IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 24, 2021, accepted December 9, 2021, date of publication January 7, 2022, date of current version February 16, 2022.

*Digital Object Identifier 10.1109/ACCESS.2022.3141385*

# HaPouch: A Miniaturized, Soft, and Wearable Haptic Display Device Using a Liquid-to-Gas Phase Change Actuator

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This work was supported by the Japan Science and Technology Agency (JST), Exploratory Research for Advanced Technology (ERATO) under Grant JPMJER1501; and the Japan Society for the Promotion of Science (JSPS) under Grant JP20K19847.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Research Ethics Committee of the Graduate school of Engineering Science, Osaka University under Application No. R2-13.

**ABSTRACT** Wearable haptic displays can provide haptic information while allowing for free body movement. Among these haptic displays, pneumatic haptic displays have the advantages of flexibility and lightweight; however, they require bulky air tubes and a heavy air compressor. To solve this problem, we propose a wearable haptic display that uses a liquid-to-gas phase change actuator and a Peltier device as a way to reduce the size of the entire system. A low-boiling-point liquid is encapsulated in the flexible bladder of the actuator, and the vaporization of the liquid, which induces the inflation of the actuator, is controlled by the external Peltier device. In this study, we implemented a pressure sensor to monitor pressure inside the liquid-to-gas phase change actuator. The pressure measurement will contribute to controlling the generated normal force. First, we characterized the pressure response concerning the design of the liquid-to-gas phase change actuator. Next, we evaluated the output normal force of the haptic display and confirmed that the maximum output force reached a few newtons, which is a similar level to the off-the-shelf wearable haptic display devices. Finally, a sensory evaluation revealed that the experimental participants perceived the haptic stimulus to their fingertips provided by the proposed haptic display in a few seconds. According to the obtained results, the proposed haptic display can be applied to applications such as human interfaces to provide force, allowing for a response time of a few seconds.

**INDEX TERMS** Haptic display, liquid-to-gas phase change actuator, soft robotics, haptics.

## I. INTRODUCTION

Recently, haptic and tactile technologies have attracted the interest of both scientific research and the electronics industry; in addition, these technologies have seen advances in presenting information to the five senses. According to their use cases, various haptic displays have been proposed and are applied to provide haptic information to various parts of the human body. Here, the fingertip has a high density of tactile mechanoreceptors [1], [2] and is highly sensitive to external stimuli; this allows us to utilize the fingertips to distinguish surrounding environments and objects. Therefore, researchers have tried to develop devices to artificially provide haptic information to the fingertips. According to their structures and use cases, these devices can be categorized into ground-based types, holdable types, and wearable types [3]. The wearable-type haptic displays can especially provide haptic information without restricting significant body movement, including hand movement. Because of this advantage, these haptic displays have been applied to force presentation in virtual reality environments or remote operations [4]–[6].

Wearable-type haptic displays have been studied for a long time, and a wide variety of principles and structures have been proposed [7], [8]. The motors and voice coil actuators,

The associate editor coordinating the review of this manuscript and approving it for publication was Zheng Chen.

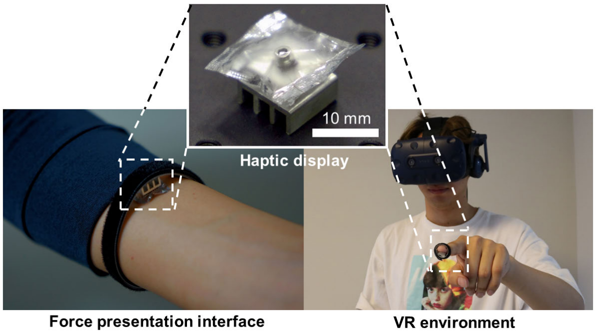


**FIGURE 1.** Example of the use cases of the proposed haptic display. The proposed haptic display is small enough to be mounted on a human body.

which have often been embedded in the conventional wearable haptic displays [9], [10], are large, stiff, and heavy. These characteristics lose portability and restrict body movement.

To address this problem, flexible and lightweight actuators such as dielectric elastomer actuators (DEAs) [11], [12] and pneumatic actuators [13]–[15] have been applied to wearable haptic displays. However, DEAs require high voltage to be driven, resulting in an increase in their size and risk of electric shock. Although the pneumatic actuators do not come with the risk of electric shock, they suffer from being too large for practical use. Off-the-shelf air compressors and air valves that are needed for the system are cumbersome and make the entire system large and heavy.

In the current study, we propose a novel miniaturized, soft, and wearable haptic display device created combining liquid-to-gas phase change actuators [16]–[22] with a Peltier device. The liquid-to-gas phase change actuators generate high displacement and force, utilizing the inflation of a closed pouch induced by the transition from the liquid to the gas phase. Although previously proposed liquid-to-gas phase change actuators are heated by flexible heaters [16]–[18], [20], [22], millimeter-wave irradiation [21], or contactless heating methods [19], the proposed haptic display can efficiently drive the actuator by controlling both heating and cooling using a Peltier device. Based on the previous basic design of a haptic display with a Peltier device [23], in the present study, we integrated a pressure sensor with the actuator of the proposed haptic display to monitor the pressure inside the liquid-to-gas phase change actuator. Sanchez *et al.* [24] tried a similar concept using a flexible pressure sensor. Their method required an additional process to fabricate the flexible pressure sensor. On the other hand, we used a commercially available pressure sensor to quickly implement pressure measurement. The sensor is low cost (less than $10), and the state of the actuator is easily estimated and allows the haptic display system to control the output of the normal force by controlling the pressure inside the actuator. Although the flexibility of the liquid-to-gas phase change actuator is diminished because of the stiffness of the Peltier device and sensor, the haptic display is still small and lightweight (only a few grams) enough to be attached to a body part, such as a fingertip. Fig. 1 shows the proposed haptic display system and its example use cases.

To explore the design guideline of the proposed haptic display, we conducted characterizations of the proposed haptic display using the integrated pressure sensor, which were never performed in our previous study [23]. First, we calculated the minimal amount of a low-boiling-point liquid, which is necessary for adequate heating, using a previously proposed theoretical model [20], [22], [25]. Next, we evaluated the effect of the amount of a low-boiling-point liquid and the size of the actuator's pouch on the pressure inside the liquid-to-gas phase change actuators. Then, we measured the output force using a force gauge to evaluate the output's normal force and its response time. Finally, we conducted a user experiment and evaluated the force perception of the haptic display.

The contributions of the current paper can be summarized as follows:

- Design the fabrication process and calculate the theoretical actuation model of the proposed haptic display using the liquid-to-gas phase change actuator, Peltier device, and pressure sensor.
- Investigate the characteristics of the proposed haptic device when varying the size of the pouch and the amount of the injected low-boiling-point liquid.
- Reveal and discuss the response of the proposed haptic display in force presentation through a user experiment.

## II. RELATED WORK

Wearable haptic or tactile displays have an important role when it comes to the feedback in virtual reality environments and remote operations [3]. Among these displays, haptic displays that provide force to users are necessary to virtually present objects. Although some haptic displays have the aim of being attached to the arm [15], [26] or leg [27], most of them have been attached to the finger [7] because we most often use our fingers to obtain the haptic information of objects.

In this type of finger-worn haptic display, a brake mechanism consisting of a motor and tendon is most often used. Leonardiset *et al.* [28] developed a wearable haptic display to provide tri-axial force using motors and a rigid parallel kinematic design. Schorr and Okamura [29] also developed a wearable haptic display using a rigid parallel kinematic design and motors to render contact, in addition to rendering shear and normal skin deformation. Khurshid *et al.* [30] proposed a haptic display to present force to the finger using a voice coil motor, which has advantages when it comes to controllability and quick response time. Culbertson *et al.* [10] applied the voice coil motor to provide vibration. Minamizawa *et al.* [31] combined a belt with motors to provide normal force and lateral force simultaneously to present the weight of a virtual object. Chen *et al.* [32] developed a wearable haptic display to represent rich haptic information on a touchscreen. This display can provide both normal force and lateral force by combining a magnetorheological fluid actuator and DC motor. These haptic displays have advantages in their controllability and quick response time because they are electrically driven and controlled. However, these actuators typically consist of stiff material, such as metal or resin, and the structures of the devices are complicated; thus, they have the problem of being hard, heavy, and bulky.

To address this problem, some researchers have proposed haptic displays that use soft and lightweight actuators such as DEAs [11], [12], hydraulically amplified self-healing electrostatic (HASEL) actuators, and pneumatic actuators [33]–[36]. DEAs are composed of electroactive polymers that deform by applying voltage, and HASEL actuators utilize the movement of a dielectric liquid induced by an electrostatic force; both have quick responsiveness. However, these actuators require a high voltage (a few kV), thus requiring a bulky external circuit to generate it while presenting a safety risk because of the possibility of electric shock. On the other hand, pneumatic actuators use the inflation of their flexible bladder induced by compressed air; thus, they can generate more force and displacement without the use of dangerous high voltage. Because of these advantages, pneumatic actuators have a high affinity for wearable haptics and tactile displays, and various haptic display systems have been proposed. Fukuda *et al.* [33] fabricated a ring-shaped haptic display to present pressure for the localization of an early-stage gastric tumor. King *et al.* [34] developed a shape display for robot-assisted surgery using a microfabrication technique and determined its optimal design with sensory evaluations. Nagano *et al.* [35] utilized vacuum pressure to present pressure distribution. Kanjanapas *et al.* [36] developed a two-degree of freedom pneumatic linear soft device to provide shear force. Although wearable haptic displays using pneumatic actuators have been applied to a wide range of applications because of their lightweight and flexible characteristics, using air compressors and air valves to drive and control the generated force of the actuators still comes with the issue of these actuators being bulky. Therefore, although the force-presenting components of these displays are small and wearable, the bulky external devices connected to them inhibit the user's free movements and do not compose truly wearable displays.

We believe that a novel wearable haptic display can be developed by using pneumatic actuators that are lightweight, that are flexible, and that do not require bulky external devices. For these actuators, we chose liquid-to-gas phase change actuators [20], which are driven by heating a low-boiling-point liquid with a heater to vaporize it and inflate plastic pouches like bladders. Liquid-to-gas phase change actuators only require a few V for the heaters, and this feature contributes to the entire system's miniaturization. We have utilized hydrofluoroether (Novec$^{\mathrm{TM}}$ 7000, 3M Company) as the low-boiling-point liquid to expect a quick response time because the boiling point of Novec$^{\mathrm{TM}}$7000 is only 34 °C [37]. To heat the low-boiling-point liquid inside the pouch, metal heaters have typically been applied to the pouch [18], [20], [22], [38]; thus, the shrinkage of pouches by cooling depends on natural cooling. This lack of an active cooling mechanism loses the controllability of the liquid-to-gas-phase change actuator and has limited the field of applications. Moreover, sensing of the air pressure inside the pouch have been not often conducted, and this results in the difficulty of feedback control.

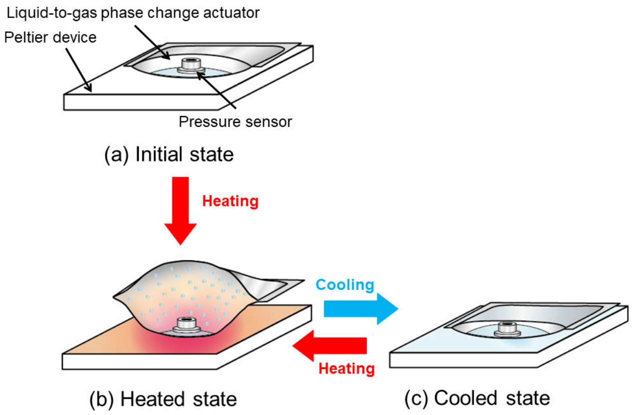
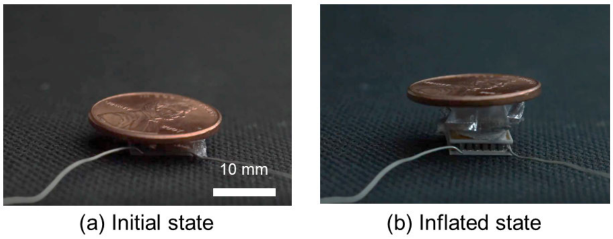


**FIGURE 2.** Structure and principle of the proposed haptic display. (a) The haptic display is flat in the initial state. (b) The haptic display is inflated by heating the liquid-to-gas-phase change actuator using the Peltier device. Inflation induces displacement and force. (c) Cooling using the Peltier device shrinks the liquid-to-gas phase change actuator.



(a) Initial state (b) Inflated state

**FIGURE 3.** Actuation of the proposed haptic display. (a) The haptic display is initially flat. (b) The haptic display induces force and displacement through heating by using the Peltier device.

## III. METHODS

### A. OVERVIEW

We developed a wearable haptic display comprised of a liquid-to-gas phase change actuator with a Peltier device and controlled it with feedback from the sensing data from a pressure sensor integrated inside the actuator's pouch. The structure and principle of the proposed haptic display are shown in Fig. 2, and the actual motion of the display is shown in Fig. 3. The liquid-to-gas phase change actuators are driven by the phase change of a low-boiling-point liquid encapsulated inside its pouch. In an initial state, when there is liquid inside the pouch, the pressure inside the pouch is low and the actuator is shrunk, as shown in Fig. 2a. When the temperature inside the pouch exceeds the boiling point of the liquid, the liquid starts to evaporate. This evaporation causes an increase in the pressure inside the pouch, and the actuator generates displacement and force by inflating

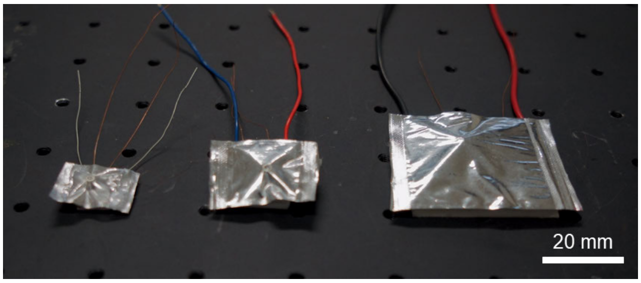
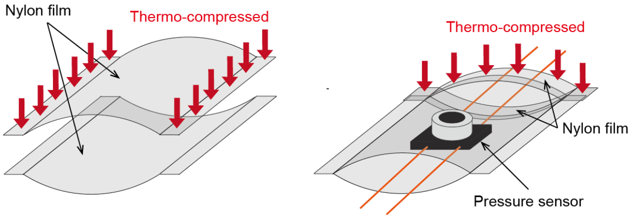
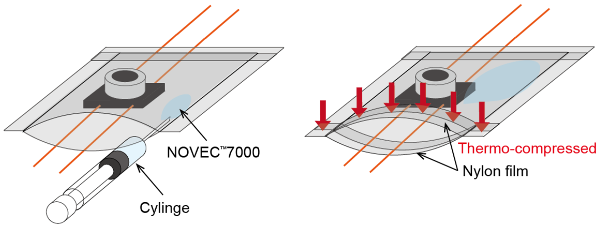


**FIGURE 4.** **Assembled haptic displays with various sizes. A pouch of the liquid-to-gas phase change actuator was fixed to a Peltier device using double-side thermal conductive tape to conduct efficient heat transfer. Left: 13 mm × 13 mm. Middle: 20 mm × 20 mm. Right: 40 mm × 40 mm.**



(a) Bond films

(b) Embed a sensor



(c) Inject liquid

(d) Encapsulate liquid

**FIGURE 5.** **Fabrication process of the liquid-to-gas phase change actuator with the integrated sensor. (a) Thermal bonding of the two opposite edges of the films. (b) Embedding the sensor with wires into the pouch and thermally bonding one edge. (c) Injecting a measured amount of the low-boiling-point liquid (Novec$^{\text{TM}}$ 7000) into the pouch. (d) Encapsulating the liquid inside the pouch by thermal bonding of the remaining edge of the pouch.**

the pouch, as shown in Fig. 2b, allowing for the proposed haptic display to provide haptic information to the user. Subsequently, when the temperature of the liquid decreases by cooling the Peltier device, the actuator shrinks again, which results in a decrease in displacement and force, as shown in Fig. 2c. In this way, we can control the output force of the haptic display by controlling the temperature of the Peltier device. To constitute the liquid-to-gas phase change actuator, we used hydrofluoroether (Novec$^{\text{TM}}$ 7000, 3M Company) as a low-boiling-point liquid because it is chemically stable and safe for human health, with a boiling point of 34 °C [37], which is slightly higher than the typical surface temperature of human skin.

We wanted to use the proposed haptic displays by mounting them on a fingertip or an arm; thus, we designed three types of haptic displays with different sizes of pouches: 13 mm × 13 mm, 20 mm × 20 mm, and 40 mm × 40 mm, and the weights of them were 1 g, 4 g, and 24 g, respectively. The proposed haptic displays are shown in Fig. 4. The size of the smallest haptic displays is sufficient to be mounted on the user's fingertip and still be lighter than the conventional haptic displays [7].

### B. FABRICATION AND IMPLEMENTATION PROCESS

Fig. 5 shows the entire fabrication process of the liquid-to-gas phase change actuator. The fabrication process is almost the same as in previous studies [18], [20], [22]; however, we added a step to integrate a pressure sensor with the pouch of the actuator. First, we cut an aluminum-coated nylon film with a thickness of 28 $\mu$ m (aluminum vapor deposition film, Yume Fusen)[1] into the designed size and thermally bonded two parallel edges of two sheets using a thermo-compressor (NL202L, Ishizaki Electronic Mfg.) (Fig. 5a). Next, we soldered copper-coated steel wires with a diameter of 80 $\mu$ m to the terminals of the sensor, sandwiched the wires between the unsealed sides of the pouch, and thermally bonded an unsealed edge of the pouch (Fig. 5b). To avoid the leakage of Novec$^{\text{TM}}$7000 via the small gaps formed by the wires, we placed additional nylon films at the edge and thermally bonded them. We injected a measured amount of Novec$^{\text{TM}}$7000 via another unsealed edge using a micropipette (Fig. 5c), and the unsealed edge was thermally bonded twice with additional films (Fig. 5d).

To constitute the haptic display, we attached the Peltier devices with a size of 9 mm × 9 mm (NL1022T, Marlow Industries), 17 mm × 17 mm (TEC-40865A-00, Akizuki Denshi Tsusho), and 40 mm × 40 mm (TES1-12739, Thermonamic Electronics Corp) to the pouches with a size of 13 mm × 13 mm, 20 mm × 20 mm, 40 mm × 40 mm. A pouch of the actuator was fixed on a Peltier device using double-sided thermal conductive tape (thermal conductive tape, Tuloka). A commercially available pressure sensor (HSPPAD143A, ALPS ALPINE) was integrated into the pouch of the actuator to monitor the state of the actuator. The precision of the pressure sensor is ±0.2 kPa. Although the pressure sensor can measure both pressure and temperature, temperature measurement inside the liquid-to-gas phase change actuator was unnecessary for the current implementation. Therefore, we only monitor pressure related to the output force of the haptic display using the sensor. Additionally, we mounted a temperature sensor (GAG10K3976, TE Connectivity) to a Peltier device for measuring and controlling the surface temperature of the Peltier device. The precision of the temperature sensor is ±1%. The maximum temperature was limited to 42 °C to avoid heat injury to human skin [39].

### C. THEORETICAL MODEL

We calculated the optimal amount of Novec$^{\text{TM}}$7000 inside a liquid-to-gas phase change actuator by using the state equation and theoretical model proposed in our prior works [20], [22], [25]. When Novec$^{\text{TM}}$7000 is in its gas state, the state

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[1] http://www.yumefuusen.co.jp/film.shtml

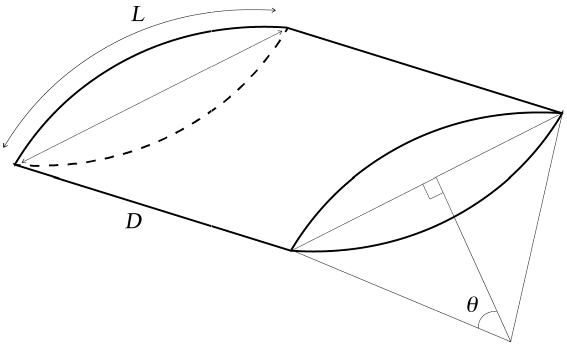


**FIGURE 6.** Theoretical model of the pouch for the full inflation and its geometric parameters.

equation can be expressed as the follows:

$$PV = \frac{m}{M}RT, \tag{1}$$

where $P$ is the pressure inside a pouch, $V$ is the volume of the chamber, $m$ is the mass of the encapsulated low-boiling-point liquid, $M$ is the molar mass of Novec$^{\text{TM}}$ 7000, $R$ is the gas constant, and $T$ is the absolute temperature of Novec$^{\text{TM}}$ 7000. Eq. (1) can be modified as the follows:

$$PV = \frac{V_l\,\rho}{M}RT, \tag{2}$$

where $V_l$ is the amount of Novec$^{\text{TM}}$7000 and $\rho$ is the density of Novec$^{\text{TM}}$ 7000.

When the pressure of Novec$^{\text{TM}}$7000 is reached at the vapor pressure at a certain temperature, the pressure in the pouch does not increase anymore. The vapor pressure of Novec$^{\text{TM}}$7000 can be calculated using the following equation [37]:

$$P_{\text{vap}} = \exp(-3548.6/T + 22.978), \tag{3}$$

where $P_{\text{vap}}$ is the vapor pressure at $T$ [K]. Novec$^{\text{TM}}$7000 can be vaporized in the pouch until the pressure reaches the vapor pressure if a sufficient amount of Novec$^{\text{TM}}$7000 is encapsulated in the pouch. After the pressure reaches the vapor pressure point, the gas and liquid phases of Novec$^{\text{TM}}$7000 coexist. The remaining liquid state of Novec$^{\text{TM}}$7000 absorbs only heat and increases the heat capacity. Therefore, to achieve a faster response, the remaining liquid state should be minimized. The minimal amount of Novec$^{\text{TM}}$7000 at a certain temperature can be expressed using Eqs. (2) and (3):

$$V_l = \frac{P_{\text{vap}}VM}{\rho\,RT}. \tag{4}$$

To calculate the minimal amount of Novec$^{\text{TM}}$7000 to fully inflate the liquid-to-gas phase change actuator, $P_{\text{vap}}$, $V$, and $T$ should be substituted into Eq. (4). $P_{\text{vap}}$ and $T$ can be estimated by the temperature of Novec$^{\text{TM}}$ 7000. $V$, which is the volume of the liquid-to-gas phase change actuator when inflated fully, can be calculated using the geometric model [20], [22], [25].

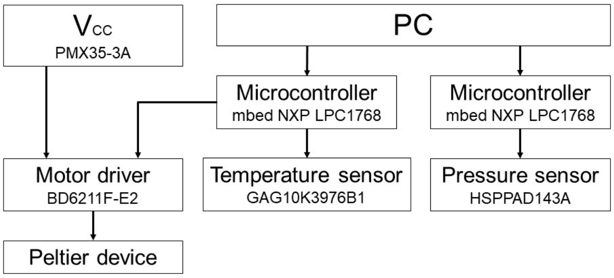


**FIGURE 7.** Circuit diagram for controlling the proposed haptic displays in the experiment.

Fig. 6 shows the geometric model of the liquid-to-gas phase change actuator and its geometric parameters. We assumed that nylon is a stiff material and that the pouch is not stretched under the pressure induced by Novec$^{\text{TM}}$ 7000. According to the theoretical model, the maximum theoretical volume of the liquid-to-gas phase change actuator can be expressed as follows:

$$V(\theta) = \frac{L^2D}{2}\left(\frac{\theta - \cos\theta\sin\theta}{\theta^2}\right), \tag{5}$$

where $\theta$ is the central angle of the circular segment, $L$ is the initial length of the pouch, and $D$ is the width of the pouch. $V(\theta)$ takes their maximum values when $\theta = \frac{\pi}{2}$, and the pouch is a cylindrical shape in this state:

$$V_{\max} = V\left(\frac{\pi}{2}\right) = \frac{L^2D}{\pi}. \tag{6}$$

$V_{\max}$ is the maximum theoretical volume of the liquid-to-gas phase change actuator. Unfortunately, the theoretical model and actual shape are different, especially in the shape of the edges of the pouch. In the theoretical model, two edges are fixed, and the other edges are open to simplifying the theoretical model. On the other hand, all edges are fixed in the actual shape. However, this simplification is necessary to calculate and estimate the deformation of the pouch easily. We discuss the effect of the simplification on the optimization of the amount of Novec$^{\text{TM}}$7000 in the following sections.

Finally, using Eqs. (4) and (6), the optimal amount of Novec$^{\text{TM}}$7000 to fully inflate the pouch of the liquid-to-gas phase change actuator can be expressed as follows:

$$V_{l,\,\min}(T) = \frac{M}{\rho}\frac{P_{\text{vap}}}{RT}\frac{L^2D}{\pi}. \tag{7}$$

Although we substituted a vapor pressure at a specific temperature in the theoretical model, a small amount of air is encapsulated in the actual liquid-to-gas phase change actuator because of the fabrication process. However, the amount is considered to be small, and we ignored the effect of air on the theoretical model. We calculated the optimal amount of Novec$^{\text{TM}}$7000 according to the design of the actuator based on this estimation in the fabrication process.

**TABLE 1.** Calculated amount of Novec$^{\text{TM}}$7000 for each pouch size.

| Actuator size | Min. Amount | 2 × Min. | 4 × Min. |
|---|---|---|---|
| 13 mm × 13 mm | 5 $\mu$L | 10 $\mu$L | 20 $\mu$L |
| 20 mm × 20 mm | 20 $\mu$L | 40 $\mu$L | 80 $\mu$L |
| 40 mm × 40 mm | 140 $\mu$L | 280 $\mu$L | 560 $\mu$L |

## IV. EXPERIMENTS

### A. PRESSURE MEASUREMENT

We evaluated the relationship between the temperature of the Peltier device and pressure inside a pouch of the liquid-to-gas phase change actuator to investigate the characteristics of the proposed haptic displays. Especially in this case, we evaluated the effects of the amount of Novec$^{\text{TM}}$7000 and the size of the liquid-to-gas phase change actuator, changing these parameters.

#### 1) EXPERIMENTAL SETUP AND PROCEDURE

The circuit diagram for controlling the proposed haptic display in the experiment is shown in Fig. 7. The Peltier device of the haptic display was connected to a power supply (PMX35-3A, Kikusui) via a full-bridge driver (BD6211F-E2, Rohm Semiconductor), and it was controlled by a microcontroller (mbed NXP LPC1768, NXP semiconductors). The maximum applied voltage and current were limited to 4.0 V and 0.45 A because of the specification of the full-bridge driver. The temperature sensor with the Peltier device and pressure sensor embedded in the pouch of the actuator were connected to a PC (Surface Pro 4, Microsoft Corporation) via microcontrollers (mbed NXP LPC1768, NXP semiconductors) to record pressure data and temperature data measured by the sensors. The sampling rates for the pressure sensor and temperature sensor were 0.01 s and 0.12 s, respectively. The measured surface temperature of the Peltier device determined the control input to the Peltier device.

To determine the injection amount of Novec$^{\text{TM}}$ 7000, we calculated the minimal amount of Novec$^{\text{TM}}$7000 at 42 °C using Eq. (7). We determined the encapsulated amounts of Novec$^{\text{TM}}$7000 to be one, two, and four times as much as the minimal amounts of each pouch. The resulting amounts of Novec$^{\text{TM}}$7000 are given in Table 1. We used the haptic display with the pouches in which these amounts of Novec$^{\text{TM}}$7000 are injected.

Here, we describe the procedure of the inside pressure measurement. Before the experiment, we kept the temperature of the Peltier device at 30 °C. Then, we heated the Peltier device until the temperature reached 42 °C. We recorded the temperature of the surface of the Peltier device and the pressure inside the actuator for 240 s. The average temperature and humidity of the room were 23.3 °C (SD:1.1) and 33.9% (SD:9.5), respectively.

#### 2) RESULTS

Fig. 8 shows the experimental results. In all the conditions, save for the size of 13 mm × 13 mm, the pressure inside the actuator reached almost 130 kPa in almost 30 s. Because the theoretically calculated value of the vapor pressure of Novec$^{\text{TM}}$7000 at 42 °C is 122.1 kPa [37], we can assume that the maximum pressure inside the actuator was saturated near the vapor pressure of Novec$^{\text{TM}}$ 7000, even though the actual pressure was slightly higher than the vapor pressure. The approximated geometric model was sufficient to estimate the sufficient amount of Novec$^{\text{TM}}$7000 based on this result. The reason for the difference between the actual maximum pressure and theoretical vapor pressure is air encapsulation. The fabrication process can not prevent air encapsulation, and the partial pressure of the encapsulated air increases the actual maximum pressure; the resulting maximum pressure is around 130 kPa at 42 °C. To obtain the more theoretical maximum pressure, the fabrication process, such as the vacuum process, which prevents air encapsulation, is required.

When the size is 13 mm × 13 mm and the amount of Novec$^{\text{TM}}$7000 equaled 5 $\mu$ L and 10 $\mu$ L, the pressure did not reach the vapor pressure, even though we encapsulated the theoretically sufficient amount of Novec$^{\text{TM}}$ 7000. In these cases, the amount of Novec$^{\text{TM}}$7000 was small, and Novec$^{\text{TM}}$7000 was vaporized in the thermal bonding process. This caused a decrease in Novec$^{\text{TM}}$7000 inside the pouches and maximum pressure in the actuator. To provide the maximum pressure, the amount of Novec$^{\text{TM}}$7000 should be larger than the amount calculated by Eq. (7). However, a large amount of Novec$^{\text{TM}}$7000 reduced the pressure response (e.g., the actuator with the size of 40 mm × 40 mm containing 560 $\mu$ L of Novec$^{\text{TM}}$ 7000) because the heat capacity of Novec$^{\text{TM}}$7000 to 42 °C was higher and more heat was required to heat Novec$^{\text{TM}}$7000 to 42 °C. Therefore, to achieve a better response, it is essential not to encapsulate too much Novec$^{\text{TM}}$ 7000.

### B. RESPONSE TIME

We conducted a heating and cooling cycle experiment to evaluate the response time of the proposed haptic displays.

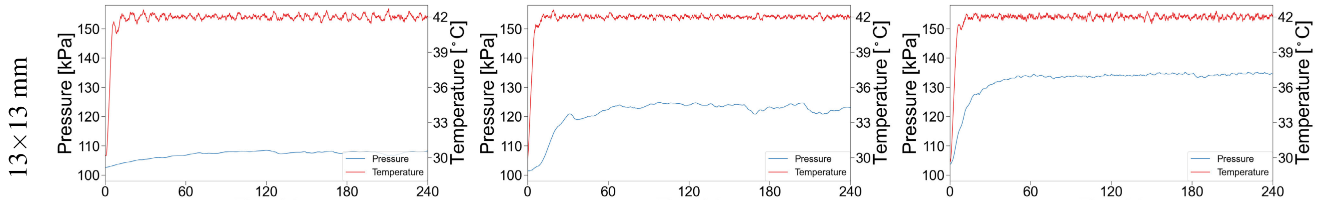
#### 1) EXPERIMENTAL SETUP AND PROCEDURE

In this experiment, we used the same equipment and setup as Section IV-A. We prepared the actuator with a size of 13 mm × 13 mmm, 20 mm × 20 mm, and 40 mm × 40 mm and encapsulated 20 $\mu$ L, 80 $\mu$ L, and 560 $\mu$ L of Novec$^{\text{TM}}$7000 to obtain vapor pressure inside the actuator, here based on the results of Section IV-A.

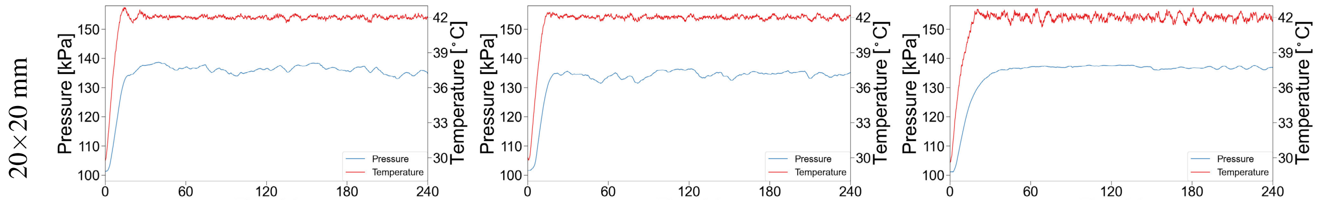
Here, we describe the procedure of the heating and cooling cycle experiment. First, we kept the surface of the Peltier devices at 30 °C and increased the temperature. In the heating cycle, we kept the temperature of the Peltier devices at 42 °C for 45 s. Then, in the cooling cycle, the temperature was kept at 30 °C for 45 s. We repeated these cycles twice.

#### 2) RESULTS

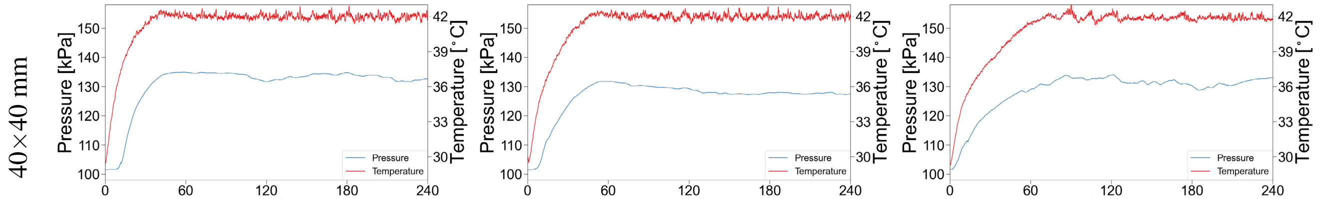
Fig. 9 shows the results of the experiment. The pressure inside the actuator increased as the temperature of the Peltier device increased. Then, the pressure decreased as the Peltier



(a) 5 µL (Min. Amount) (b) 10 µL (2 × Min.) (c) 20 µL (4 × Min.)



(d) 20 µL (Min. Amount) (e) 40 µL (2 × Min.) (f) 80 µL (4 × Min.)



(g) 140 µL (Min. Amount) (h) 280 µL (2 × Min.) (i) 560 µL (4 × Min.)

**FIGURE 8.** **Experimental results for the pressure measurement. The pressure inside the liquid-to-gas phase change actuator was saturated near the vapor pressure. In the case of the small actuator design, a small amount of Novec$^{TM}$7000 resulted in low saturated pressure because the fabrication process did not prevent the vaporization of Novec$^{TM}$ 7000.**

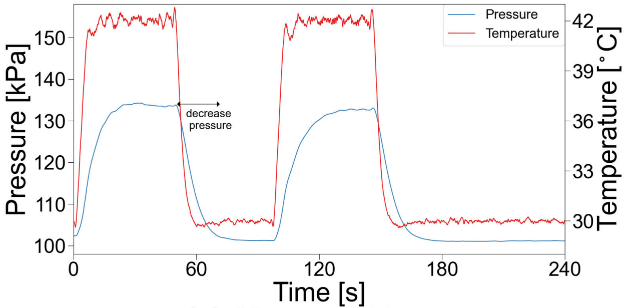
device cooled. We can observe that when the actuator and sizes of the Peltier device were larger, it took a long time to increase and decrease the temperature and pressure because of the higher heat capacity of the liquid-to-gas phase change. When we compared the time to decrease the pressure between the proposed haptic display (13 mm × 13 mm) and previous work [19], [20], [24], we found that our haptic display was shorter (Our result: about 20 s, [19]: 30-60 s, [20]: 20-70 s, [24]: 50 s). Therefore, we believe that the miniaturization of the liquid-to-gas phase change actuator and cooling with the Peltier device achieves a better response.

On the other hand, the pressure reached the vapor pressure of Novec$^{TM}$7000 in 20 to 30 s, and this saturation time is the same as the conventional liquid-to-gas phase change actuators [19], [20], [24]. Heating for 20 to 30 s is necessary to obtain maximum pressure, and there is a possibility that humans can perceive force generated by the actuator in a shorter time, because of perception characteristics. We will investigate the time to perceive the force in the experiment in Section IV-D.

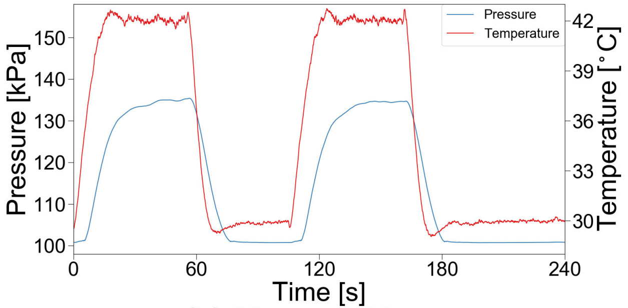
Fig.10 shows the relationship between temperature and pressure during the second heating and cooling cycle. Hysteresis was observed in the relationship between temperature and pressure during the cooling and heating cycles. There were sections where the pressure did not increase even if the temperature increased and sections where the pressure decreased even if the temperature remained constant. This suggests a delay between the temperature change of the Peltier device and the internal pressure change of the actuator. Additionally, the smallest haptic display exhibited a quick response in pressure during the heating cycle. The considerable reason for the quick response is the heat capacity. The smallest haptic display contained the smallest amount of Novec$^{TM}$7000 and had lower heat capacity. Therefore, the Peltier device was able to heat the liquid to the boiling point quickly through the thermal conductive tape. On the other hand, when the haptic display was larger, the amount of Novec$^{TM}$7000 was larger and more heat was required to reach the boiling point. As a result, the pressure increased to around 36 °C. During the cooling cycle, the haptic displays exchanged heat with the cooler atmosphere through their surfaces in addition to the Peltier devices. Therefore, the smaller haptic display with a smaller amount of Novec$^{TM}$7000 and a small surface area exchanged less heat, while the haptic display with a larger amount of Novec$^{TM}$7000 and a large surface area exchanged much heat. As a result, the temperature of Novec$^{TM}$7000 derived from the temperature of the Peltier device was consistent, regardless of the size, and the trend of the curves during the cooling cycle was almost the same.

### C. FORCE MEASUREMENT

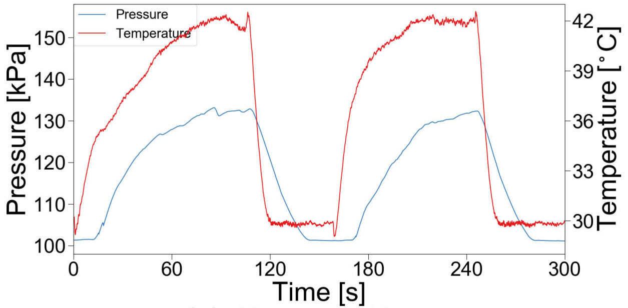
We conducted an output force measurement to evaluate the relationship between the temperature of a Peltier device, the pressure inside the actuator, and the generated output force.



(a) 13 mm × 13 mm



(b) 20 mm × 20 mm



(c) 40 mm × 40 mm

**FIGURE 9.** **Experimental results of the heating and cooling cycle experiment. (a) 13 mm × 13 mm. (b) 20 mm × 20 mm. (c) 40 mm × 40 mm. The change in the pressure well coincided with the change in the temperature of the Peltier device. The results suggest that the temperature control of the Peltier device is effective in controlling the output force of the haptic display.**

### 1) EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup is shown in Fig. 11. We fixed the haptic display on a linear stage. The haptic display was contacted on a digital force gauge (ZTS-50N, Imada) and kept its position. We attached a urethane rubber to the tip of the force gauge to mimic human skin. Placing a flexible force sensor between the urethane rubber and finger is another considerable measurement setup. However, flexible force sensors generally have lower precision and linearity than the digital force gauge. Additionally, the commercially available flexible sensors may not be able to follow deformation perfectly due to their stiffness derived from polyimide. From the above considerations, we believe that the selected measurement setup well emulates the actual use case and applied the measurement setup in this experiment.

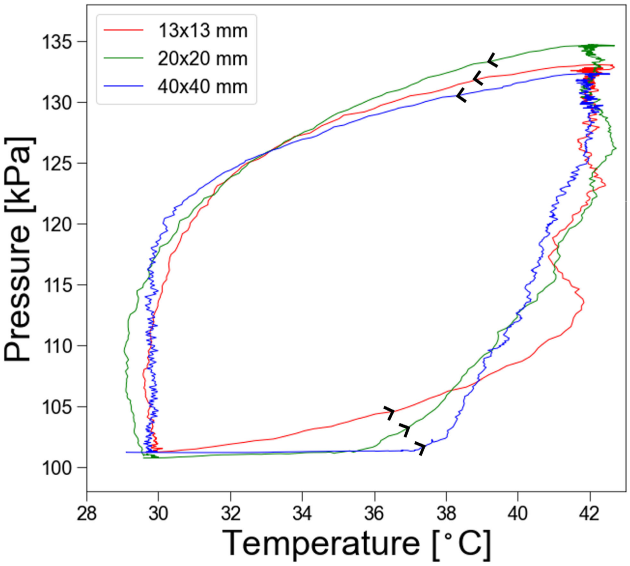


**FIGURE 10.** **Hysteresis characteristics of the haptic displays. The lower sides show the curves for the heating cycle, and the uppersides show the curves for the cooling cycle. The curves for heating were slightly different among each haptic display because of the difference in the heat capacity.**

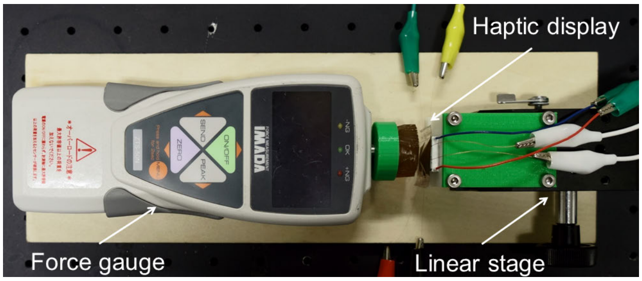
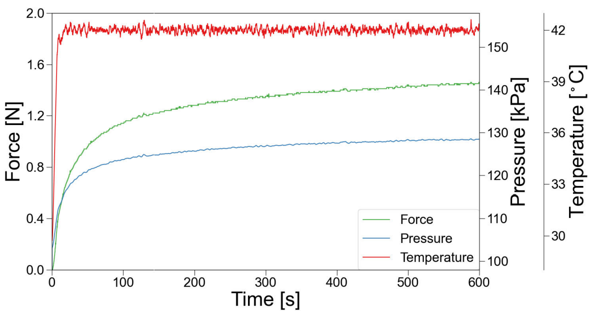


**FIGURE 11.** **Experimental setup for force measurement. The temperature of a Peltier device, the pressure inside the actuator, and the generated output force were recorded using the sensors in the haptic display.**

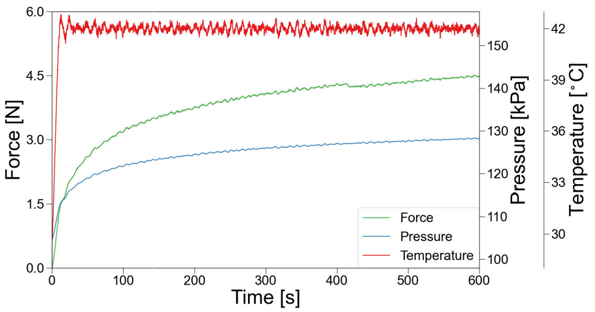
Here, we describe the procedure of the experiment. We initially set the temperature of the Peltier device at 30 °C. Then, we increased the temperature to 42 °C and kept it. We recorded the temperature of the Peltier device, the pressure inside the pouch, and the output force for 600 s. We evaluated three haptic displays, and the sizes of the actuators were 13 mm × 13 mm, 20 mm × 20 mm, and 40 mm × 40 mm. The amounts of Novec$^{\mathrm{TM}}$7000 were the same as Section IV-B. The temperature and humidity of the room were 23.0 °C and 27.1%, respectively.

### 2) RESULTS

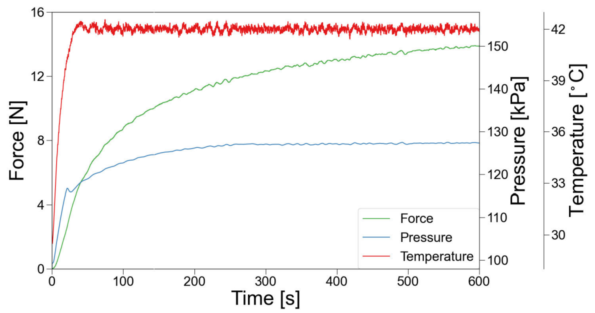
Fig. 12 shows the result of the experiment. As the temperature of the Peltier device increased, both the pressures inside the actuator and output force increased. After about 100 s from the start of heating, the pressure and temperature had become saturated. Subsequently, the changes in the pressure and output normal force became quite small, and the change in the force well reflected the change in the pressure.



(a) 13 mm × 13 mm



(b) 20 mm × 20 mm



(c) 40 mm × 40 mm

**FIGURE 12. Experimental results of the force measurement. (a) 13 mm × 13 mm. (b) 20 mm × 20 mm. (c) 40 mm × 40 mm. The output normal force largely increased for 100 s or less. After that, the force gradually increased. The smallest haptic display exhibited a quicker response, and the miniaturization appeared to contribute to achieving a quick response.**

The trend for the response of the pressure shown in Fig. 12 was similar to the trend shown in Fig.8, although the force gauge constrained deformation of the actuator as shown in Fig. 11. The considerable reason for this is that there was only a small difference in the maximum volume of the actuator. Therefore, there was also only a small difference in the amount of gas and heat required for the deformation, and this resulted in a similar response. The relationships between the output force and pressure inside the actuator are shown in Fig.13. The pressure linearly increased when the actuator was small. On the other hand, the largest actuator exhibited nonlinearity. We considered that a smaller design is suitable to provide accurate force.

The maximum output forces at 42 °C were 1.3 N, 4.0 N, and 13.0 N for actuators with sizes of 13 mm × 13 mm, 20 mm × 20 mm, and 40 mm × 40 mm, and the larger actuator provided higher output force. As a result, we considered that the haptic display can provide a force of 1 N or more to users because we attached a human skin mimic to the force gauge. The just noticeable difference (JND) for force to the index finger is the minimal detectable difference in applied force and is said to be approximately 10% of the base force [40], although the finger was well fixed and some conditions were different. The reported JNDs for force in other articles are around 10% [41], [42] and we considered that the JND for a force of 10% is a reasonable value. Therefore, if the base force is small, the small output force generated via the haptic display in a few seconds can be sufficient to provide perceivable force.

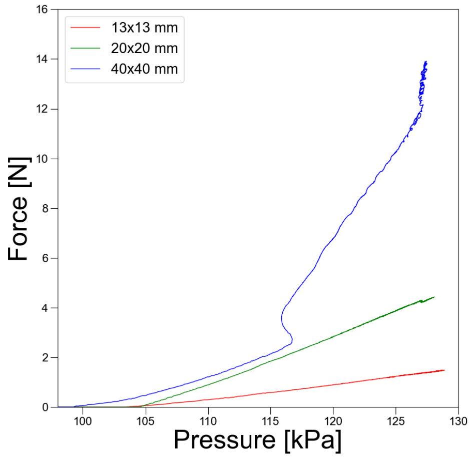


**FIGURE 13. Relationship between output force and pressure inside the actuator. The output force gradually increased when the increase in the pressure exceeded a few kPa. Actuators with sizes of 13 mm × 13 mm and 20 mm × 20 mm exhibited linear relationships. On the other hand, Actuators with sizes of 40 mm × 40 mm did not exhibit linearity.**

Lower pressure inside the actuator generated a smaller force, as shown in Fig. 12. When the pressure inside the actuator is less than the vapor pressure of the low-boiling-point liquid, the pressure changes according to the state equation. Therefore, by lowering the temperature of the Peltier device, which determines the temperature of the low-boiling-point liquid, the pressure inside the actuator can be lowered when the internal pressure does not reach the vapor pressure. In this way, we believe that lowering and keeping the pressure inside the actuator will decrease the intensity of the generated force.

### D. SENSORY EVALUATION

Through a user experiment, we evaluated whether the participants could perceive force using the proposed haptic display.

#### 1) EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup is shown in Fig. 14. We used the haptic display with a size of 13 mm × 13 mm, here with amount of Novec$^{\mathrm{TM}}$7000 being 20 $\mu$ L. The haptic display

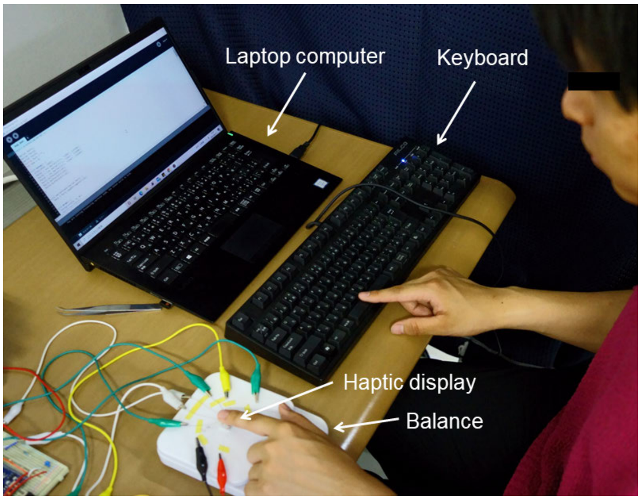


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**FIGURE 14.** Experimental setup of the sensory evaluation. The sensors were connected to a laptop computer to record the temperature and pressure. The time when the participants perceived the force was determined by key input.

was fixed to an electronic balance (KF-200, Tanita) using thermal conductive tape (thermal conductive tape, Tuloka). An external keyboard was connected to a laptop computer (VAIO SX 14, VAIO) for recording the inputs of the participants. Before the experiment, we asked the participants to experience the output force of the haptic display freely. We also trained the participants to press the haptic display with a force of almost 50 g using the electronic balance.

In the experiment, the participants placed their left index fingers on the haptic display. The initial temperature of the Pertier device was 28 °C to prevent the inflation of the actuator without heating. At the start of the experiment, we increased the temperature of the Peltier device to 42 °C to inflate the actuator. Then, we asked the participants to press the assigned key of the keyboard using their right index fingers when the participants felt force induced by the haptic display. We recorded the surface temperature of the Peltier device, the pressure in the liquid-to-gas phase change actuator, and the time when the participant perceived it. We repeated the procedure five times per participant. We recruited eight people for the experiment (seven were male, and one was female). The average age of the participants was 21.9 years old (SD:2.3). The average temperature and average humidity of the room were 24.2 °C (SD:1.6) and 30.0% (SD:12.7), respectively.

### 2) RESULTS

Fig. 15 shows the results of the sensory evaluation. The vertical axis shows the change in the pressure inside the actuator because the initial pressures slightly differed among the trials. According to the results, the participants perceived force within 3 s in 65% of all trials and within 6 s in all trials. Among the trials where the participants perceived force, the change in the pressure ranged from 2 kPa to 12 kPa. Then, the resulting output force after a few seconds is considered to be 0.34 N (2 kPa × $(0.013\ \mathrm{m})^2$) – 2.03 N (12 kPa × $(0.013\ \mathrm{m})^2$), here considering the condition when the entire area of the actuator was covered by the participant's fingerpad. The calculation assumes the ideal condition; the actual output force was smaller than the calculated force. In this experiment, the participants fixed their fingers with a pressing force of 0.050 kg × 9.8 N/kg = 0.49 N. Therefore, the change in the force (0.34–2.03 N) is much greater than the just noticeable difference (JND) for the pressing force, which is 0.49 N × 10% = 0.049 N. Even if the actual contact area was half or less of the ideal contact area and the participants could perceive the output normal force.

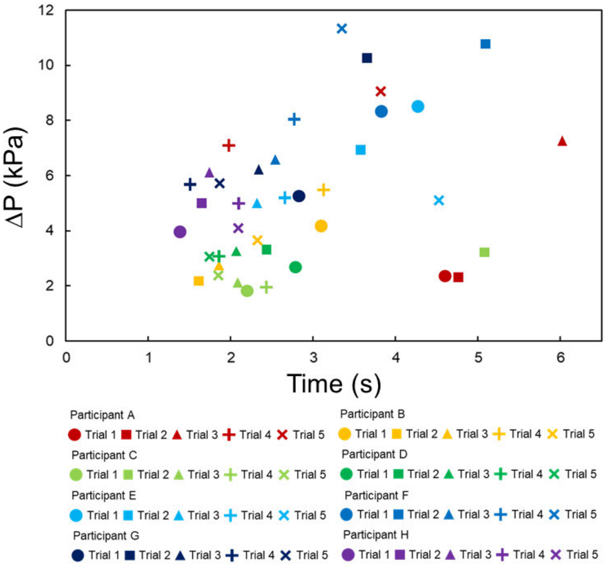

**FIGURE 15.** Relationship between the time when the participant perceived the force and pressure at the time. All participants tended to perceive force within 6 s. Although the change in the output force was small, the participants could detect a small change.

For the trials where the participants took more time (over 3 s) to perceive the normal force, we can assume two cases: the participants needed high pressure to perceive the normal force, and the haptic display took time to increase the pressure. The reason for the first case is the contact between the haptic display and fingerpad. In this experiment, the participants only placed their fingers on the haptic display. This resulted in unstable contact and loss of the efficiency regarding the force transmission, even though the contact force was maintained at 0.49 N. The reason for the second case is the unstable and uncontrollable position of the low-boiling-point liquid inside the pouch. The liquid was not always on the Peltier device, and this deteriorated the heat transfer.

In this experiment, the subjects were facing forward. Additionally, the haptic display was covered by the subject's finger, and the pouch was only slightly inflated because of the slight increase in the pressure inside the actuator shown in

Fig. 15. These conditions made it difficult for the subjects to perceive the deformation of the haptic display visually. Therefore, we conclude that visual information did not influence the perceptual judgment of contact force.

In summary, the sensory evaluation revealed the potential to provide normal force to users within a few seconds. However, the time was not constant because of the contact between the haptic display and finger and the position of a low-boiling-point liquid.

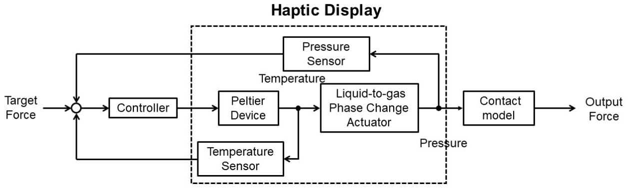

**FIGURE 16.** **Circuit diagram for controlling the proposed haptic display to deliver a desired level of force.**

## V. DISCUSSION

### A. RESPONSE TIME

The response time is an essential factor for force presentation. It is said that the time delay between a haptic stimulus and visual stimulus should be less than 1 s [43]–[45]. Therefore, the proposed haptic display is currently unsuitable for applications such as haptic feedback in virtual reality or remote operation, even though the haptic display can provide the perceivable force in a few seconds. On the other hand, the haptic display is capable of presenting normal force, which is equivalent to that of conventional wearable haptic display devices [7] and can be applied to apply force in cases of notification that do not need a quick response time.

Improvement of the response time will expand the field of application. According to the obtained result, the response time improved as the design of the liquid-to-gas phase change actuator became smaller. Further miniaturization has the potential to achieve a quicker response time. Additionally, Peltier devices that are durable to higher electrical currents can apply and absorb more heat, and this will also contribute to a quicker response time. Keeping the ideal contact between the fingerpad and haptic display device is also an important factor in achieving a quicker response time. Thus, a method to fix the haptic display should be considered and investigated for sufficient force transmission.

Precise temperature control of the Peltier device, such as setting an optimal initial temperature and parameters, enables the liquid-to-gas phase change actuator to be inflated with a lower amount of heat. For this purpose, a detailed theoretical model for the heat transfer and further experiments are required. Then, to avoid skin burn, the temperature of the Peltier device should be carefully controlled.

### B. AMOUNT OF LOW-BOILING-POINT LIQUID

The maximum output normal force generated by the liquid-to-gas phase change actuator was determined by the amount of the low-boiling-point liquid and its temperature. Additionally, the maximum pressure inside the actuator almost agreed with the vapor pressure of the low-boiling-point liquid. According to the obtained results, the amount of liquid did not greatly change the response time, even though a large amount of the liquid reduced the response time of the output normal force.

Here, it is important not to encapsulate too much low-boiling-point liquid than the amount of encapsulation, where all of the liquid vaporizes at vapor pressure. There is only a slight difference in response time, even if the amount of the low-boiling-point liquid is several times larger than the optimal amount. The injection and heat bonding processes might reduce the encapsulated amount of the low-boiling-point liquid because of the vaporization of the liquid. When the amount of the liquid is too little, this results in preventing the vapor pressure from being reached; thus, it is desirable to encapsulate more than the minimum amount. However, from the aspect of avoiding an increase in heat capacity, it is desirable to use as small an amount as possible. Because there has been little discussion on the amount of liquid contained in liquid-to-gas phase change actuators, the findings of the current study can help design them.

### C. STABILITY OF FORCE PRESENTATION

We revealed that the proposed haptic display could provide a few N of normal force, which is sufficient to provide perceivable force to humans. Additionally, 65% of the experimental participants perceived the force within 3 s, and the other participants perceived it within 6 s. The reasons for this difference in the perceived time are the fixing method and position of the liquid inside the actuator. In the experiment, the participants only placed their fingers on the haptic display, and the contact condition between the haptic display and fingers were slightly different among each trial; in addition, the insufficient contacts caused the lower response. The contact between the haptic display and fingers should be considered and improved to achieve a constant response time. The unstable position of the liquid was induced by the small amount of injected liquid and can be improved by determining the optimal amount that allows the liquid to form contact with the heating part. Moreover, applying more heat enables the actuator to be inflated fully in a shorter time and achieve higher pressure, and this results in a shorter response time.

Fig.16 shows the control diagram for the desired force. According to the results shown in Fig.12, there is a correlation between the pressure inside the actuator that is determined by the temperature and generated force. Therefore, we believe that the generated force can be optimally controlled by the pressure inside the haptic display and temperature of the Peltier device without externally mounted force sensors, although detailed modeling for the contact is necessary.

## VI. CONCLUSION

In the current paper, we embedded a pressure sensor in a simple and light haptic display using a liquid-to-gas phase change actuator and Peltier device. The sensor is low cost and expected to contribute to the precise control of the haptic display. To characterize the haptic display, we conducted several experiments. According to the pressure measurement, the pressure inside the actuator coincided with the temperature of the Peltier device, and the proposed concept is suitable for controlling the pressure inside the liquid-to-gas phase change actuator, which relates to the output force. The force measurement revealed that the proposed haptic display could generate an output force of 1 N, which is equivalent to that of a conventional wearable haptic display. A sensory evaluation showed that 65% of the experimental participants perceived the output force of the haptic display within 3 s, and all of them did so within 6 s.

This study revealed the fundamental characteristics of the proposed haptic display and the point to be improved. The response time, which determines the potential application, is an important characteristic of haptic displays and should be improved. In addition, we did not optimize the components of the proposed haptic display, such as the electrical components and shape of the haptic display; we believe that this optimization will contribute to a quicker response time of the haptic display. Furthermore, we will investigate the applications of the proposed haptic display such as a VR environment.

## REFERENCES

[1] R. S. Johansson and Å. B. Vallbo, "Tactile sensory coding in the glabrous skin of the human hand," *Trends Neurosci.*, vol. 6, pp. 27–32, Jan. 1983.

[2] W. T. Navaraj, C. G. Núñez, D. Shakthivel, V. Vinciguerra, F. Labeau, D. H. Gregory, and R. Dahiya, "Nanowire FET based neural element for robotic tactile sensing skin," *Frontiers Neurosci.*, vol. 11, p. 501, Sep. 2017.

[3] D. Wang, K. Ohnishi, and W. Xu, "Multimodal haptic display for virtual reality: A survey," *IEEE Trans. Ind. Electron.*, vol. 67, no. 1, pp. 610–623, Jan. 2020.

[4] M. Maisto, C. Pacchierotti, F. Chinello, G. Salvietti, A. De Luca, and D. Prattichizzo, "Evaluation of wearable haptic systems for the fingers in augmented reality applications," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 511–522, Oct. 2017.

[5] A. Tzemanaki, G. A. Al, C. Melhuish, and S. Dogramadzi, "Design of a wearable fingertip haptic device for remote palpation: Characterisation and interface with a virtual environment," *Frontiers Robot. AI*, vol. 5, pp. 1–15, Jun. 2018.

[6] C. Fang, Y. Zhang, M. Dworman, and C. Harrison, "Wireality: Enabling complex tangible geometries in virtual reality with Worn multi-string haptics," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2020, pp. 1–10.

[7] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 580–600, Oct./Dec. 2017.

[8] J. Yin, R. Hinchet, H. Shea, and C. Majidi, "Wearable soft technologies for haptic sensing and feedback," *Adv. Funct. Mater.*, vol. 31, no. 39, Sep. 2021, Art. no. 2007428.

[9] I. Choi, E. W. Hawkes, D. L. Christensen, C. J. Ploch, and S. Follmer, "Wolverine: A wearable haptic interface for grasping in virtual reality," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2016, pp. 986–993.

[10] H. Culbertson, J. M. Walker, M. Raitor, and A. M. Okamura, "WAVES: A wearable asymmetric vibration excitation system for presenting three-dimensional translation and rotation cues," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, 2017, pp. 4972–4982.

[11] G. Frediani, D. Mazzei, D. E. De Rossi, and F. Carpi, "Wearable wireless tactile display for virtual interactions with soft bodies," *Frontiers Bioeng. Biotechnol.*, vol. 2, pp. 1–7, Sep. 2014.

[12] X. Ji, X. Liu, V. Cacucciolo, Y. Civet, A. El Haitami, S. Cantin, Y. Perriard, and H. Shea, "Untethered feel-through haptics using 18-$\mu$m thick dielectric elastomer actuators," *Adv. Funct. Mater.*, vol. 31, no. 39, Sep. 2020, Art. no. 2006639.

[13] M. Raitor, J. M. Walker, A. M. Okamura, and H. Culbertson, "WRAP: Wearable, restricted-aperture pneumatics for haptic guidance," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2017, pp. 427–432.

[14] W. Wu and H. Culbertson, "Wearable haptic pneumatic device for creating the illusion of lateral motion on the arm," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 193–198.

[15] M. Zhu, A. H. Memar, A. Gupta, M. Samad, P. Agarwal, Y. Visell, S. J. Keller, and N. Colonnese, "PneuSleeve: In-fabric multimodal actuation and sensing in a soft, compact, and expressive haptic sleeve," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2020, pp. 1–12.

[16] T. Akagi, S. Dohta, S. Fujimoto, Y. Tsuji, and Y. Fujiwara, "Development of flexible thin actuator driven by low boiling point liquid," *Int. J. Mater. Sci. Eng.*, vol. 3, no. 1, pp. 55–59, 2015.

[17] Y. Tsuji, S. Dohta, T. Akagi, and Y. Fujiwara, "Analysis of flexible thin actuator using gas–liquid phase-change of low boiling point liquid," in *Proc. 3rd Int. Conf. Intell. Technol. Eng. Syst. (ICITES)* (Lecture Notes in Electrical Engineering), vol. 345. Berlin, Germany: Springer Verlag, 2016, pp. 67–73.

[18] K. Nakahara, K. Narumi, R. Niiyama, and Y. Kawahara, "Electric phase-change actuator with inkjet printed flexible circuit for printable and integrated robot prototyping," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2017, pp. 1856–1863.

[19] T. Hiraki, K. Nakahara, K. Narumi, R. Niiyama, N. Kida, N. Takamura, H. Okamoto, and Y. Kawahara, "Laser pouch motors: Selective and wireless activation of soft actuators by laser-powered liquid-to-gas phase change," *IEEE Robot. Automat. Lett.*, vol. 5, no. 3, pp. 4180–4187, Jul. 2020.

[20] K. Narumi, H. Sato, K. Nakahara, Y. A. Seong, K. Morinaga, Y. Kakehi, R. Niiyama, and Y. Kawahara, "Liquid pouch motors: Printable planar actuators driven by liquid-to-gas phase change for shape-changing interfaces," *IEEE Robot. Autom. Lett.*, vol. 5, no. 3, pp. 3915–3922, Jul. 2020.

[21] S. Ueno and Y. Monnai, "Wireless soft actuator based on liquid-gas phase transition controlled by millimeter-wave irradiation," *IEEE Robot. Autom. Lett.*, vol. 5, no. 4, pp. 6483–6488, Oct. 2020.

[22] T. Usui, H. Ishizuka, T. Hiraki, Y. Kawahara, S. Ikeda, and O. Oshiro, "Fully flexible liquid-to-gas phase change actuators with integrated liquid metal heaters," *Jpn. J. Appl. Phys.*, vol. 60, no. SC, Mar. 2021, Art. no. SCCL11.

[23] R. Uramune, H. Ishizuka, T. Hiraki, Y. Kawahara, S. Ikeda, and O. Oshiro, "HaPouch: Soft and wearable haptic display devices using liquid-to-gas phase change actuator," in *Proc. Adjunct Publication 33rd Annu. ACM Symp. Interface Softw. Technol.*, 2020, pp. 53–55.

[24] V. Sanchez, C. J. Payne, D. J. Preston, J. T. Alvarez, J. C. Weaver, A. T. Atalay, M. Boyvat, D. M. Vogt, R. J. Wood, G. M. Whitesides, and C. J. Walsh, "Smart thermally actuating textiles," *Adv. Mater. Technol.*, vol. 5, no. 8, Jul. 2020, Art. no. 2000383.

[25] R. Niiyama, X. Sun, C. Sung, B. An, D. Rus, and S. Kim, "Pouch motors: Printable soft actuators integrated with computational design," *Soft Robot.*, vol. 2, no. 2, pp. 59–70, Jun. 2015.

[26] N. Agharese, T. Cloyd, L. H. Blumenschein, M. Raitor, E. W. Hawkes, H. Culbertson, and A. M. Okamura, "HapWRAP: Soft growing wearable haptic device," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 5466–5472.

[27] T.-H. Yang, H. Son, S. Byeon, H. Gil, I. Hwang, G. Jo, S. Choi, S.-Y. Kim, and J. R. Kim, "Magnetorheological fluid haptic shoes for walking in VR," *IEEE Trans. Haptics*, vol. 14, no. 1, pp. 83–94, Jan. 2021.

[28] D. Leonardis, M. Solazzi, I. Bortone, and A. Frisoli, "A 3-RSR haptic wearable device for rendering fingertip contact forces," *IEEE Trans. Haptics*, vol. 10, no. 3, pp. 305–316, Jul./Sep. 2017.

[29] S. B. Schorr and A. M. Okamura, "Three-dimensional skin deformation as force substitution: Wearable device design and performance during haptic exploration of virtual environments," *IEEE Trans. Haptics*, vol. 10, no. 3, pp. 418–430, Jul. 2017.

[30] R. P. Khurshid, N. T. Fitter, E. A. Fedalei, and K. J. Kuchenbecker, "Effects of grip-force, contact, and acceleration feedback on a teleoperated pick-and-place task," *IEEE Trans. Haptics*, vol. 10, no. 1, pp. 40–53, Jan. 2017.

[31] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, and S. Tachi, "Gravity grabber: Wearable haptic display to present virtual mass sensation," in *Proc. ACM SIGGRAPH Emerg. Technol.*, 2007, p. 8.

[32] D. Chen, A. Song, L. Tian, L. Fu, and H. Zeng, "FW-touch: A finger wearable haptic interface with an MR foam actuator for displaying surface material properties on a touch screen," *IEEE Trans. Haptics*, vol. 12, no. 3, pp. 281–294, Sep. 2019.

[33] T. Fukuda, Y. Tanaka, A. M. L. Kappers, M. Fujiwara, and A. Sano, "A pneumatic tactile ring for instantaneous sensory feedback in laparoscopic tumor localization," *IEEE Trans. Haptics*, vol. 11, no. 4, pp. 485–497, Oct. 2018.

[34] C.-H. King, M. O. Culjat, M. L. Franco, J. W. Bisley, E. Dutson, and W. S. Grundfest, "Optimization of a pneumatic balloon tactile display for robot-assisted surgery based on human perception," *IEEE Trans. Biomed. Eng.*, vol. 55, no. 11, pp. 2593–2600, Nov. 2008.

[35] H. Nagano, K. Sase, M. Konyo, and S. Tadokoro, "Wearable suction haptic display with spatiotemporal stimulus distribution on a finger pad," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 389–394.

[36] S. Kanjanapas, C. M. Nunez, S. R. Williams, A. M. Okamura, and M. Luo, "Design and analysis of pneumatic 2-DoF soft haptic devices for shear display," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1365–1371, Apr. 2019.

[37] 3M Company. *3M Novec 7000 Engineered Fluid*. Accessed: Aug. 14, 2021. [Online]. Available: https://multimedia.3m.com/mws/media/121372O/3m-novec-7000-engineered-fluid-tds.pdf

[38] S. Hirai, T. Nagatomo, T. Hiraki, H. Ishizuka, Y. Kawahara, and N. Miki, "Micro elastic pouch motors: Elastically deformable and miniaturized soft actuators using liquid-to-gas phase change," *IEEE Robot. Autom. Lett.*, vol. 6, no. 3, pp. 5373–5380, Jul. 2021.

[39] T. Suzuki, T. Hirayama, K. Aihara, and Y. Hirohata, "Experimental studies of moderate temperature burns," *Burns*, vol. 17, no. 6, pp. 443–451, Dec. 1991.

[40] S. Allin, Y. Matsuoka, and R. Klatzky, "Measuring just noticeable differences for haptic force feedback: Implications for rehabilitation," in *Proc. 10th Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst. (HAPTICS)*, 2002, pp. 299–302.

[41] X. D. Pang, H. Z. Tan, and N. I. Durlach, "Manual discrimination of force using active finger motion," *Perception Psychophys.*, vol. 49, no. 6, pp. 531–540, Nov. 1991.

[42] L. A. Jones, "Matching forces: Constant errors and differential thresholds," *Perception*, vol. 18, no. 5, pp. 681–687, Oct. 1989.

[43] S. Kameyama and Y. Ishibashi, "Perception of synchronization errors in haptic and visual communications," in *Proc. Multimedia Syst. Appl. IX*, 2006, pp. 67–74.

[44] C. Jay, M. Glencross, and R. Hubbold, "Modeling the effects of delayed haptic and visual feedback in a collaborative virtual environment," *ACM Trans. Comput.-Human Interact.*, vol. 14, no. 2, p. 8, Aug. 2007.

[45] J. M. Silva, M. Orozco, J. Cha, A. E. Saddik, and E. M. Petriu, "Human perception of haptic-to-video and haptic-to-audio skew in multimedia applications," *ACM Trans. Multimedia Comput., Commun., Appl.*, vol. 9, no. 2, pp. 1–16, May 2013.

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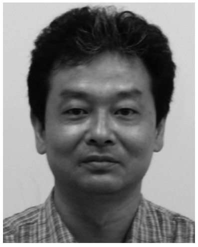

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