ThermoCaress: A Wearable Haptic Device with Illusory Moving Thermal Stimulation

Yuhu Liu
The University of Tokyo
liu@isi.imi.i.u-tokyo.ac.jp

Satoshi Nishikawa
The University of Tokyo
nishikawa@isi.imi.i.u-tokyo.ac.jp

Young ah Seong
Hosei University
The University of Tokyo
yabird@gmail.com

Ryuma Niiyama
The University of Tokyo
niiyama@isi.imi.i.u-tokyo.ac.jp

Yasuo Kuniyoshi
The University of Tokyo
kuniyosh@isi.imi.i.u-tokyo.ac.jp

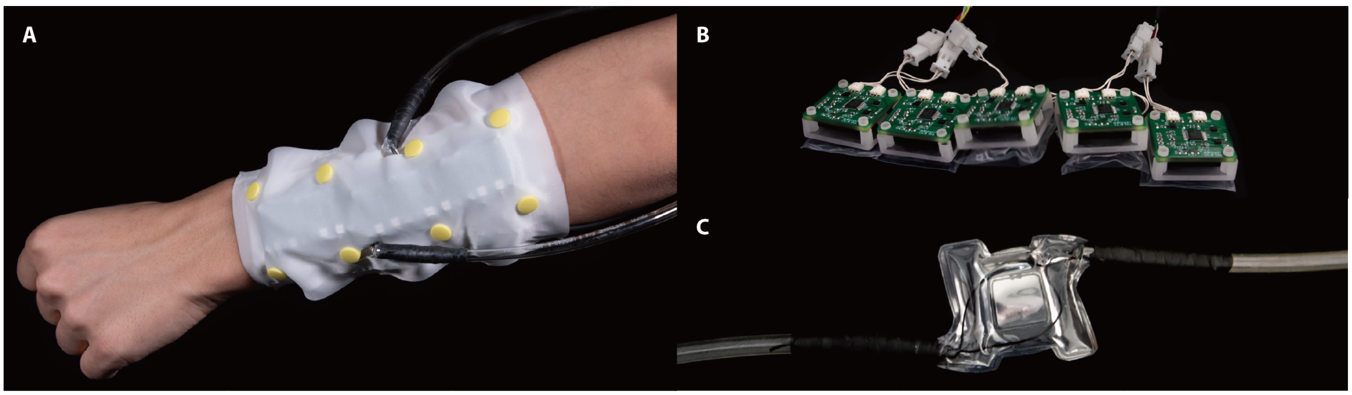

Figure 1: (A): Wearing ThermoCaress on forearm. (B): ThermoCaress uses five sets of a microblower and an air pouch to present pressure force. (C): ThermoCaress uses a water pouch to present temperature.

ABSTRACT

We propose ThermoCaress, a haptic device to create a stroking sensation on the forearm using pressure force and present thermal feedback simultaneously. In our method, based on the phenomenon of thermal referral, by overlapping a stroke of pressure force, users feel as if the thermal stimulation moves although the position of temperature source is static. We designed the device to be compact and soft, using microblowers and inflatable pouches for presenting pressure force and water for presenting thermal feedback. Our user study showed that the device succeeded in generating thermal referrals and creating a moving thermal illusion. The results also suggested that cold temperature enhance the pleasantness of stroking. Our findings contribute to expanding the potential of thermal haptic devices.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; *Systems and tools for interaction design*; • **Computing methodologies** → *Perception.*

KEYWORDS

Haptics, Pneumatic actuation, Thermal referral, Thermal stroking, Soft wearable device

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1 INTRODUCTION

Contact with others is one of our innate and natural needs. The most intimate part of interpersonal relationships arises from contact, for example, when a baby calms down in his/her mother's arms; therefore, touch is a very important element in communication. Humans, as social animals, have developed their sociability through contact interactions with others during the evolutionary process, as exemplified by grooming. One study reported that emotions can be communicated to others simply by touching without seeing the other person [18].

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In 2020, COVID-19 has spread worldwide, and people's lifestyles are changing dramatically. There has been a significant increase in online interactions and a decrease in face-to-face meetings. COVID-19 has led to the development of distant communications. Although information is conveyed by video and audio, it is not possible to touch other people over long distances. As the number of non-face-to-face interactions is increasing, new technology is needed to enable people to interact in intimate way, even at a distance.

A series of studies in the field of neurosciece revealed that caress-like interpersonal touch, especially on the forearm, can evoke pleasant feelings [4, 18]. This pleasant stroke, so called C-tactile (CT) afferent system, is most dramatic when stimulated by human skin [1].

When contact occurs on human skin, we perceive a sense of pressure and temperature through the receptors. When a person engages in touch communication, the static pressure and temperature as well as movement while touching are involved, as represented by CT stroking. Therefore, it is necessary to reproduce the pressure sensation of being touched, the temperature sensation of being touched, and the dynamic movement of both pressure and temperature sensations for rich tactile communication. To create the sensation of touch movement, the easiest method is to simply place a number of tactile elements and thermal elements; however, this makes the device huge and complex. It is difficult to present a sense of temperature movement in simple devices; therefore, no haptic interface has yet to solve this problem.

According to the phenomenon of thermal referral, when temperature and tactile sensations are given to two nearby points on the skin, the temperature is also perceived at the point where the tactile sensation is given [10]. Although thermal referral does not relate to the dynamic movement of stimulation, we believe that, if the tactile stimulus site continuously shifts, the transferred temperature site will shifted together.

In this study, we propose ThermoCaress, a sleeve-type haptic device that can reproduce the illusion of a moving thermal sensation, which has been difficult to achieve previously, by moving the pressure stimulation with a simple actuation method. By expanding thermal referrals, ThermoCaress can reduce the number of thermal components. We chose to use the forearm to present the touch sensation because forearms are the body parts that are most frequently involved in touch communication.

This device is composed of air system to reproduce pressure, water system to reproduce temperature, and cloth to contain them. ThermoCaress is a soft wearable device that does not have any hard material in direct contact with the skin. The softness is suitable for wearable devices. In addition, we realized a compact pneumatic system that does not require a large air compressor or complicated tubes using a microblower in a small sphygmomanometer as the actuator to drive the air.

To evaluate the performance of the device, we conducted a user study. In the user study, we confirmed that the device generates thermal referral and thermal movement sensation, and investigates the relationship between the site of thermal stimulation and thermal movement illusion. Additionally, we used subjective evaluations via a questionnaire to determine how temperature affects the pleasantness of CT stroking in this device.

The moving sensation of temperature realized by ThermoCaress has a wide range of applications, including in entertainment, communication, training, mental health, and physical health.

The contributions made by this study are as follows:

- By expanding thermal referral, we established a method for presenting a sense of thermal movement.;
- The relationship between temperature-moving strokes and pleasant feeling was investigated.;
- We achieved softness, which is suitable for wearable devices, using air and water.;
- A compact pneumatic system was realized using microblowers, without any extensive equipment such as tubes, pumps, and compressors.;
- We proposed several examples of applications using our devices in daily life.

2 RELATED WORKS

2.1 Thermal Feedback in Human-Computer Interaction

There are metaphorical expressions based on temperature, such as "having warm feelings" and "having a cold attitude;" however, beyond their linguistic expression, temperature is known to have the power to shape perceptions and interpretations of social relationships [22]. In a study by Williams and Bargh, it was shown that people rated others as warmer and made more altruistic choices after having a warm cup of coffee than after having a cold cup of coffee [51].

To take advantage of this effect of temperature, a number of studies have been conducted in the field of Human-computer interaction (HCI) to provide appropriate temperature presentation depending on the situation. In the early days, the necessary functions and guidelines for temperature presentation were investigated from the perspective of human perceptual performance, and thermal feedback was shown to be useful for mobile interaction [24, 50]. Halvey et al. examined the effects of the environment on thermal presentation. They found that thermal presentation over clothing increased comfort, while requiring more intense stimulation [15], and that the environmental temperature, and not the humidity, affected the perception of thermal stimuli [14].

Although the effect of temperature on emotion has been investigated, there is still no uniform view. Wilson et al. found that people tended to rate cold stimuli as more comfortable than warm stimuli [55], while Salminen et al. found that an increase of 4 °C effectively increased arousal, dominance, and valence [44]. In another study by Salminen et al., warmth was preferred to cold in terms of arousal and dominance, but valence was not affected by temperature [43]. Furthermore, Tewell et al. reported strong individual differences in valence among users [46].

The interpretation of the messages conveyed by temperature is also focused on using thermal feedback as a communication medium. Wilson et al. investigated the interpretation of thermal stimuli in various scenarios [53], also asked users to interpret the emotions that the thermal stimuli were trying to convey, and mapped them to valence and arousal [54].

Temperature stimulation as a communication medium has also received attention in combination with other modalities. The combination of vibratory and visual stimuli has been shown to increase the range of available emotions in the space of valence and arousal [52]. As a multimodal medium that includes temperature stimuli, a wide range of potential applications have been demonstrated, including in image- and music-related experiences [13], text messages [46], and voice messages [8].

It is necessary to develop thermal feedback technology to apply the effects of thermal feedback in the real world. In particular, a compact and wearable temperature-display device can be used to expand the range of applications. ThermalBracered is a wristband-type temperature-presenting device that uses six thermal modules and has been investigated for usability in real-world scenarios such as when walking and reading [37]. A smaller device that can be worn on a fingertip has also been developed [58]. Thermal feedback has also been used to improve the immersion of virtual reality experiences by attaching a thermal module on a head-mounted display [36, 40, 41].

As a means of providing thermal feedback, Peltier devices have been widely used. Owing to the characteristics of the Peltier device, its thermal feedback is limited by the temperature change, and there is a time delay in presenting the target temperature. On the other hand, in recent years, several alternative methods that use fluids have been proposed. Using water that has already been heated or cooled, the pre-adjusted temperature can be quickly presented [28, 42]. HydroRing presented temperature and vibrations by running water through a ring-shaped tube attached to a fingertip [16]. Therminator presented the temperature by attaching a tube to the arm [12]. ThermAirGlove is a glove-shaped device that presents the texture of an object in virtual reality using hot and cold air [3]. On the other hand, these fluid-based methods are at a disadvantage because the fluid needs to be stored externally and maintained at a certain temperature, and tubes are required for fluid transmission. In contrast, these methods have an advantage in the heat transfer rate because the contact surface can be deformed to adhere to the skin. We also thought that soft and organic contact with fluid was more likely to cause pleasure than contact with a hard Peltier device. Therefore, we chose water as the temperature source for our prototype.

2.2 Pneumatic Interfaces

While previous pneumatic tactile presentations were not suitable for the stimulation of small areas, they were used for the sensation of being enveloped in a large area. For this reason, pneumatic tactile presentation has been used as a means of conveying hug sensations in remote communication [31, 45].

On the other hand, in the field of robotics, Pouch Motor [33, 34], a pneumatic actuator that is soft, safe, and capable of deforming and adapting to objects of various shapes, was proposed. This technology has also been applied in the field of HCI to create pneumatic user interfaces [9, 35, 48, 57].

The safety and adaptability features of pneumatic actuators are also highly compatible with those of tactile interfaces. In recent years, pneumatic haptic devices have evolved from earlier wearable devices with large-area pressure presentations to recent systems with more localized stimuli. In Force Jacket, 26 airbags are placed in the jacket and sleeves to provide quick and complex haptic feedback throughout the upper body [7]. Several attempts have also been made to present pressure on the arms with devices such as Squeezeback, which hacks a commercial sphygmomanometer to give natural notice on the wrist [38], and PneuHaptic, which places multiple small airbags around the circumference of the arms to trigger a range of tactile sensations [17]. PneuSleeve has six stretchable pneumatic actuators around the arm to enable the presentation of compression, skin stretching, and vibration [59].

2.3 Stroking Devices

In the field of neuroscience, the effects of touch through CT afferent fibers have been investigated. It has been shown that people feel pleasant when the hairy skin are gently stroked at moderate speeds (1–10 cm/s), which is known as affective touch [2, 4, 29]. This caress-like stroke is most effective at 32 °C, which is close to the temperature of human skin [1].

In the field of HCI, several attempts have been made to apply various haptic illusions [27] to create mediated social haptic devices with the aim of recreating this CT stroking. It has been shown that vibrotactile stimulation can provide a sense of continuous movement to an arm by sequentially driving an array of motors [23, 39]. Using this illusion, Huisman et al. created a device to produce six different types of stimuli (poke, hit, press, squeeze, rub, and stroke) on an arm [20]. They also indicated that pleasant feelings are generated by the strokes of vibrotactile motors while stating that vibratory stimuli do not directly stimulate CT [21].

Along with of vibration, other methods of presenting the sensation of strokes on an arm have been tested, such as using an air jet to blow an arm [47], using a stick driven by shape memory alloy (SMA) [26], using a plaster array driven by SMA [32], and using a pressure force from a voice coil [6]. In addition, using multi-dimensional tactile stimuli consisting of vibration and pressure from voice coils and rotational shear from motors, a wider range of information transfer has been created [25]. On the other hand, Wo and Culbertson presented a lateral motion by sequentially inflating a row of pneumatic actuators [56]. According to this study, short inflation times create a more continuous and pleasant sensation, but the pressure change during inflation does not affect continuity and pleasantness [56].

Thus, several attempts have been made to present stroke sensations using various approaches. In contrast, while 32 °C enhances the effect of CT stroking [1] and temperature itself has an emotional effect [54], presenting temperature strokes is technically difficult and has not yet been attempted in HCI.

2.4 Thermal Referral

When thermal and tactile stimuli are applied to two nearby points on the skin, temperature can be felt in both areas; this phenomenon is known as thermal referral. When a middle finger was given tactile stimuli and index and ring fingers were given thermal stimuli, the middle finger also felt temperature [10]. In this phenomenon, it was also reported that the transferred temperature sensation disappeared when the tactile stimulation was removed from the middle finger, suggesting a strong association between thermal and tactile sensations [10].

In addition, in the three-fingered thermal referral, the middle finger feels the same temperature as the bilateral fingers, but the intensity of the temperature is lower [19]. This fact suggested a hypothesis of "temperature averaging," where multiple temperature stimuli may be added, and then, redistributed to the areas where tactile stimuli are felt.

Thermal referrals were also observed in the two fingers and arms [11, 49]. Moreover, it was found that a cold sensation was less likely to cause thermal referral than a warm sensation [11]. It is inferred that the number of cold sensory receptors is greater than that of warm sensory receptors; therefore the resolution for a cold sensation is relatively high [27].

Recently, it has been reported that thermal referral does not necessarily require a sense of touch, and that heat can be felt in the middle finger without tactile stimulation when the index and ring fingers are exposed to heat in the air [5]. While this helps to solve the fundamental principles of thermal referral, it does not ignore the interaction between the sense of touch and warmth.

Thus, while the phenomenon of thermal referral has been investigated, there are still few examples of engineering applications of this phenomenon [49].

3 HARDWARE

3.1 Concept

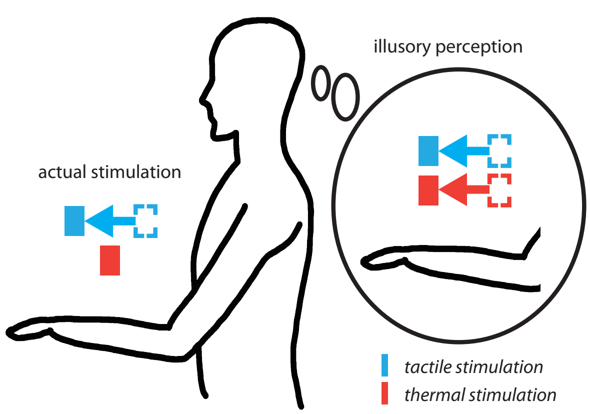

Figure 2: Concept of ThermoCaress. Users feel the illusory movement of thermal stimulation (red) with tactile stimulation (light blue) even though its actual position is fixed.

In this study, we introduce a prototype, ThermoCaress (Fig. 1 (A)). ThermoCaress is a sleeve-type wearable device that provides tactile and thermal stimulation to the user's forearm.

Previous research has shown that, when tactile and thermal stimuli are close to each other, the temperature is also transferred to the tactile side. This phenomenon is known as thermal referral [10]. In our prototype, by using and applying thermal referral, we gave users the illusion that the thermal stimulus position is moving while it is actually in a fixed position, by dynamically changing the position of the tactile stimulus (Fig. 2).

ThermoCaress is driven by air and water, and most of the devices are made of soft materials. This makes it suitable for a wide range of users, from children to adults, and enables them to use it safely. ThermoCaress also has an advantage in heat transfer efficiency because its thermal actuator can fit on the skin, where as conventional thermal interfaces using a Peltier device do not.

3.2 Hardware Implementation

ThermoCaress has a body made of cloth, an air system for pressure stimulation, and a water system for thermal stimulation. In this section, we describe the structure of the device for each of these parts.

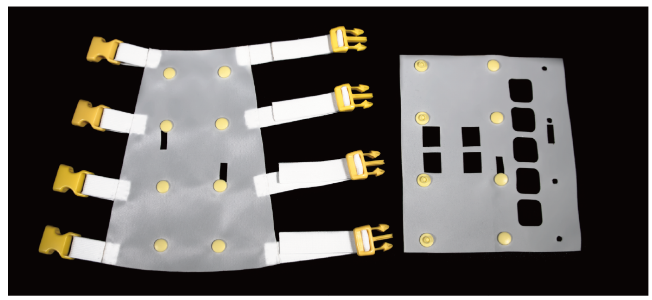

Figure 3: Cover part (left) has elastic bands to be attached to an arm. Pocket part (right) has five holes to install air pouches, two slits to insert tubes, and four slits to increase thermal conductivity.

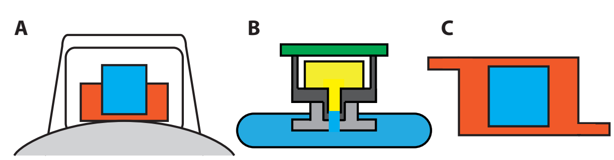

Figure 4: (A): A water pouch (red) and air pouches (light blue) are arranged in the order from the closest to skin (gray). (B): The single air drive unit consists of an air pouch (light blue), a microblower (yellow), a driver circuit (green), and attachments (gray and dark gray). (C): The water pouch (red) has a square area (light blue) where the water does not flow to transmit the pressure of air pouch placed above.

3.2.1 *Sleeve-like device.*

The body of ThermoCaress is made of cloth and consists of two parts: a pocket for storing the actuator and a cover for mounting it (Fig.3). Each pocket and cover had eight buttons to be attached and removed easily. This makes it easy to replace the actuators stored in the pocket.

The pocket is a rectangular cloth, 16 cm long and 14 cm wide, and can be folded to form a cylinder. The actuators are arranged in such an order that the water pouch is the closest to the skin, followed by the air pouches (Fig. 4 (A)). The cloth has holes for actuator placement, holes for button insertion, slits to insert tubes, and slits to increase thermal conductivity. The cover was 18 cm long and 8 cm wide on the wrist end and 14 cm in width on the elbow end, with four pairs of adjustable elastic straps and snaps on the sides so that the entire device could be fitted to the arm.

3.2.2 Air system for pressure force. The pressure was presented in air (Fig. 1 (B)). The ThermoCaress pneumatic system differs from conventional pneumatic devices in that it does not use tubes to transmit air. The device was equipped with five independent air actuators, each of which contained a microblower (MZB3004T4) used in a small sphygmomanometer. Focusing on a single air drive unit, it consists of a 2.5 cm square air pouch, a microblower, a drive circuit, and a pair of attachments (bottom and top) that holds them together (Fig. 4 (B)). The attachments were 3D printed using ProJet MJP 2500 Plus. The top attachment is inserted into the bottom attachment by a screw mechanism, and the area between the parts is sealed by the o-rings. By applying a voltage of 9–18 V to the drive circuit, the air pouch inflates.

ThermoCaress can present a sense of stroking over a distance of 100 mm by driving five air pouches sequentially. In this case, according to a previous study [56], it is possible to increase the continuity of the stroke by overlapping the timing of air pouch inflation. The microblowers are controlled by a Teensy 4.0, and can be turned on and off independently.

Figure 5: ThermoCaress (left) is connected to a water source (right) with tubes.

3.2.3 Water system for thermal stimulation. Thermal presentation was performed using water. While the water pouch can take various shapes, we describe the minimum configuration (Fig. 1 (C)) in this section. The effect of the size and location of the water pouch on the haptic perception is be discussed in Section 4. This minimum configuration of the water pouch is 4 cm long and 4.5 cm wide, with holes on both sides to connect to tubes for letting the water in and out. The edge was sealed by CNC printing with a soldering iron. There is a 1.8 cm square area in the center where water does not flow, so that the pressure generated by the air pouch located above the water pouch can be transmitted efficiently (Fig. 4 (C)). Therefore, the temperature presentation takes place on both sides, slightly offset from the row of air pouches, but it is difficult to distinguish between the left and right sides of the temperature presentation because of the low spatial resolution of temperature sensations. Because the crease can possibly prevent water flow if the pouch is accidentally folded, wires with a diameter of 0.5 mm were inserted between the inlets and outlets to maintain the water flow route. The connection between the water pouch and tube was made by wrapping self-welding tape around the joint. The out diameter of the tube was 6 mm, and the inner diameter was 4 mm.

The shape of the water pouch changes when the water flow is turned on and off; the pouch generates a small amount of tactile sensation on its own. However, because the air and water pouches are driven simultaneously when the device is in use and the sensation of the water pouch is much weaker than the pressure from the air pouch, it does not interfere with the pressure presentation.

Water drive and temperature control were performed away from the device itself. In our setup, we stored water in a bucket, pumped it out with small pumps (with a flow rate of 200 L/h), and maintained the temperature with low-temperature cookers (Fig. 5). Drainage is performed by the weight of the water itself because the flow of water is quick enough. The water flow was controlled using a solenoid valve (VDW22HZ1D). The pump and valve are controlled by a Teensy 4.0, and can be turned on and off independently.

3.3 Measurement of Pressure Characteristics

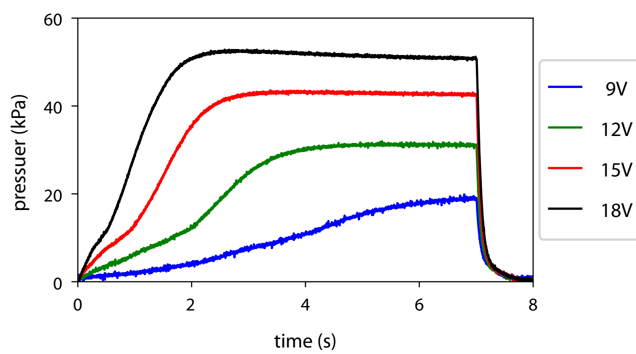

Figure 6: Pressure Characteristics of an air component of ThermoCaress with different voltage.

The device that we constructed presents the pressure and temperature. The temperature can be easily adjusted by changing the parameter of the low-temperature cooker, but the pressure characteristics of the air pouch driven by the microblower are unknown. Therefore, we measured the pressure of the air pouch at different voltages (9 V, 12 V, 15 V, and 18 V). To measure the internal pressure, the air pouch was connected to a pressure sensor (MIS-2503-015G) with no external force. The pressure was recorded for 7 s of inflation and 1 s of deflation.

The results are presented in Fig. 6. In every condition, the pressure first increased, and then, reached an equilibrium state. The higher voltage led to a faster increase in the pressure and a higher equilibrium pressure. When the voltage supply was stopped, the air pressure immediately dropped to zero in every condition. We assumed that the inflation speed was sufficiently high at 15 V to perceive the sufficient pressure during a stroke descried in the user study, as described in the following section. On the other hand, we felt the equilibrium pressure in 18 V is so high that we can feel pain. Thus, we used 15V to drive the microblower in the user study.

4 USER STUDY

We created a new haptic device called ThermoCaress, which provides a sense of thermal movement based on the theory of thermal referral. In this section, we investigate whether ThermoCaress is capable of reproducing thermal referral, whether it is possible to present a moving thermal illusion, and how temperature affects the pleasant feeling of stroking.

4.1 Hardware for User Study

4.1.1 Air system. The air system used in this section is the same as that described in Section 3.2.2. The five air pouches are labeled A_0, A_1, A_2, A_3, and A_4 from the elbow end to the wrist end.

Figure 7: The water pouch used in the user test has three chambers so that it can change the size and the position of thermal stimulation.

4.1.2 Water system. As shown in Fig. 7, we created a new water pouch to investigate the relationship between the shape of the water pouch and perceived sensation. This water pouch is 125 mm long and 45 mm wide, and divided into three water chambers, labeled W_0, W_1, and W_2 from the elbow end to the wrist end. Each of the three water chambers has holes to connect the tubes for letting water in and out, and can be switched on and off independently by the three valves attached to the water supply side. The water pouch has five 1.8 cm water-impenetrable areas in the center to place the air pouches above.

We set three different temperatures (T_0 = 25 °C, T_1 = 32 °C, and T_2 = 42 °C), which were used in the previous work [1]. For the three temperature presentations, three buckets of water with temperatures of 25 °C, 35 °C, and 50 °C were prepared using low-temperature cookers. The temperature of the water in the buckets was determined by measuring the temperature of the water pouch using a non-contact thermometer. The measurements were made for each temperature while the water was flowing, because the temperature could drop as the water flowed through the tubes. Each bucket contains a pump connected to a valve. Furthermore, two additional valves were connected to drain the water left in the tube when changing the water temperature.

4.2 Stimuli Set

We designed 12 types of stimulus sets to generate thermal referral (TR group) and 18 types of stimulus sets to generate a sense of thermal movement (ST group). additionally, six stimulus sets were chosen from both the TR and ST groups (three each) to compare the two groups.

4.2.1 Thermal referral group. In the TR group, the site of thermal stimulation was fixed at W_0 (the elbow end). Furthermore, 12 stimulus sets were designed in combination with three different temperatures (T_0 = 25 °C , T_1 = 32 °C , and T_2 = 42 °C) along with four different pressure stimulation sites $A_{01}(A_0\&A_1)$, $A_{12}(A_1\&A_2)$, $A_{23}(A_2\&A_3)$, and $A_{34}(A_3\&A_4)$. The two independent variables are temperature T and pressure presentation position A. When driving A_{01}, the temperature and pressure stimuli are felt in the same place, and the distance between them increases in the order of A_{12}, A_{23}, and A_{34}. The stimulating time was 3.75 s, which was the same as the duration of stroke designed in the ST group.

4.2.2 Stroke group. In the ST group, we designed 18 different stimulus sets in combination with three different temperatures (T_0 = 25 °C, T_1 = 32 °C, and T_2 = 42 °C) and six different combinations of adjacent water pouches (W_0, W_1, W_2, W_{01} $(W_0\&W_1)$, $W_{12}(W_1\&W_2)$, and $W_{012}(W_0\&W_1\&W_2)$), in which the driving method of the air pouches was fixed. The independent variables are the water pouch driving position W and temperature T. The air pouches were driven sequentially to create strokes at a speed of 4 cm/s with timing controls to ensure that nearby pouches always inflate from A_0 to A_4 sequentially. This inflation system was designed by referring to a previous study [56].

4.2.3 T-S group. The stimulus sets used for the comparison between the TR and ST groups were defined as the T-S group. These stimuli belong to the TR or ST groups, and are not new stimulus patterns. Thus, the three TR conditions (T_0, A_{01}), (T_1, A_{01}), and (T_2, A_{01}) along with the three ST conditions (W_0, T_0), (W_0, T_1), and (W_0, T_2) are defined as the T-S group. The two independent variables are temperature T and pressure presentation method (which determines whether to sequentially inflate air pouch A_m or just inflate two air pouches A_{01}).

4.3 Procedure

Participants sat in front of a desk, and placed their left arm on the desk while wearing the device. At the beginning of the experiment, a stroke was performed as a reference stimulus by the five air pouches without any temperature presentation. During the reference stimulus, illustrations of the arm and device along with the position corresponding to the driving air pouch are shown on an iPad (Fig. 8 (A)). In addition, it was announced that the pleasantness of this reference stimulus was to be remembered as "0" for comparison in the later evaluation of pleasantness. This reference

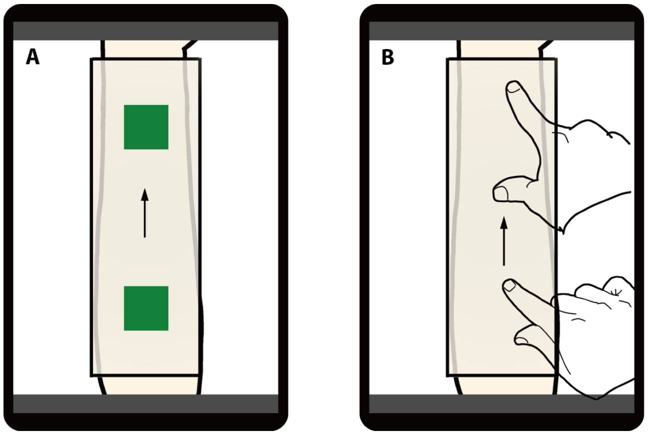

Figure 8: The iPad in front of participants displays the illustration of ThermoCaress in actual size. (A): A green square moved in accordance with inflating air pouches during the reference stimulation. (B): Participants answer the perceived position of thermal stimulation by sliding their fingers.

stroke was repeated several times until the participants memorized the stimulation.

In each trial, the stimulus was given after a 5-s resting period after the start signal. After a 5-s relief period, the participants were asked to reproduce the stimulus with the iPad in front of them. During this phase, the iPad showed illustrations of the arms and devices. The stimuli were reproduced with two fingers of the right hand, and the positions of the bottom and top of the perceived position of the thermal stimulation were traced with two fingers. If the participants felt that the position of the thermal stimulation moved, they slid their fingers to present their shifting position (Fig. 8 (B)). The iPad displayed an illustration of the device in actual size, and hid both ends of the forearm; therefore, all participants with different forearm sizes could use this system to participate. After the reproduction of the stimulation, the participants were asked to rate the pleasantness of the stimuli on a 7-point Likert scale from -3 to 3.

After sufficient practice with the procedure, 90 trials were conducted; i.e., 30 stimulus sets were conducted three times each. The 30 stimulus sets were presented in random order so that the participants would not become accustomed to either the TR or ST group.

Two questions were asked after the experiment. The first question, Q_1, was "Did you notice that the place of thermal stimulation and pressure force is different in the direction perpendicular to the stroke direction?" with showing the Fig. 4 (C) and the second question, Q_2, was for additional free comments.

The user test was conducted in September in a laboratory with an air conditioning set at 25 °C.

4.4 Participants

An unofficial pilot test conducted before the user study showed that ThermoCaress would be expected to generate sufficient thermal referral and thermal movement sensations; therefore, we conducted experiments with 12 participants (10 males, 2 females, 1 left-handed, ages 21–24). All participants were asked to wear short sleeves so that they could wear the ThermoCaress directly against the skin. The participants were given a $20 Amazon gift card as a reward for the 1.5-h experiment. The user study passed an ethical review at the University of Tokyo.

4.5 Analysis

The total distance of thermal movement X_{diff}, the time average of the thermal position X_{mean}, the time average of the thermal area $S_{m}ean$, the thermal area at the beginning of the stimulus S_{start}, the thermal area at the end of the stimulus S_{end}, and the thermal area changing ratio $S_{\text{rate}} = S_{\text{end}}/S_{\text{start}}$, were extracted from the data collected on the iPad. Using these data, we analyzed whether thermal referral and thermal moving illusion actually occurred, and how they performed in ThermoCaress. We also analyzed the effect of temperature on CT stroking from the results of the pleasantness evaluation E.

4.5.1 Analysis: Thermal referral. To confirm the occurrence of thermal referral, we analyzed the time average of the temperature position X_{mean} in the TR group. After Mauchly's test of sphericity, Greenhouse-Geisser correction was performed if necessary, and then, F and p-values were calculated using 2-way repeated measures ANOVA. If there was a significant difference ($p < 0.05$), a post-hoc test was performed using the Tukey-Kramer method.

We also analyzed the time average of the thermal area S_{mean} in the TR group to identify the characteristics of thermal referral in our device. The analysis method was the same as that for X_{mean}.

4.5.2 Analysis: Thermal movement. The total distance of the temperature movement X_{diff} was analyzed in the T-S group to investigate the moving sensation of temperature. The analysis method was the same as that described in Section 4.5.1. To determine the characteristics of thermal moving sensation, we analyzed the total distance of temperature movement X_{diff}, the time average of the thermal area S_{mean}, and the thermal area changing ratio S_{rate} in the ST group. The analysis method was the same as that described in Section 4.5.1.

4.5.3 Analysis: Pleasantness evaluation. To investigate the effect of thermal feedback for CT stroking, we conducted two analyses of the pleasantness evaluation E. First, the analysis was conducted in the T-S group to investigate whether pleasantness differs between with and without pressure stroking. The analysis method was the same as that described in Section 4.5.1. The analysis was also conducted within the ST group to examine which parameters contributed to pleasantness when pressure was moving. The analysis method was the same as that described in Section 4.5.1.

4.6 Results

Figure 9 show the results of the user study. Error bars in the graphs indicate standard errors. In Fig. 9: (F), the haptic stimuli that are significantly different from zero as a result of a two-sided test, are denoted by *: $p < 0.05$, **: $p < 0.01$, and ***: $p < 0.001$.

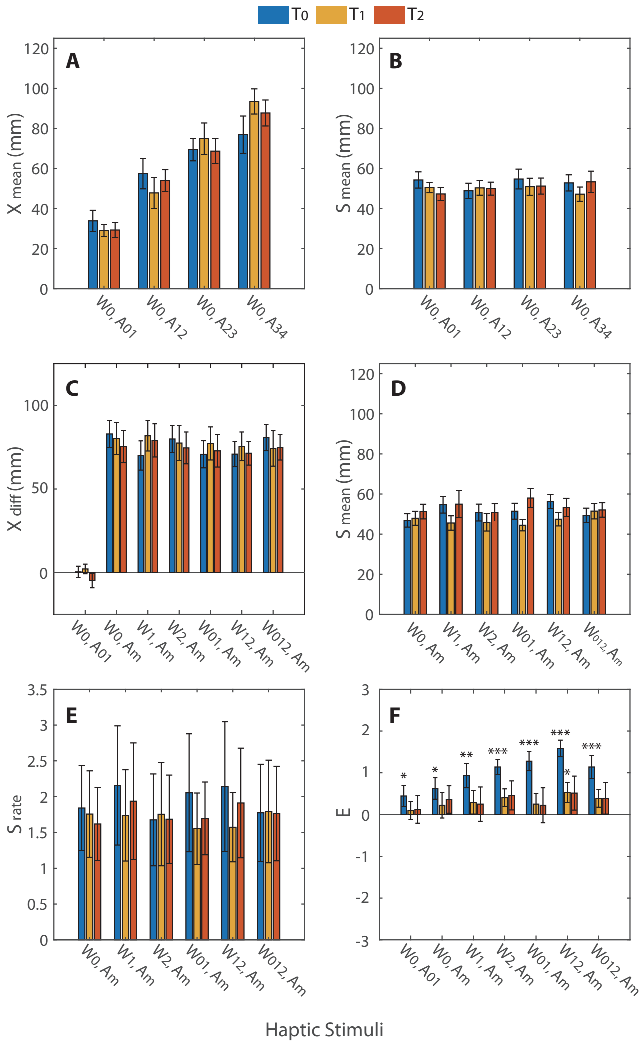

Figure 9: Results of the user study. (A) Time average of thermal position in the group TR. (B) Time average of thermal area in the group TR. (C) Total distance of thermal movement in the group ST and the group T-S. (D) Time average of thermal area in the group ST. (E) Changing ratio of thermal area in the group ST. (F) Pleasantness rating in the group ST and the group T-S.

4.6.1 Result: Thermal referral. The results of 2-way repeated measures ANOVA on X_{mean} within the TR group showed a significant difference ($F(3, 33) = 52.09, p < 0.001(4.1 \times 10^{-8})$) in the independent variable A. When subjected to a post-hoc test, all combinations of A were significantly different. The combinations of adjacent pressure stimulus positions resulted in $p < 0.01(9.6 \times 10^{-3})$ for A_{01} and A_{12}, $p < 0.001(9.4 \times 10^{-4})$ for A_{12} and A_{23}, and $p < 0.001(6.7 \times 10^{-5})$ for A_{23} and A_{34}. Neither a main effect of the independent variable T nor an interaction between A-T was found.

The results of the 2-way repeated measures ANOVA on S_{mean} within the TR group showed no main effect or interaction.

4.6.2 Result: Thermal movement. The results of the 2-way repeated measures ANOVA on X_{diff} within the T-S group showed a significant difference ($F(1, 11) = 89.48, p < 0.001(1.3 \times 10^{-6})$) in the independent variable A. When subjected to a post-hoc test, a significant difference ($p < 0.001(1.3 \times 10^{-6})$) was found between with and without pressure stroking. Neither a main effect of the independent variable T nor an interaction between A-T was found.

The results of the 2-way repeated measures ANOVA on X_{diff} within the ST group showed no main effect or interaction.

The results of the 2-way repeated measures ANOVA on S_{mean} within the ST group showed a significant difference ($F(2, 22) = 4.65, p < 0.05(0.040)$) in the independent variable T. When subjected to a post-hoc test, a significant difference was found between T_0-T_1 ($p < 0.01(9.2 \times 10^{-3})$) and T_1-T_2 ($p < 0.05(0.042)$). Neither a main effect of the independent variable W nor an interaction between T-W was found.

The results of the 2-way repeated measures ANOVA on S_{rate} within the ST group showed no main effect or interaction.

4.6.3 Result: Pleasantness evaluation. The results of the 2-way repeated measures ANOVA on E within the T-S group showed no main effect or interaction.

The results of the 2-way repeated measures ANOVA on E within the ST group showed a significant difference ($F(2, 22) = 4.99, p < 0.05(0.035)$) in the independent variable T. When the independent variable T was subjected to a post-hoc test, a significant difference ($p < 0.001(8.2 \times 10^{-4})$) was found between T_0 and T_1. There was no interaction between T-W.

4.6.4 Result: Questionnaires after the user test. For question Q_1, which asked whether users noticed the difference of the position between pressure and temperature in the direction perpendicular to the stroke direction, 11 of 12 participants answered that they did not.

In the free comments, there were two opposite opinion that "the warm stimulus was more pleasant" and "the cold stimulus was more pleasant." One of the participants who said the cold was more pleasant noted that a possible reason was "because it was summer." There were also comments such as, "It was easy to understand the temperature near the wrist," "It felt good when the cold stimulus came after the warm trial," and "the device itself felt good even though the experiment took a long time."

5 DISCUSSION

The result of Section 4.6.1 shows that ThermoCaress can generate thermal referral. It can be seen from Fig. 9: (A) and Fig. 9: (B) that the values of X_{mean} and S_{mean} coincided with the pressure-presented area, indicating that the participants perceived the temperature primarily in the pressure-presented area rather than at the temperature source. In previous thermal referral studies, the pressure force derived from tactile-presented and temperature-presented areas was equal [10, 11, 19, 27], so the temperature sensation on the two parts was distributed equally. On the other hand, because the two stimuli pressures given by the device were not equal in this study, it is possible that more heat was redistributed to the air pouch stimulus area where stronger pressure was felt, and thus the temperature was mainly felt in the pressure presentation area.

When considering the versatility of the application, this uneven thermal redistribution is a useful feature because it allows the temperature to be transferred to certain spots in a broader area. Owing to the design of the user study in which participant can choose only a single spot they felt temperature, it is impossible to know whether the participants felt the temperature at the point where the water pouch presented as a heat source, but it was revealed that ThermoCaress has an ability to cause thermal referral.

The results of X_{diff} in Section 4.6.2 show that ThermoCaress can represent thermal movement regardless of the temperature, location, and size of the water pouch. Although its movement distance is only about 80 mm, which is shorter than the distance of 100 mm between A_0 and A_4 where the pressure actually moved, ThermoCaress was capable of creating a movement sensation at an efficiency of approximately 80%. The post-hoc test for S_{mean} revealed that the area perceived at T_1 is small. This is because the cold and warm sensory receptors respond at peak temperatures of $T_0 = 25$ °C and $T_3 = 42$ °C, while both of them are weaker at $T_1 = 32$ °C; therefore, the intensity of the thermal stimuli that participants felt was weaker at temperature T_1. On the other hand, the result, which stated S_{rate} was about 1.5–2 in all the stimulus patterns (Fig. 9: (E)), was probably because the moving temperature left a trail of residual temperature behind.

The results of E in Section 4.6.3 show that presenting the temperature in ThermoCaress increases pleasantness compared to conventional pressure-only strokes in some conditions. The results showed that the cold stimulus was particularly pleasant. It was surprising result because CT stroking was believed to be most pleasant in $T_1 = 32$ °C [1]. Meanwhile, the result that cold stimulus is better than hot stimulus is consistent with the result of Wilison's study [55]. We believe the reason why $T_0 = 25$ °C stimulus was preferred may be "because it is summer," as the comments on the questionnaire suggested. From the results of the other comments, it was observed that some people preferred cold temperature, while others did not. It may be necessary to measure biological responses for objective evaluation, such as EEG and neural signals, in addition to subjective evaluations by questioning.

Overall, there was no effect on perception based on the position of the water pouch. It can be said that a water pouch with a minimum configuration of 4 cm in length, as described in Section 3.2.3, was sufficient to represent the thermal movement. A minimal configuration of water pouches allows a smaller water system because only a small amount of water is needed.

Most participants did not notice any gap between the position and temperature positions in the around-arm direction. This result suggests that there was no problem with the current placement of the water pouches, as shown in Fig. 4: (C).

6 APPLICATIONS

In the field of HCI, thermal feedback has attracted significant attention and a number of applications have been proposed [36, 37, 40, 41, 46]. However, the previous methods of thermal feedback were limited to static positions, and the potential of temperature has not been fully exploited. In contrast, our proposed device, ThermoCaress, can dynamically move the apparent temperature position by using pressure, and is capable of expressing more diverse contact patterns. Thermal stroking can be applied to the scenarios described in the following sections.

6.1 Application: VR game

Temperature is often used as haptic feedback in virtual reality games [28, 36, 40, 41]. Thermal stroking can also be used effectively in this application to pursue a realistic sensation for immersive experience (Fig. 10 (A)). The effect of thermal stroking can be used in various situation, such as energy gathering in the arm when shooting a special attack, a pleasant feeling when using a heeling potion, or an unpleasant feeling from the direction of the attack toward the center of the body.

6.2 Application: Communication tool

Thermal interfaces have been used in communication media [46]. Because ThermoCaress can present a sense of temperature movement, it is possible to realize diverse tactile expressions that were not possible in the past. For example, it allows us to interact naturally with others in online video calls (Fig. 10 (B)) and social VR platforms. In addition, the communication partner does not have to be a person. For example, by combining it with the agent in a smartwatch, it is expected to make people feel as if the agent lives in their arm.

6.3 Application: Training

Due to the spread of COVID-19, an increasing number of people are training online at home. In some cases, people receive private instruction from a remote location, but the information they receive is limited to audio and video, so that the quality of instruction is lower than that of face-to-face sessions. As a support of audio and visual, ThermoCaress provides an advantage in posing and movement instruction such as yoga (Fig. 10 (C)), dance, and bodybuilding. It is expected that students wearing the device would feel as if their instructor are really holding their body, making the lessons feel more intimate.

6.4 Application: Mental health

It has been shown that interaction with a soft, plush robot such as Paro has a positive effect on the mental health of elderly people and patients with dementia [30]. While these robots are targets that users can actively interact with, if our device is passively attached to their bodies, there could also be a positive effect on their mental health. Further research on the long-term use of ThermoCaress for mental health is needed.

6.5 Application: Physical health

The temperature and pressure generated by ThermoCaress can also have a direct effect on stimulated body like massage. For example, when a user becomes tired while working on a computer, an effective massage with appropriate temperature and pressure can be provided to relieve fatigue. By applying the findings of this study to existing massage chairs, we can further enhance physical healing by providing pressure in addition to temperature stroking. These findings are immediately applicable to the industry.

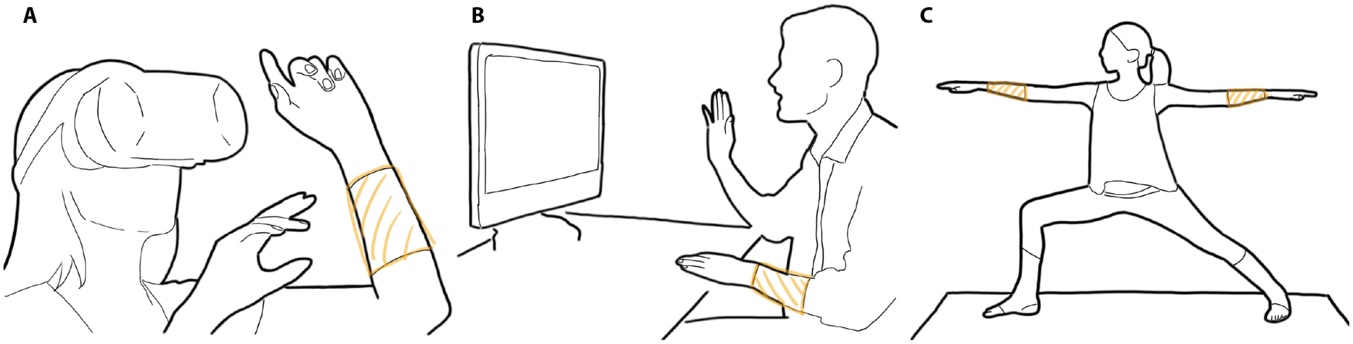

Figure 10: Possible examples of application of ThermoCaress. (A): Haptic feedback in VR entertainment. (B): Online communication tool. (C): Online training for posing instruction.

7 LIMITATION AND FUTURE WORKS

Through the user study, we observed the illusion of thermal movement. We investigated the pleasantness of the stimulation according to a study on CT stroking [2, 29]. In the future, we will attempt an affective evaluation to investigate the effect of thermal stroking on affective computing.

From the results of the user study, we could not find any difference among the different numbers of actuating water pouches. However, considering temperature averaging [19], the intensity of the temperature that users felt would change in accordance with the number of water pouches. To investigate this, it is necessary to ask participants about the intensity of the temperature. If this hypothesis were supported, the size of the water pouch would be a trade-off between thermal efficiency and water flow.

To apply the device in daily use, we need to make the entire device smaller. The size of the water system is a drawback when using liquid to present thermal feedback. Considering that there is no need to prepare a large amount of water flow for such a tiny water pouch, our current water system is excessively large. The system should work if it were smaller, such as a 500 mL plastic bottle, so that the entire system can be portable by placing the bottle, circuit, and other components within a bag.

We are also thinking about extending the position of the device on body to effectively apply thermal movement illusion. Because the resolution of tactile sensation differs among body parts, it is necessary to investigate the capability of the thermal movement illusion in each body part. Making the device compact and extending the available body parts will broaden its usability and usage.

8 CONCLUSION

In this study, we proposed ThermoCaress, a soft wearable haptic device. Expanding the known phenomenon of thermal referral, by moving the position of tactile stimulation, we achieved the illusion of thermal movement. In the user study, we confirmed that both thermal referral and thermal movement occurred. The results also suggests that our device can positively affect the generation of pleasant feelings by adding cool temperatures. We hope that our results will contribute to broadening the interaction experience over a wide area.

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