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Evaluating the Performance of a Thermal Contact Sensor in Capturing Thermal Transients for Material Recognition via Heat Transfer

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***Abstract*—Tactile perception is essential for material recognition, with thermal transients playing a key role in conveying information about object material composition. This study evaluates the performance of a thermal contact sensor designed to capture the characteristics of skin thermal responses during contact with a wide range of materials. The sensor, constructed using a heat-resistant glass contact surface and an integrated heating system, was evaluated by comparing temperature responses with human fingers when contacting materials. Experimental results showed that while the thermal contact sensor successfully captured material-dependent temperature responses, differences in heat transfer dynamics between the sensor and human fingers were observed in the initial cooling rate and total temperature change during contact. Although the sensor differs from the human finger, it has its own unique characteristics and provides valuable responses for material recognition. To further enhance its performance, incorporating a soft material could improve contact with different surfaces, potentially refining its thermal response. The thermal contact sensor has significant potential for creating large-scale thermal datasets, which could advance applications in haptic displays and robotic material recognition systems.**

***Index Terms*—Haptics, Thermal material recognition, Heat transfer, Thermal contact sensor.**

I. Introduction

Tactile perception plays a crucial role in human interaction with the physical world, providing essential sensory feedback for material recognition. Among various tactile cues, changes in skin temperature upon contact with objects offer critical information for recognizing the material of the objects, as they depend on the thermal properties of the contacted material, such as thermal conductivity, heat capacity, thermal effusivity etc. Dynamic changes in skin temperature have been extensively utilized in the development of thermal displays, a type of haptic interface that simulates realistic thermal sensations, and tactile sensors, which classify materials based on heat transfer characteristics [1]. For instance, Cai et al. [2] simulated skin temperature changes, using their ThermAirGlove pneumatic glove, when contacting foam, glass, and copper, achieving an 87.2 % material-identification accuracy, with statistically no significant difference from real objects. Gabardi et al. [3] showed that dynamic temperature transient helps material discrimination. They simulated the dynamic skin-surface temperature transients of urethane, glass, and copper using a wearable Peltier-based fingertip interface and achieved 76.2 % material-discrimination accuracy.

Skin temperature data has been collected using human fingers. Balasubramanian et al. [4] established the SENS3 database, cataloging skin temperature changes during static contact. While the database is extremely valuable, it has limitations caused by using human fingers. One limitation is the difficulty of collecting large-scale data. Data collection using human fingers requires human involvement and cannot be automated, limiting dataset scale. Furthermore, when data collection is conducted over an extended period, maintaining consistent surface conditions becomes difficult due to the effects of hand sweat. In addition, controlling the initial temperature of human fingers is inherently difficult. The temperature of human fingers have a range of approximately 8 degrees [5], preventing from measuring at the desired initial temperature. An alternative approach is to use finger-shaped tactile sensors instead of human fingers. BioTac [6] is a multi-tactile sensor in the form of a finger, which can measure force, vibrations, and temperature. Although BioTac can measure its temperature with a consistent surface not influenced by sweat, it is not specifically designed to replicate the thermal responses of human fingers. As a result, it is not well-suited for thermal displays to simulate thermal sensations when touching materials. To address these limitations, a thermal contact sensor capable of capturing the characteristic temperature dynamics of human fingers presents a promising solution. A thermal contact sensor enables automated data collection while maintaining consistent surface conditions. Moreover, by integrating a heating mechanism, it is possible to precisely control the initial temperature before contact, overcoming the variability seen in human fingers.

A large-scale dataset of skin temperature changes collected with the thermal contact sensor can contribute to the development of thermal displays for material recognition. Thermal

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models have been used to characterize simulated temperature changes for contact materials [2] [3] [7]. However, these models rely on predefined thermal properties of both the contact materials and the finger, and therefore cannot be directly applied to unknown materials, complex surfaces composed of multiple or layered materials. Large-scale skin temperature datasets may enable temperature characterization for contact materials to be simulated using machine learning.

Additionally, such datasets could support the development of tactile sensors for automatic material classification systems. Studies have explored material recognition for robotic hands using thermal cues [8] [9] [10]. Bhattacharjee et al. [8] demonstrated that material classification can be achieved using machine learning based on temperature data obtained from a thermistor attached to a Kapton heater in contact with various materials. If this approach is integrated with a thermal contact sensor that accurately mimics human thermal responses, the collected temperature data could be utilized as haptic feedback, enabling users to perceive materials more realistically.

This study aims to develop a thermal contact sensor that approximates the characteristic thermal responses of human fingers. Rather than precisely replicating the temperature profile, the focus is on capturing key thermal dynamics sufficient for distinguishing and recognizing different materials. By leveraging this sensor, we seek to construct a large-scale dataset of skin temperature changes, which contribute to advancements in haptic interfaces and tactile sensing technologies.

II. System Development

We developed a thermal contact sensor that effectively captures thermal responses upon contact with materials. The contact surface material of the sensor was selected based on the thermal effusivity tolerance range identified in our previous study [11], which ensures that the thermal responses when contacting a wide range of materials approximate those of a human finger. Thermal effusivity is a key property defined as the square root of the product of thermal conductivity (W/m·K), density (kg/m^3), and specific heat (J/kg·K) according to ISO standard 22007-7:2023, effusivity (J/m^{2}s$^{1/2}$K) [12]. It represents how effectively materials transfer heat with objects they contact. Contact results in heat moving from the skin to the object due to typically higher temperatures of the skin compared to most objects, thus lowering the skin's temperature. Therefore, thermal effusivity significantly influences the perceived change in skin temperature during hand-object interactions and affects how we perceive the thermal nature of the materials. A simulation using a thermal model demonstrated that a material with thermal effusivity in the range of 1090 - 1281 (J/m^{2}s$^{1/2}$K) produces thermal transients similar to those of human fingers [11]. The similar temperature change was defined as within ±5% of the temperature change observed in human fingers. The tolerance range was identified by examining temperature variations in the effusivity of human fingers with the thermal model developed by Ho and Jones [13], based on the semi-infinite body assumption.

Fig. 1(a) illustrates the overview of the thermal contact sensor. The contact material is heat-resistant glass (Heat-resistant glass, CAN DO CO., LTD.) with a contact surface measuring approximately 50 mm × 50 mm and a thickness of 5.4 mm. The effusivity of this glass, measured with thermal effusivity meter (TPS-EFF, Thermotest), was 1212 (J/m^{2}s$^{1/2}$K). This value is within the tolerance range [11]. A thermistor (56A1002-C8, ALPHA TECHNICS) was attached at the center of the contact surface to measure the temperature with an adhesive bond (see Fig. 1(b)). The thermistor, measuring just 400 microns in diameter, was selected to minimize its impact on the heat transfer process. To regulate the initial temperature of the thermal contact sensor, a rubber heater (SR100-20-50-50-P, THREE HIGH CO., LTD) was placed on the glass, and a Pt100, a temperature sensor, was positioned between the glass and the heater (see Fig. 1(a), (c)). The heater was connected to a digital temperature controller (YD-15N, YAGAMI Inc.), which monitored the Pt100 reading and employed PID control to regulate the rubber heater's output. By setting the controller's temperature setpoint above the desired contact-surface temperature, the thermistor at the contact surface of the thermal contact sensor was adjusted to the required initial temperature. The entire sensor was encased in a 3D-printed PLA frame. To ensure the frame did not touch the contact material, the glass was designed to protrude 1 mm from the frame. Clay weights were added inside the frame to achieve a total weight of 150 g (approximately 1.47 N), which falls within the typical range of contact forces exerted by a human finger when touching objects [15] [16].

III. Experiment

A. Participants

Three females and a male with normal tactile sensory abilities participated in the experiment after giving informed

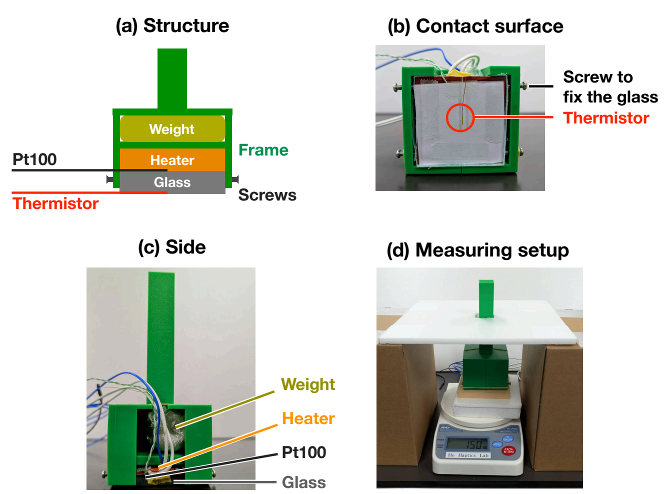

Fig. 1. Overview of the thermal contact sensor. (a) Layered structure of the sensor (b) Contact surface made of heat-resistant glass attached with a thermistor. (c) The side has a hole for cables to come out. (d) Measuring setup

consent. Their ages ranged from 22 to 24 years. This experiment was approved by the ethics committee of the Department of Design, Kyushu University

B. Materials

Table 1 lists the contact materials used in the experiment. We selected five materials with a wide range of thermal effusivity, commonly encountered in daily life. These materials were shaped into blocks measuring 100 mm × 100 mm × 10 mm and were mounted on a foam base.

C. Apparatus

Temperatures of the human fingers and the thermal contact sensor were measured using a measurement system (Portable Temperature Measurement System, Fujimoto Inc.). The system consisted of a thermistor (56A1002-C8, ALPHA TECHNICS), a smartphone app, a circuitry-based measuring instrument, a built-in microcontroller and an analog-to-digital (AD) converter. Temperature data was sampled at approximately 200 Hz. The contact material was placed on a digital scale (HL-2000i, A&D Company) to provide feedback the contact force to participants. To measure the initial temperature of the contact material, a thermistor connected to the measurement system was affixed to its surface. The thermistor was secured with tape in an area untouched by the fingers. During measurements with the thermal contact sensor, the top of the frame was positioned to fit into a horizontal guide made of styrofoam board (see Fig. 1(d)). This setup was designed to prevent movement after contact, which could be caused by traction forces from the cables or other external factors.

D. Procedure

All measurements were conducted in a room maintained at 25 °C, with those using the thermal contact sensor performed after the human finger measurements. The initial temperature of the human finger at contact moment with materials was on average 29.68 °C. To ensure similar conditions, the thermal contact sensor was also measured at a comparable initial temperature, set between 29.5 °C and 30 °C right before contact. The thermal contact sensor was put on the surface of the material for about 15 seconds. The temperature of the thermal contact sensor was recorded for a total of 18 seconds, including the contact duration and several seconds before contact. To ensure that the material and thermal contact sensor returned to their initial temperatures, a 3-minute waiting period between the trials was implemented. Each material was measured ten times.

TABLE I
CONTACT MATERIALS

Material	Aluminum	Glass	Acrylic	Wood	Foam
Effusivity ($J/m^2s^{1/2}K$)	22,585[a]	1323[b]	598[b]	262[b]	27[b]

[a]The value is from reference [14].
[b]The values are measured with a thermal effusivity meter (TPS-EFF, Thermotest).

In the measurement with human fingers, the participants first washed their hands with soap. Subsequently, they sufficiently warmed themselves with hot water bottles and wore warm clothing during the measurements, since the experiments were conducted in winter and the body temperature had been low. A thermistor was attached to the pads of their index fingers using liquid adhesive and mesh bandage tape (see Fig. 2). After a beep sound, participants placed the fingertip of their index finger on the surface of the material for 15 seconds, repeated ten times for each material. During contact, participants were instructed to maintain approximately 150 g (1.47 N) on the screen of the scale as well as the thermal contact sensor.

IV. Result

The temperature data of the human fingers and the thermal contact sensor were resampled using a weighted moving average to obtain data points at 25 ms intervals. This resampling aligned the data points across trials and removed noise. Subsequently, the moments when the fingers or the sensor contacted the material were visually identified on the time-temperature graph as the points where the temperature dropped rapidly. Data from one participant during contact with Foam were excluded because the temperature change was too small to reliably detect the contact moment. The initial temperatures (mean ± SD) of the human fingers, the thermal contact sensor, and the contact materials were 29.68 ± 0.38 °C, 29.77 ± 0.11 °C, and 25.11 ± 0.14 °C, respectively. Fig. 3 illustrates the temperature changes of the human fingers and the thermal contact sensor from the contact points upon contact with the five materials. The temperature of the sensor decreased more rapidly at the contact and approached an asymptote more quickly than that of the human fingers.

We calculated the initial cooling rate of temperature change at the moment of contact and the total temperature change over a 10-s period. These two metrics characterize skin temperature dynamics and have been identified as the most important thermal cues for material recognition [1] [17].

The initial cooling rate was calculated as the temperature gradient at 0.1 second after contact. Fig. 4 illustrates these rates. A two-way ANOVA was conducted with the rate as

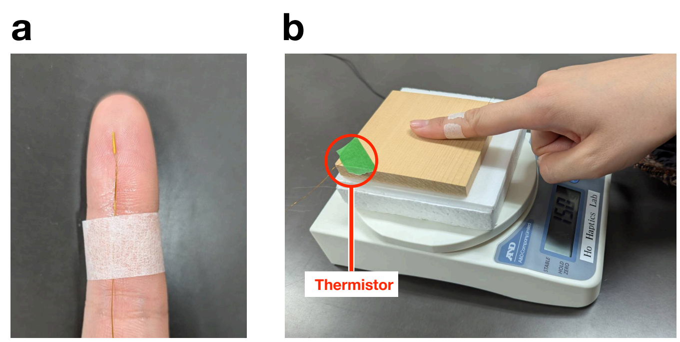

Fig. 2. (a) A thermistor was attached to the pad of the index finger to measure changes in skin temperature. (b) The participant touching the contact material. The thermistor placed at the left-hand corner of the material surface was used to measure the initial temperature of the material.

the dependent variable, and measuring mode (human finger or thermal contact sensor) and material as independent variables. The results revealed a significant main effect of measuring mode ($F(1) = 36.5$, $\eta^2 = 0.064$, $p < 0.001$), a significant main effect of material ($F(4) = 61.6$, $\eta^2 = 0.432$, $p < 0.001$), and a significant interaction between measuring mode and material ($F(4) = 14.6$, $\eta^2 = 0.102$, $p < 0.001$). To further examine the nature of the interaction, we conducted simple main effect tests followed by post hoc comparisons. First, we tested the simple main effect of *material*, using *measuring mode* as the moderator. The results indicated significant differences among the five materials for both the human finger ($F(4) = 20.6$, $p < 0.001$) and the thermal contact sensor ($F(4) = 42.6$, $p < 0.001$). Next, we tested the simple main effect of *measuring mode*, using *material* as the moderator. Significant differences between the human and the sensor were observed for Aluminum ($F(1) = 40.5$, $p < 0.001$), Glass ($F(1) = 49.1$, $p < 0.001$), and Acrylic ($F(1) = 4.3$, $p = 0.038$).

Post hoc tests revealed significant differences among materials for each measuring mode. For the human finger, significant differences were found between Acrylic and Wood ($p = 0.017$), and between Wood and Foam ($p < 0.001$). For the thermal contact sensor, a significant difference was observed between Glass and Acrylic ($p = 0.042$).

The total change was calculated as the temperature at 10 seconds after contact minus the temperature at the moment of contact. Fig. 5 illustrates the total change in temperature. A two-way ANOVA was conducted with the total change as the dependent variable, and measuring mode and material as independent variables. The results revealed a significant main effect of measuring mode ($F(1) = 38.8$, $\eta^2 = 0.008$, $p < 0.001$), a significant main effect of material ($F(4) = 1159.2$, $\eta^2 = 0.935$, $p < 0.001$), and a significant interaction between measuring mode and material ($F(4) = 12.9$, $\eta^2 = 0.010$, $p < 0.001$). To further examine the nature of the interaction, we conducted simple main effect tests followed by post hoc comparisons. First, we tested the simple main effect of *material*, using *measuring mode* as the moderator. The results indicated significant differences among the five materials for both the human finger ($F(4) = 1517.3$, $p < 0.001$) and the thermal contact sensor ($F(4) = 336.2$, $p < 0.001$). Next, we tested the simple main effect of *measuring mode*, using *material* as the moderator. Significant differences between the human and the sensor were observed for all materials tested: Aluminum ($F(1) = 7.9$, $p = 0.005$), Glass ($F(1) = 50.2$, $p < 0.001$), Acrylic ($F(1) = 5.8$, $p = 0.017$), Wood ($F(1) = 15.5$, $p < 0.001$), and Foam ($F(1) = 10.8$, $p = 0.001$). Post hoc tests revealed significant differences between materials for both measurement modes. For the human finger and the thermal contact sensor, all material pairs showed significant differences ($p < 0.001$).

V. Discussion

The thermal contact sensor exhibited thermal response trends similar to those of human fingers across different ma-

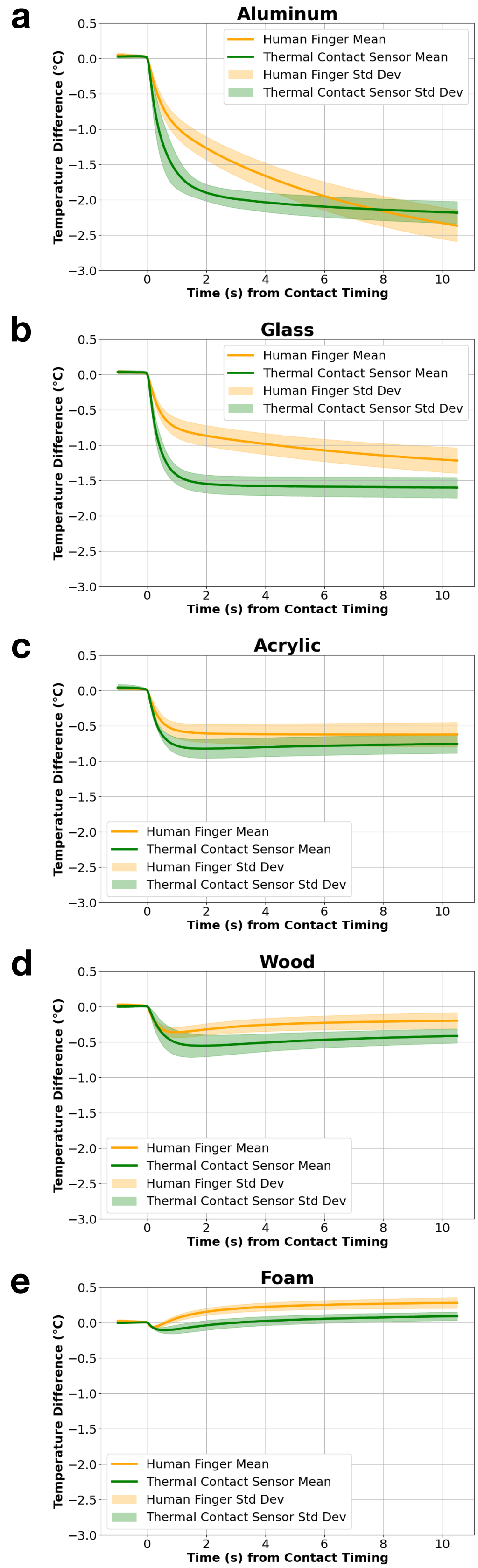

Fig. 3. Comparison of temperature change between human fingers and the thermal contact sensor for (a) Aluminum, (b) Glass, (c) Acrylic, (d) Wood, and (e) Foam. The 0-second indicates the moment of contact. The solid lines and shaded areas represent means and standard deviation, respectively.

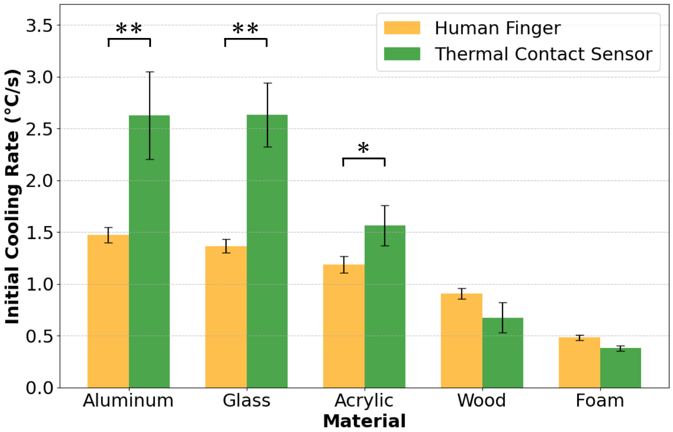

Fig. 4. Comparison of the initial cooling rate between the human fingers and the thermal contact sensor. The error bars represent standard errors. * and ** respectively indicate p <0.05 and p <0.01 in the simple main effect test of measuring mode using material as a moderator.

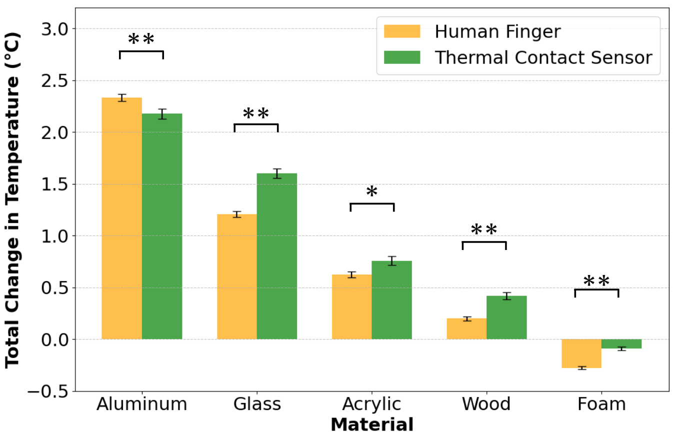

Fig. 5. Comparison of total change in the temperature between human fingers and the thermal contact sensor. The error bars represent standard errors. * and ** respectively indicate p <0.05 and p <0.01 in the simple main effect test of measuring mode.

terials. For both the sensor and the human finger, temperature dropped rapidly upon contact and then gradually approached an asymptote. Notably, for materials such as Wood and Foam, both measuring modes showed a V-shaped trend, with temperature increasing after reaching a minimum. These results suggest that the thermal contact sensor effectively captures temperature changes comparable to those of human fingers.

The V-shaped temperature changes result from heat transfer from the finger or the thermal contact sensor to the material, gradually warming the contact area over time [18]. As shown in Fig. 3 and Fig. 4, in the initial few seconds, the sensor transferred heat to the material more efficiently than the human finger. However, the temperature rebound in the V-shaped pattern was less pronounced in the sensor. This discrepancy may stem from differences in thermal properties and exothermic mechanisms between human fingers and the sensor. The differences in thermal conductivity, specific heat, and density between the human finger and the sensor play a major role. The sensor, with its higher thermal conductivity and lower heat capacity, loses heat more rapidly and shows a steeper initial temperature drop [19]. In contrast, the human finger's higher heat capacity allows it to store more thermal energy and resist surface temperature changes, contributing to a slower, more sustained thermal response [13]. At the same time, the human fingers and the sensor have differences in dynamic heat supply. In fingers, blood perfusion in the dermis continually brings core-temperature blood to the pad [13]. Although contact force compresses capillaries and limits the effect [20], this flow slows the rate of surface cooling or even partially restores the skin temperature over time. The sensor, by contrast, uses a rubber heater to keep a Pt100 element 5.4 mm below the surface at its set-point. When the Pt100 cools, the controller increases heater output. Because the heat source is deeper and its power must be actively modulated, the feedback may have responded with different latency and magnitude than the finger's perfusion-based mechanism.

Our results demonstrated that, although the thermal contact sensor showed less distinct differentiation between materials based on the initial cooling rate compared to human fingers, it achieved clear and statistically significant separation across all material pairs in terms of total temperature change. These findings highlight the sensor's capability to capture meaningful thermal responses comparable to those of human skin. Moreover, while human perception relies more heavily on the initial cooling rate for material discrimination [21], total temperature change may serve as a more robust and practical feature for material classification in engineering applications.

To better understand the sensor's performance, we analyzed its temperature response characteristics in more detail. The sensor's temperature profiles revealed several distinct features. First, for profiles that approach an asymptote, the sensor cools more rapidly than the human finger, reaching its steady-state value sooner. This quick response enables the sensor to provide total temperature change information at an earlier stage.

Second, compared to the human finger, the thermal contact sensor shows smaller total temperature changes for materials with extreme thermal effusivity, such as Aluminum and Foam, and larger changes for materials with intermediate thermal effusivities. While this narrows the overall range of total temperature change, it does not impair the sensor's performance—extreme materials still produce distinct and easily recognizable temperature profiles. Additionally, the relatively large temperature changes observed for intermediate materials are less susceptible to noise, which further supports reliable material differentiation.

Third, the initial cooling rate of temperature change in the thermal contact sensor showed greater variability compared to that of the human finger (see Fig. 3). As a result, the sensor distinguished fewer material pairs based on this measure. One possible reason for this variability is the sensor's structural design. The thermistor (0.4 mm diameter) was mounted in a 0.1 mm deep groove and slightly protruded from the rigid glass surface to ensure contact. However, this rigid, flat surface made the sensor prone to slight movement during placement, resulting in inconsistent thermal responses at the moment of contact. In contrast, although the thermistors on human fingers also protruded, the softness of the skin allowed it to conform to the contacted surface, yielding more stable and consistent thermal responses. Further improvement could be achieved by using soft materials in the sensor's design to enhance contact stability and reduce variability.

In this study, the material for the thermal contact sensor was selected based on the thermal effusivity tolerance range identified in our prior work [11]. While the sensor successfully captured key characteristics of human thermal responses, some discrepancies were observed in both the initial cooling rate and the total temperature change across multiple material pairs. These differences suggest room for further improvement in approximating human-like thermal transients, potentially through refinement of material selection or structural design. Re-evaluating contact surface materials could address this issue. Alternative materials that fall within the effusivity tolerance range include Nylon 6 (1119 $J/m^2s^{1/2}K$) [22] and PEEK (1140 $J/m^2s^{1/2}K$) [23] [11]. However, despite being within the simulated tolerance range, heat-resistant glass resulted in greater temperature changes than human fingers, particularly during the first few seconds of contact. This suggests that the simulated tolerance range may not fully align with real-world conditions, as it was derived from a simplified thermal model that does not fully capture complex thermal interactions.

The thermal contact sensor with a heat-resistant glass with effusivity in the tolerance range exhibited greater temperature changes than human fingers. Also, considering the importance of material softness for contact stability, an alternative material should be explored. One potential option is silicone (KE-12, Shin-Etsu Chemical Inc.) [24] with effusivity of 725.4 ($J/m^2s^{1/2}K$) as measured with a thermal effusivity meter (TPS-EFF, Thermotest). This value is slightly lower than that of human fingers, however, its softness may enable more consistent temperature changes compared to the heat-resistant glass used in this study. A thermal contact sensor made of a soft material may better replicate variations in thermal interaction corresponding to contact force. Ho and Jones [13] demonstrated that human fingers adjust their contact area based on applied force, which subsequently affects skin temperature changes. However, the thermal contact sensor in this study maintained a fixed contact area, preventing it from reproducing this characteristic. This limitation could potentially be addressed by using a soft, compliant material that deforms under pressure, thereby mimicking the dynamic contact mechanics of human fingers.

Another limitation of our system is the detection process of the contact moment. We detected the moment by eyes. Since the initial cooling rate is calculated focusing on a short time of 0.1 second, a small error in the detected moment becomes a large error in the rate. To address the limitation and establish an efficient method to detect the contact moment, we can incorporate a force/pressure sensor to precisely detect the moment, thereby improving the accuracy of rate estimation.

The contact materials have the potential to improve material classification systems. The characteristics of the temperature change of the thermal contact sensor were likely attributed to the heat-resistant glass on the contact surface. In the material classification system by Bhattacharjee [8], the thermistor was directly attached to the heater. Modifying the material of the contact surface between the heater and the object can potentially characterize the obtained temperature change, according to the application environment and the desired range of temperature change.

Thermal contact sensors have the potential to create large-scale datasets that accurately replicate the thermal responses of human fingers when interacting with different materials. These datasets could be applied to thermal feedback systems for material recognition and machine-learning-based material classification in robotic hands [8] [9] [10]. To facilitate such applications, it is crucial to collect extensive datasets encompassing a diverse range of materials and initial conditions. In this study, we successfully controlled the initial temperature of the sensor within a narrow range of 0.42 °C, aligning it with that of human fingers. This capability demonstrates the feasibility of precise temperature control during data collection. Furthermore, the mechanical controllability of the sensor enables the development of an automated data acquisition system, eliminating the variability associated with human-dependent measurements. Therefore, the thermal contact sensor, with its high precision in initial temperature control and automation capability, holds significant potential for efficiently generating large-scale datasets.

Moving forward, we aim to develop an enhanced thermal contact sensor that incorporates material softness to better replicate human thermal responses. Additionally, we plan to design an automated system capable of efficiently measuring temperature dynamics comparable to those of human fingers. These improvements will further advance haptic interface technology and tactile sensing applications.

VI. CONCLUSION

This study evaluated the performance of a thermal contact sensor designed to capture thermal transients during material contact in a manner comparable to human fingers. The sensor successfully reproduced overall trends in temperature responses, including the characteristic V-shaped profiles observed with low-effusivity materials, demonstrating its potential for material recognition. Furthermore, we found that the total change is suitable for material recognition in engineering application than initial cooling rate as opposed to humans. However, greater variability in the initial cooling rate compared to human fingers suggests room for improvement in measurement stability. Incorporating softer materials to improve surface conformity may help reduce this variability. Future work will focus on optimizing the sensor's material and structural properties and developing an automated data collection system to enable large-scale thermal datasets. These advancements will support the development of haptic interfaces and tactile sensors for material classification applications.

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