feedback matched the specific visual details of each interaction. These results align with previous research findings that high stimulus resolution of haptic devices contributes to enhancing the haptic experience [79], emphasizing the Flip-Pelt device's ability to provide distinguishable different haptic stimuli. Notably, the Flip-Pelt condition, which provides both the flipping peltier elements method and pressure feedback, was the most effective in enhancing the haptic experience due to the integrated sensation of pressure and temperature. This integration of haptic sensations, along with visual experience congruence, heightened the ability to perceive contact with virtual objects. Although visual information is the most dominant in cognitive judgment through multisensory integration [33], the occurrence of multisensory incongruence beyond an acceptable threshold degrades user experience [15]. Consequently, we emphasize the importance of temporal congruency between the contact moment of pressure and temperature, highlighting its capability in enhancing the perceived realism and haptic experience.

6.1.3 RQ3: Between the Flip-Pelt's rapid thermal stimulation and pressure feedback, which contributes more to enhancing the haptic experience in VR demo scenarios? In addressing Research Question 3, the dominant factor varied between the two tested demo scenarios: pressure feedback was paramount in *Sensory Massage*, while rapid thermal transitions predominantly influenced the *Take a Shower* experience. This distinction evidences that the primary haptic feedback enhancing the user experience is contingent upon the context of the content.

We conducted post-experiment surveys to validate these findings, querying participants on the types of sensations they primarily focused on and anticipated in each scenario. In the *Sensory Massage* scenario, 10 out of 14 participants (71%) identified pressure sensation as their focal point and expectation. Conversely, in the *Take a Shower* scenario, 9 out of 14 participants (64%) reported thermal sensation as their focal point and expectation. This variation suggests that expected sensation types are context-dependent, potentially influencing the extent to which haptic feedback enhances the user experience. Consistent with our observations, previous studies [62] have delineated that the physical attributes eliciting various haptic sensations differ, implying that the relevance of different haptic sensations is dictated by the physical properties necessitated by the content. Particularly, in the *Take a Shower* content, that rapid thermal feedback was perceived to have a larger impact on the haptic experience than the pressure feedback do is worth attention. Traditionally, haptic feedback has focused on vibration [41, 42, 52, 71], pressure [8, 13], and texture [28, 79], as these directly indicate the point of contact. However, our result indicates that in such interaction scenarios, thermal feedback can contribute more to the perception of interacting objects and localization of physical contact.

6.2 Scalability of the Flip-Pelt System to Other Body Parts

The Flip-Pelt system, which was initially tested on the forearm and designed for modular use, can be adapted to other body parts due to its cell-level stimulus delivery. For instance, integrating it into VR shoes can simulate the sensations of the floor's warmth (Figure 13 (a)) or coolness (Figure 13 (c)) when walking on various virtual terrains such as hot lava (Figure 13 (d)) or a cold caves (Figure 13 (e)). Additionally, its pressure feedback feature, enabled by servo motors, can replicate the varied textures of terrains such as rugged caves or smooth surfaces, aligning with methods that use vibrational [84, 91], fluid [83], and electrical [92] stimulation for such experiences.

Hands are another potential application area for the Flip-Pelt's thermal sensation, as we frequently interact with objects in VR using our hands. Similar to research that has demonstrated the conveyance of texture through the special design of haptic controllers [95], simulated grasping and touching [10], or provided force feedback [80], the Flip-Pelt system can be integrated into VR handheld controller to offer thermal sensations. For example, attaching semi-cylindrical aluminum parts around a peltier element in a VR controller can provide users with temperature changes, such as holding a hot pan (Figure 14 (d)) or throwing a snowball (Figure 14 (e)) in VR.

While our current prototype demonstrates the concept of rapid thermal feedback by physically flipping a rigid peltier element, we believe that the underlying principle of utilizing both the cool and warm sides of the peltier element could be extended to flexible thermal conductors [60] or flexible TEDs [49]. Incorporating such

Figure 13: Flip-Pelt system applied in VR shoes: (a) Contact with a warm surface, (b) Peltier element rotating within the sole space, (c) Contact with a cool surface, (d, e) Example scenarios in VR contents.

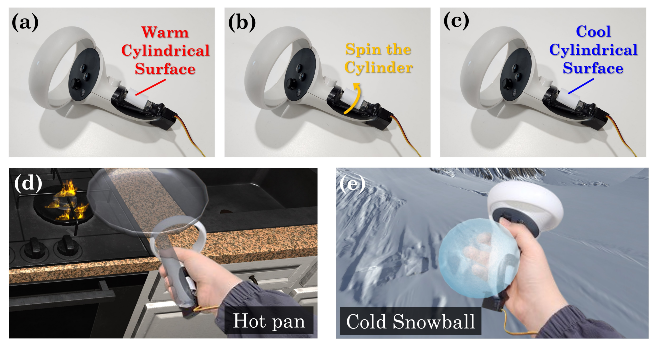

Figure 14: Flip-Pelt system applied in VR controller: (a) Contact with a warm cylinderical surface, (b) Peltier element spinning within the controller, (c) Contact with a cool cylinderical surface, (d, e) Example scenarios in VR contents.

flexible peltier elements could enable the application of Flip-Pelt to various body parts, particularly those involved in frequent interaction and deformation, where traditional rigid peltier elements may face challenges.

7 LIMITATIONS AND FUTURE WORK

7.1 Mechanical Design Constraints and Enhancements

Flip-Pelt was designed to simulate stiffness by controlling the motor angle to have the peltier surface push against the skin. Since the silicone layer is a hard material with minimal deformation, the major source of texture is mechanical pressure. However, due to the differences in material texture on the dual-sided peltier element, slight textural differences might affect the perceived texture during initial skin contact. Future improvements should aim to make the surface textures on both sides of the peltier element identical to minimize any perceived differences. Additionally, the motor-driven structure of Flip-Pelt causes slight variations in the stimulation points of the warm and cool sides on the skin, as seen in Figure 6 (c). This occurs due to the motor axis being located at the edge of the peltier element, resulting in a drift in the stimulation point. In contrast, the cylindrical peltier approach shown in Figure 14 uses a central rotation axis, maintaining a consistent stimulation point. To address this issue and adopt a similar design for the arm sleeve-type Flip-Pelt, a sliding rail and cam follower mechanism can be integrated, allowing the peltier element to move up and down during a 180° flip, thereby maintaining the stimulation point. These mechanical design guidelines should be considered in future device designs.

7.2 Limited Lifetime of Dual-sided Peltier Elements

The Flip-Pelt utilizes dual-sided peltier elements to provide warm or cool sensations. However, due to thermal conduction, the cool side eventually rises above the threshold temperature for feeling cold, limiting its use to approximately 196 s. This short lifetime can lead to frequent interruptions in user experience, diminishing the realism and continuity of virtual interactions [51]. Additionally, the need for regular cooldown periods may reduce the overall efficiency and practicality of the device in extended VR sessions. Therefore, it is crucial to explore advanced thermal management solutions. Designs incorporating mini motor fans [43, 60, 89] and small heat sinks [22, 76], along with wearable heat sinks [59], offer relatively compact solutions for thermal circulation that are suitable for integration into our Flip-Pelt device. Additionally, to extend the system's lifetime, we suggest software strategies akin to controlling scent release by proximity to virtual objects [3]. By toggling the Flip-Pelt's voltage off when distant from heat or cold sources in VR, we prevent unnecessary pre-warming or cooling, thus enhancing the device's operational lifetime.

7.3 Challenges in Maintaining Consistent Temperatures on the Cool Side of Peltier Elements

Dual-sided peltier elements maintain the hot side below 40 °C, but the cool side fluctuates between 16 °C to 28 °C with a 2.0V input, lacking consistent temperature regulation. The average rate of temperature change on the cool side is 0.08 °C/s, which falls below the threshold for the human skin's thermal receptors to readily detect due to thermal adaptation, making temperature changes challenging to perceive at speeds less than 1 °C/s [48]. Despite this, due to the variability in skin sensitivity due to factors like gender [27, 77], ages [5, 40], and body parts [32], inconsistent cool side control remains a limitation. To improve independent temperature control of each side, two peltier elements with a heat sink and an insulation layer between them could be a potential solution.

8 CONCLUSION

In this study, we introduced Flip-Pelt, which employs motor-driven Peltier elements for rapid thermal stimulation. Our approach provides thermal and tactile feedback in a manner that simulates contact with physical objects, using prewarmed or cooled Peltier elements for rapid thermal feedback along with co-located pressure feedback. Flip-Pelt users could differentiate stimuli with different patterns and stiffness levels with an accuracy rate of 83%. Particularly, the flipping Peltier method outperforms traditional current direction control methods, enhancing users' ability to recognize varying virtual object patterns by 15%. This improvement emphasizes how the temporal congruency between thermal feedback and visual experience resulting from rapid temperature stimuli can lead to improved stimuli distinguishability.

The alignment of thermal and haptic feedback with the visual experience also led to an enriched VR user experience in our experiment. In VR demo scenarios, Flip-Pelt improved the overall haptic experience, enhancing aspects such as *Autotelic*, *Expressivity*, *Immersion*, and *Realism*, compared to other conditions without rapid thermal transition or pressure feedback. These improvements emphasize the importance of synchronizing thermal and tactile feedback to achieve a cohesive haptic experience. We believe our method can be scaled to various body parts that interact with objects, allowing users to benefit from the multisensory integration of thermal and pressure sensations aligned with the visual experience.

ACKNOWLEDGMENTS

This work was partially supported by the Gwangju Institute of Science and Technology (GIST)–Massachusetts Institute of Technology (MIT) Research Collaboration Grant in 2024, the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2024-00343397), and the Ministry of Science and ICT (MSIT), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2024-RS-2024-00436398) supervised by the IITP (Institute of Information & Communications Technology Planning & Evaluation).

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