Human-interactive soft robotic technologies have potential in numerous applications such as automatic home-use robots, industrial systems, and Internet of Things (IoT) concepts. One approach to improve soft robotics is to integrate multiple soft sensors to monitor diverse information simultaneously, similar to human skin, without sacrificing mechanical flexibility and softness. This study reports multiple sensor integration, called an electronic skin (e-skin), embedded in a pneumatic balloon-based soft robotic hand. The sensors have good sensitivity to different stimuli but are insensitive to bending of the structure. By integrating multiple tactile force sensors \((2 \times 2 \text{ pixels})\), sliding or slipping movements of an object from a soft robotic hand can be monitored by measuring the time delay of tactile forces in the sensors as well as the tactile force generated by the pneumatic robot and external stimulus such as human contact. This information prevents the robotic hand from dropping an object by providing real-time feedback, which is used to determine the tactile force. In addition to the fundamental characteristics, demonstration of pneumatic actuation and multiple sensing detections are successfully addressed as the first proof-of-concept.

Robotic technologies make society more convenient and comfortable, especially for manufacturing processes. These technologies are now available for human-interactive applications in our daily life. One approach to realize human-friendly robots is a soft material-based robot, called a soft robot. Ideally, a soft robot should consist of only soft materials. This includes its actuators and sensors. Often air pressure in a pneumatic balloon structure is used for actuation because it can control multiple bending angles similar to human joints by arranging the structures. Another important functionality is sensors to monitor environmental conditions and to determine the appropriate manipulation force.

For a human-interactive friendly robot, the sensors should be composed of a soft material-based electronic skin (e-skin) integrated with the soft robot. Although different types of e-skins have been reported to monitor pressure and temperature distributions, an e-skin-integrated soft robot is yet to demonstrate. It should be noted that a single pixel of a tactile force sensor integrated with a soft robot was proposed recently.

For a human-friendly soft robot with functionalities similar to human skin, this study proposes a soft robotic hand integrated with an e-skin to monitor tactile pressure and temperature, without sacrificing the soft functionality of the robot. By integrating an e-skin, the tactile pressure to grab an object and the friction movement of an object from the hand can be monitored. Additionally, the temperature of the target object can be evaluated. These functionalities are very similar to human skin. In particular, monitoring the slipping of an object from a soft robotic hand can provide a feedback signal to tune the grabbing force, which may prevent dropping an object. Although a human hand has this functionality, a robotic hand currently does not due to the complexity of integrating multiple sensors. However, successful integration should advance robotics toward realizing practical human-interactive robotic applications.

There are two key challenges to build this platform. The first is the integration of sensors in a high-strain region where bending occurs in a soft robot without sacrificing the actuation force. The other is to optimize the sensing sensitivity to match the actuation force, detectable threshold pressure, and temperature by touching an object. To address these challenges, this study demonstrates an e-skin-integrated soft robot platform, which monitors the tactile pressure distribution and temperature. The device structure and materials are arranged such that they are insensitive to the bending of the soft robot. Herein, sliding of an object for feedback control is featured to determine the tactile force as this functionality is yet to demonstrate.

To mimic a human hand, the pneumatic balloon soft-robotic hand was designed to actuate using air pressure. Figure 1a shows the device structure with three layers using silicone rubber. Figure 1b exhibits the e-skin designed with four tactile force sensors and one temperature sensor on a pneumatic balloon-based soft robotic finger. Using silver (Ag) thread interconnections, under bending and inflation (i.e., stretching) conditions, the resistance change of the sensors can be stably measured as...
functions of the tactile force and temperature. By applying air pressure into the pneumatic balloon, a soft robotic hand with four fingers can be actuated (Figure 1c,d) to grab an object or shake hands with a human (Figure 1e,f).

The actuated bending angle almost linearly increases with the air pressure up to the threshold pressure of $\approx 6$ kPa (Figure 1g). This bending is due to the expansion of silicone rubber structures on only one side of the actuator. The bending angle strongly depends on the bottom silicone rubber thickness (Figure S3, Supporting Information). This is because a thinner layer provides more flexibility for bending. As long as the applied air pressure is not too high, the pneumatic balloon actuator can be repeatedly operated (Figure 1h). The robotic finger can generate tactile force with a threshold force around 10 kPa of air pressure, and almost no hysteresis is observed in the tactile force detection between inflation and deflation of the balloon (Figure 1i).

The sensing mechanism for tactile force utilizes the contact resistance change between the Ag thread and the conductive paper. Figure 2a shows that the contact area between these increases as the tactile force increases, which decreases the electrical resistance. This contact resistance change as a function of applied force is caused by the rough surface of the thread and paper (Figure 2b). Therefore, the contact area difference depends on the applied force.

Figure 2c plots the resistance as a function of the applied force. The resistance was measured when the applied force continuously increased. Without force, the Ag thread and conductive paper are almost an open-circuit with a large resistance. Applying a force drastically decreases the electrical resistance from hundreds of kilo ohms to hundreds of ohms. This is mostly attributed to the contact of the Ag thread and the conductive paper. Applying a higher force gradually decreases the resistance because deformation of the thread and paper slightly increases the contact area. Although the device structure and mechanism are simple, the sensor can be used repeatedly and reliably (Figure 2d).

Relatively stable real-time monitoring at different forces can be also monitored (Figure 2e,f). The response time of this tactile sensor is less than 0.5 s (Figure 2e inset). This response time is limited by the equipment used in this study to apply and release

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**Figure 1.** E-skin-integrated pneumatic soft robotic hand. a) Schematic of the soft robotic hand structure with three layers: a pneumatic balloon layer, tactile force sensor layer, and temperature sensor layer. b) Photo of e-skin integrated with four tactile force sensors and a temperature sensor embedded in the soft robotic hand. Photos of c) opening the hand, d) closing the hand, e) holding a ball, and f) shaking hands with a human. g) Actuation bending angle as a function of applied air pressure. Inset shows the definition of the angle. h) Cycle test of the bending angle at an applied pressure of $\approx 50$ kPa. i) Generated tactile force at different air pressures.
the force. Since force detection relies on the mechanical contact between two materials, the response speed can be fast. Due to the mechanical contact and space between the conductive paper and the Ag thread, the sensor does not detect the actuator bending up to 1.5 cm, which is the maximum bending of the soft actuator in this study. This insensitivity to the bending is an important functionality to distinguish an object precisely. Furthermore, the real-time measurements indicate that the sensor has almost no hysteresis when the force is applied and released.

Another functionality to imitate human skin is temperature detection of a grabbed object. For stable and reliable temperature detection in a soft robotic hand, the fabrication process and material compositions were optimized from the temperature sensor that we have reported previously.\cite{19} The solution-based temperature sensor is comprised of conductive SnO$_2$ nanoparticles and single-walled carbon nanotube (SWCNT). After forming the sensor materials on a film, organic materials, including surfactants, are removed by rinsing with hot deionized (DI) water ($\approx$70 °C) to realize a long-time stability.

Figure 3a shows the resistance change ratio of the temperature sensor at different measured temperatures as a function of the SnO$_2$ concentration in 4 mL DI water and 40 μg SWCNTs. The resistance change was measured by continuously increasing the temperature. Due to electron hopping conduction at different temperatures, the resistance, $R$, is expressed by

$$R = R_0 \exp \left( \frac{E_a}{2kT} \right)$$

where $R_0$ is the resistance at the defined initial temperature, $E_a$ is the activation energy, $k$ is the Boltzmann constant, and $T$ is the measured temperature. The trend of the resistance change in Figure 3a agrees well with this equation. Therefore, the sensitivity and activation energy are extracted (Figure 3b). Increasing the SnO$_2$ concentration shows a higher sensitivity and activation energy, suggesting that a higher barrier height between SnO$_2$ and carbon nanotubes (CNTs) is created. Although a higher sensitivity is better suited for a precise measurement, we used a 40 mg SnO$_2$ solution in this soft-robotic application after considering the stability.

For the flexibility and the tactile force sensor, insensitivity to substrate bending is important. Figure 3c describes the resistance as a function of the bending radius up to 1.5 cm. Substrate bending does not strain the temperature sensor because the sensor is fabricated on a polyethylene terephthalate (PET) film so that it is free from the actuator bending in the silicone rubber. Consequently, the temperature sensor shows a good insensitivity against the actuation of the soft robotic hand.

The long-time stability when changing the environmental temperature between $\approx$14 and $\approx$44 °C was tested using an environmental control oven. The temperature sensor is highly stable with an error less than $\pm$0.15 °C (Figure 3d). Compared with the results using a flexible temperature sensor reported previously,\cite{19} this temperature sensor has a much better behavior after a week. Optimizations of the material composition ratio and fabrication process are responsible for the high stability. Another important parameter is hysteresis response of the sensor. Figure 3d shows that this sensor has almost no hysteresis between forward and backward temperature change.

As a proof-of-concept for an e-skin-integrated soft robotic hand, four-pixel tactile force sensors and a temperature sensor were integrated on a soft finger structure. The remaining three...
fingers did not have sensors. The soft robotic hand can hold an object, but the inflation and deflation conditions of the balloon actuators cause the object to slip (Figure 4a,b).

Before an object heated at $\approx 36.5 \, ^\circ\text{C}$ was placed in the soft hand (30 s), force sensors show 0 gf, whereas the temperature sensor shows room temperature (RT) ($\approx 22.5 \, ^\circ\text{C}$). After inflating the pneumatic balloon, the soft hand grabs the object ($\approx 80 \, \text{s}$), and the pneumatic actuation generates a tactile force of $\approx 2 \, \text{gf}$, measured by the force sensors (#3 and #4). Due to non-contact onto sensors #1 and #2, the tactile force is zero. Simultaneously, the temperature sensor indicates a temperature ($\approx 36 \, ^\circ\text{C}$) higher than RT ($\approx 22 \, ^\circ\text{C}$). However, the temperature is slightly lower ($\approx 0.5 \, ^\circ\text{C}$) from the object temperature. This difference is attributed to the cooling effect through the silicone rubber. After removing the warmed object from the hand, the temperature sensor indicates that the temperature decreases slowly (Figure 4a). The response time for the temperature sensor is $\approx 100 \, \text{s}$ for heating and $\approx 180 \, \text{s}$ for cooling. It takes a long time to return to the original temperature due to the low thermal conductivity of the silicone rubber. This effect is also observed by an infrared (IR) camera image after removing the object from the hand (Figure 4b).

Once the output signals for both force and temperature sensors were stable, the object was removed forcibly from the soft hand by sliding the object from the fingers. Upon sliding the object, force sensors #1 and #2 detect the force instantaneously with a time difference from the force detection of sensors #3 and #4. By removing the object manually, the time difference, $D$, is about 50 ms, as described in Figure 4c,d, which are enlarged results from Figure 4a. The time delay between #1 and #3 (Figure 4c) and #2 and #4 (Figure 4d) are consistent.

This functionality where a force change is detected instantaneously and a time delay allows feedback to the actuated force is critical to prevent the robotic hand from dropping an object. Such functionality can be achieved by integrating multiple sensors without sacrificing the actuation operation. Furthermore,

Figure 3. Temperature sensor. a) Normalized resistance change ratio for different SnO$_2$ compositions in a SWCNT/DIW solution as a function of temperature. Arrow shows the temperature sweep direction. b) Sensitivity and activation energy for each SnO$_2$ composite temperature sensor. c) Temperature sensor resistance as a function of bending radius of the soft robotic hand. d) Long-time temperature monitoring using a sensor with a control measurement via a commercial thermocouple.
at \( \approx 200 \text{ s} \), the air pressure is removed to deflate the balloon. However, none of the sensors show a malfunctional signal, demonstrating that the sensors are insensitive to the bending of the soft robots even under real-time use conditions.

As a control experiment to confirm the bending effect on the temperature sensor, another experiment using an object at RT was conducted. Figure S4, Supporting Information shows that the measured temperature is constant while the soft robotic hand grabs an object on detecting the object slipping (Figure S4b, Supporting Information) under inflation and deflation of the pneumatic balloon actuators. Furthermore, the soft robotic hand can detect the tactile force and temperature generated by a human hand (Figure S5, Supporting Information). More importantly, each sensor can measure the tactile force generated by a human finger independently. With these functionalities, the soft robotic hand has the capability to imitate human fingers and to detect a handshake with a human (Figure S6, Supporting Information).

This study reports a soft robotic hand integrated with tactile force sensors and a temperature sensor to realize a human-skin functionality. By considering the device structure and sensor integration process, the sensors show a good sensitivity toward each stimulus and insensitivity to the structure’s bending. Although the number of sensors is still limited, the approach to integrate several sensors (i.e., 2 × 2 tactile sensor and one temperature sensor) should be a good progress in the field of soft robotics. Additionally, the e-skin-integrated soft robotic hand can monitor sliding of an object by detecting the time delay of the tactile force. This provides real-time feedback so that the robotic hand can adjust the actuation force to prevent dropping an object. In this study, we focused on the fabrication and integration of multiple sensors embedded into a pneumatic balloon-type soft robotic hand, a feedback system could not be developed. System integration with hardware (sensors and robots) and software (feedback system, etc.) should be conducted in the near future to build human-friendly and intelligent robotics. Although this signal-processing and signal-feedback system require further development, this device platform holds promise as a method to realize a human–robot interactive society.

**Experimental Section**

*Device Fabrication:* Plastic molds were prepared by a 3D printer to form the pneumatic balloon layer structure (Figure S1(1), Supporting Information). After assembling the molds (Figure S1(2), Supporting Information), a silicone rubber solution (KJR-9060, Shin-Etsu Chemical Co., Japan) was poured into the mold and cured at 90°C for >60 min (Figure S1(3), Supporting Information). After delaminating the silicone rubber from the mold, the pneumatic balloon layer with an air-pressure channel was formed (Figure S1(4), Supporting Information). Next, a 1 mm thick silicone rubber sheet was prepared to seal the air pressure by covering the pneumatic balloon layer. Tactile force sensors were fabricated on another 1 mm thick silicone rubber sheet. For the tactile sensor, SWCNT solution (TUBALL, Kusumoto) was coated over a paper film to create a conductive layer. After attaching the conductive paper sheet on the silicone rubber, Ag threads (AGpos II, Mitsufuji) were sewn over the conductive paper. The tactile sensor layer (Figure S1(5), Supporting Information) with a 0.5 mm thick silicone rubber passivation layer (Figure S1(6), Supporting Information) was bonded over the sealing layer using a silicone rubber solution as an adhesive. Due to this process, Ag threads were fixed in the silicone layer. A resistive temperature sensor consisting of a mixture of SWCNT and SnO\(_2\) nanoparticles was printed onto a PET film (38 μm thickness) with a passivation layer using a SIFEL polymer (SIFEL2661, Shin-Etsu Chemical Co., Japan).

![Figure 4. Soft robotic hand demonstration.](image-url)
Chemical). Ag electrodes were screen-printed for the interconnection of the sensor. A PET film was used for the temperature sensor to prevent stretching of the sensor during inflation of the pneumatic balloon. Then the temperature sensor was laminated on the robotic hand and connected to the Ag threads to read the output signal. Finally, a 0.5 mm thick passivation sheet was laminated over the sensors. Figure S2, Supporting Information shows a more detailed structure of the soft actuator.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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