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All-Day Mobile Healthcare Monitoring System Based on Heterogeneous Stretchable Sensors for Medical Emergency

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***Abstract*—Epidermal and wearable electronic sensor technologies have gained extensive interest in recent years owing to deliver real-time healthcare information to the personalized smartphone. Herein, we proposed a fully integrated wearable smart patch-based sensor system with Kirigami-inspired strain-free deformable structures having temperature and humidity sensors along with a commercial acceleration sensor. The presented fully integrated wearable sensor system easily attaches to the skin to accurately determine the body information, and integrated circuit including read-out circuit and wireless communication transfer medical information (temperature, humidity, and motion) to mobile phone to assist with emergencies due to "unpredictable" deviations and to aid in medical checkups for vulnerable patients. This article addresses the challenge of all-day continuous monitoring of human body biological signals by introducing the well-equipped breathable (water permeability ~ 80 gm$^{-1}\cdot$h^{-1}), excellent adhesion to the skin (peel strength < 200 gf/12 mm), biocompatible, and conformable smart patch that can absorb the moisture (sweat) generated from the skin without any harshness and allowing the users' to continuously monitor the early detection of diagnosis. Furthermore, the proposed patch-based medical device enables wireless sensing capabilities in response to rapid variation, equipped with a customized circuit design, low-power Bluetooth module, and a signal processing integrated circuit mounted on a flexible printed circuit board. Thus, a unique platform is established for multifunctional sensors to interface with hard electronics, providing emerging opportunities in the biomedical field as well as Internet-of-Things applications.**

***Index Terms*—Flexible printed circuit board (FPCB), kirigami–serpentine heterogeneous structure, smart patch device, water permeable, wearable.**

I. INTRODUCTION

WEARABLE mobile healthcare devices are among the most rapidly developing electronics in modern technology owing to advances in novel flexible processes, ultrathin devices and sensors, and flexible/stretchable materials [1]–[3]. More essentially, healthcare affects the quality of life more than any other field; consequently, the development of sensors that are able to continuously sense for early signs of health issues is promising in the field of patch-based wearable electronic devices [4], [5]. Toward this goal, sensors need to interact continuously with the human epidermis to collect health data [6], [7]. Various strategies toward mechanically stable and conformable structures (i.e., Kirigami, serpentine, and curved) have been studied in which wearable sensors mimic human skin slippage/movement while being handled [8]–[12]. Recently, strain-free novel mechanical structures and materials have been adopted from nature to accommodate various deformations under external complex stress environments [13], [14]. Furthermore, traditional high-performance electronic materials exhibit superior performance to intrinsically flexible/stretchable electronic materials in areas such as high-linearity and fast-response time [15]. Thus, combining traditional electronics with that of Kirigami-inspired structural engineering has drawn increasing interest in monitoring the biological signals of the human body with high accuracy and low error rates under environments with various levels of robustness [16], [17].

The importance of all-day real-time monitoring systems through flexible and stretchable sensors is increasing in

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biomedical appliance research and in the healthcare industry [18]. Body temperature is a vital sign in all types of healthcare settings because a healthy human body has a thermoregulation system that maintains homeostasis within specific boundaries [19]. Thus, body temperatures that are outside the normal range indicate that a person may have diseases resulting in an imbalance of body thermoregulation [20]–[22]. The body humidity level is an important key point of concern in human health, involving body fluids that contain metabolites and electrolytes, which are able to provide vital information regarding human health [23], [24]. Although continuous monitoring of temperature and humidity is valuable, simultaneous monitoring of physical activities, such as running, walking, and falling, is also of great importance in human health [25]. Thus, a smart wearable device that can synchronously respond and collect data from the human body is of considerable demand, such that the technology can be integrated into the conventional integrated circuit (IC), including wireless communication and read-out IC for early detection and continuous monitoring of temperature and sweat-related diseases [26]. Thus, it is necessary to not only develop more convenient devices but also accurately measure facile information of human temperature and sweat condition, as well as sharp motion detection, which can serve as a significant and reliable diagnosis device for universal healthcare settings.

Herein, we report a novel structure inspired by nature, three-dimensional (3-D)-deformable, and two-dimensional (2-D) stretchable platforms for wearable mobile healthcare for point-of-care diagnostics that are conformably attached to skin. This structure includes a platinum (Pt)-resistance thermometer, humidity sensor, signal-processing IC, wireless communication module, and long-life battery. Furthermore, the representative wearable device has a fall-down detection feature, by means of a commercialized three-axis accelerometer sensor that is mounted on the device. Thus, personal movement is also continuously monitored in any care setting. To establish the long-term real-time monitoring biological signals of the human body, the anisotropic conductive film (ACF) bonding method has been utilized for bonding between a soft electronic device (Kirigami–serpentine inspired sensory system) and a flexible electronic device (electronic IC system). In addition, body temperature, humidity, and motion detection are provided via a mobile phone to assist with emergencies due to "unpredictable" deviations and aid in medical checkups of vulnerable patients. Although the mobile healthcare device presented here was initially intended to measure body temperature, sweat conditions, and patient movement, it may be further enhanced with various sensors to measure heart rate and oxygen saturation, which can be used as a smart interface that bridges the information gap between humans and electronic devices, providing a platform for "augmented human electronics."

II. Result and Discussion

A. *Patch-Based Emergency Device*

The skin-conforming patch-based gadget is able to detect body temperature, humid level, and motion, which are important indicators when treating certain patients with various types of fevers or infectious diseases. The multifunctional sensors are able to 1) achieve precise assessment through continuous signal processing, 2) accumulate biological data in a database reflecting an individual's health status from day to day, and 3) ensure clinical validation-based temperature, humid level, and motion variations after medical treatment. In addition, the data measured across the mobile device are sent to healthcare providers; these data help to provide real-time emergency notifications of changes in a patient's condition. The proposed device shows promise for enabling clinicians to receive physiological information for the continual monitoring of temperature in order to advance new convergences in the medical field. The aforementioned description illustrates the conceptual overview of the presented mobile health-care device as shown in Fig. 1(a).

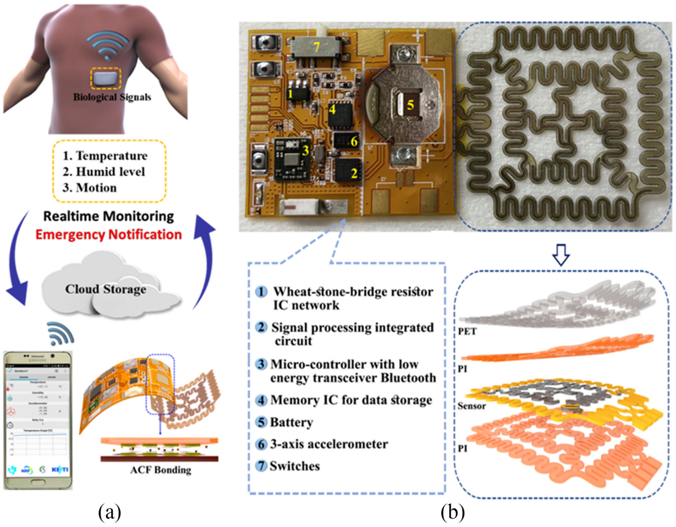


Fig. 1. (a) Schematic concept of the proposed patch-based biomedical device attached to a subject's left lower rib cage for responding the emergency situations with respect to the body temperature, humid level, and fall down detection. (b) A real image of interfaces of the circuit layout and heterogeneous stretchable sensors for data acquisition, signal processing, and transmission with the labeling of each electronic component with the schematic layout of the layer-by-layer design of heterogeneous temperature sensor.

The multifunctional biomedical device for monitoring the human body temperature, humid, and motion is embedded with the following components:

1) wheatstone bridge resistor IC network;
2) customized signal processing IC;
3) microcontroller with low energy transceiver Bluetooth (BLE) device;
4) memory IC for data storage;
5) Battery;
6) Three-axis accelerometer;
7) switches [see Fig. 1(b)].

The entire operating system of the presented biomedical device serves to amplify, filter, modulate, convert, control, and transmit the biological signals obtained from the proposed temperature, humidity, and motion sensors, as described in Section II-E. The layer-by-layer design of the proposed sensors explains the detailed illustration of stretchable design and encapsulation of heterogeneous stretchable sensors from top to bottom [see Fig. 1(b)].

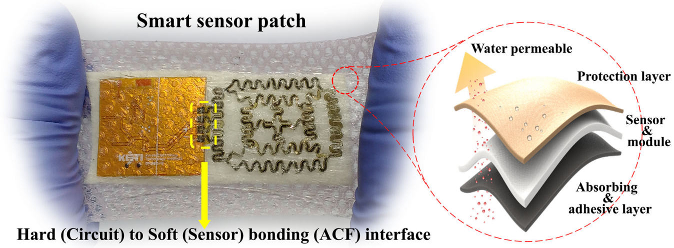


Fig. 2. Photograph of the stretchable patch design describing the bonding between the sensor and the FPCB.

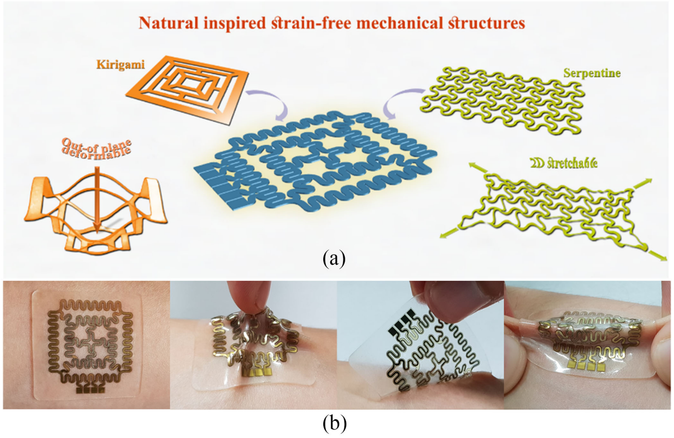


Fig. 3. 3-D deformable heterogeneous sensors design. (a) Conceptual layout of 3-D deformable nature-inspired Kirigami–serpentine based heterogenous sensors. (b) Optical images of the proposed sensor while attaching, pulling, detaching and compressing.

The wearable biomedical sensors device designed for humanly medical purposes that can easily be attached to any part of the human body, similar to a Band-Aid. The stretch-ability and conformability of the smart wearable patch device along with the flexible printed circuit board (FPCB) and natural-inspired heterogeneous sensors have been described as a photograph (see Fig. 2). Herein, we used ACF bonder to establish a stable all-day real-time monitoring of biological signals of human body and a perfect contact between electrodes and support the use of the heterogeneous stretchable sensors in various environments, such as those with different shapes and conditions. In addition, due to the unique design of the proposed medical device, users can place the sensor on any preferred part of the body due to its flexibility and soft texture. While considering the effect of human skin due to the bandage device, we have designed a patch in a way to oppose the harshness and protect the human skin from skin allergies. The patch design consists of three layers as shown in the schematic layout of Fig. 2 (discussed in more detail in experimental section in supplementary materials).

B. Geometry and Fabrication Illustration of Kirigami–Serpentine Heterogeneous Sensors

Fig. 3(a) schematically illustrates the novel structural design inspired by both Kirigami and serpentine patterns that are able to deform three-dimensionally and simultaneously stretchable in 2-D. As of now, 2-D spring-shaped structural layouts inspired by 3-D helical spring have been adopted and deeply studied in constructing various stretchable electronic devices.

Similarly, Kirigami, an ancient art of paper cutting and folding, presents another way of building 2-D structural layouts into 3-D deformable architectures with high levels of spatial mechanical deformations normal to the plane of the structure, thus enabling new ways of building strain-free mechanical structures for futuristic flexible and stretchable electronic devices. Moreover, state-of-the-art electronic devices in modern technology aim to be integrated into complex environments such as knees and elbows that can accommodate large strain and geometrical deformations under strain-free mechanical structures stretching in three dimensions [27]–[32]. Based on the advantages led by these natural inspired structures, we have designed and fabricated a stretchable and spatial deformable sensory system that is sticky, conformable, and mechanically robust to achieve high levels of sensing performances. Moreover, the smart sensor design attached to the human skin exhibited very good conformal, flexible, and stretching abilities upon deliberately pulling, detaching, and squeezing as shown in Fig. 3(b).

To fabricate the temperature and humidity sensor, first, a solution-based proportional integral (PI) was chosen as a flexible material owing to its excellent thermal stability (up to ∼500 °C; conventional thin-film Si technology) and smoothness on the substrate after coating [33]–[35]. Then, the solution was spin-coated on a rigid glass substrate as a bottom flexible layer of the proposed sensors. To ensure the smoothness and uniformity, the spin-coated PI layer was baked in an oven for 2 h at 300 °C and followed by the lift-off process for patterning the stretchable thermometer with a coating of lift-off resist and photo-resist (PR), respectively. The length, width, and thickness of the serpentine-shaped layout of the temperature sensor were specifically premeditated to manipulate a resistance of 5 kΩ to dissipate the low-power consumption. As the proposed patch-based medical device operating voltage is 3.3 V, the resistance of the temperature sensor was optimized in terms of sensitivity, area, and fabrication limit. Before the deposition of the Pt thin film on the PI-coated substrate, we have performed a reactive-ion etching (RIE) process to remove the residues of PR that remain after the wet-etching process and to obtain a cleaner pattern of the thermometer. The deposited Pt thin film was clearly removed through remover (mr-rem 700) and dried for 10 min. To develop the capacitive-type humidity sensor, we have designed a serpentine-shaped interdigitated humidity sensor to obtain the high sensitivity of water-vapor contents while attached to the human body. In order to pattern the gold (Au) contact electrode of the proposed temperature sensor, the pattern of the serpentine-shaped interdigitated humidity sensor was also fabricated through the aforementioned lithographic process simultaneously. To advance the electrical and mechanical performance of the defined sensors, the PI is spin-coated again on the patterned temperature and humidity sensors. After baking the top PI at the same condition, we laminated a polyethylene-terephthalate (PET) film being a topmost layer. The laser cutter technique was proposed to pattern the PET

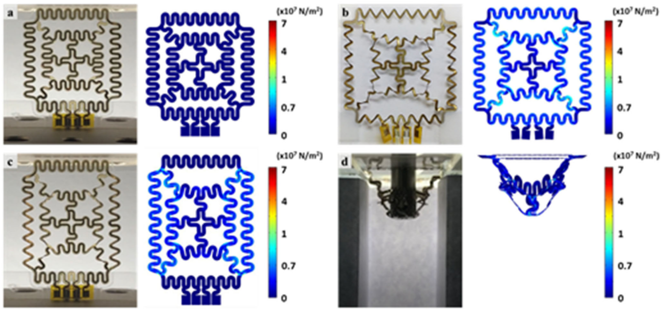


Fig. 4. Stretching experiment along with FEM simulation: (a) Pristine state, (b) *xy*-direction, (c) *x*-direction, and d) *z*-direction up to 30% stretching.

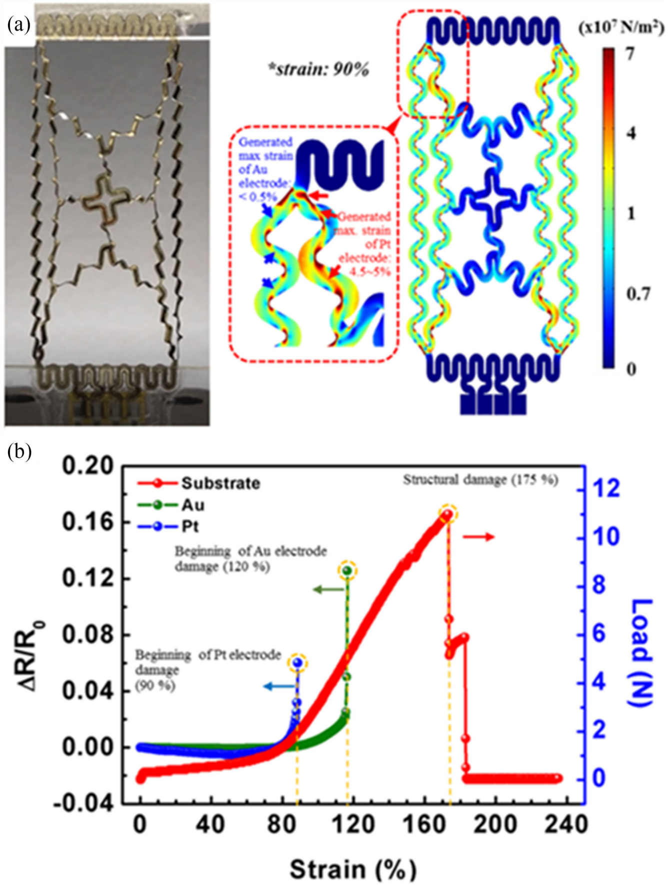


Fig. 5. (a) FEM simulation and (b) experimental representation of Au/Pt electrode and substrate from beginning to damage in the *x*-direction, respectively.

and top/bottom PI layer and manually peeled off through the tweezers as shown in the fabrication steps of the stretchable sensors. The stretchable temperature and humidity sensors were smoothly peeled off from a rigid glass and then followed by an RIE process on the bottom PI for 3 min at 100 W to enhance the sensitivity of the humidity sensor. The described fabrication process leads to the extraordinary performance of the sensors with high reliability and excellent consistency. In addition, the final optical image and the PI/PET layer design of the Kirigami–serpentine heterogeneous sensors for laser cutter design as described above in the fabrication process are shown in the Supplementary material Fig. S1a and b. The schematic layout of the Kirigami–inspired heterogeneous design of temperature and humidity sensors are described, respectively, interdigitated serpentine-shaped humidity sensor (Supplementary material Fig. S1c) and temperature sensor (Supplementary material Fig. S1d) along with the parameter's representation of Au and Pt.

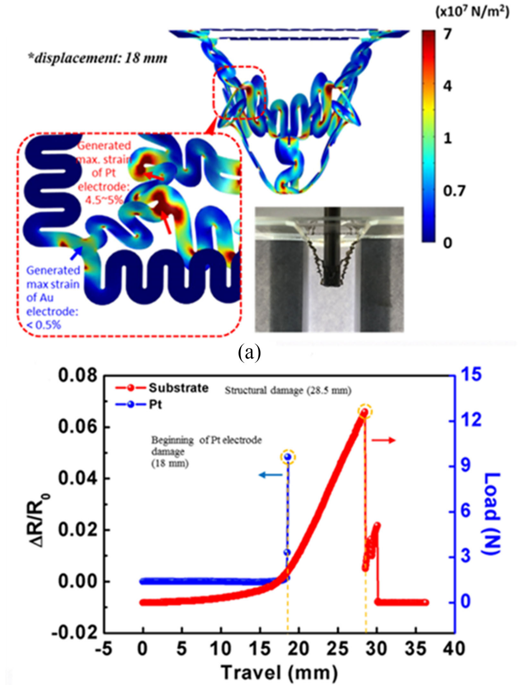
C. Mechanical Stress and Strain Robustness Analysis

The Kirigami-inspired heterogeneous stretchable sensors are designed specifically for real-time monitoring of human health for clinical emergency situations which need to be capable of high flexibility and stretch ability. Moreover, the attached healthcare sensor should be nothing wrong with normal activities and motions (squeezing, compressing, pushing, and pulling) in daily lives; as previously stated, the movements raise the mechanical strain within 30% of the sensor due to the nature of human [27]–[32]. Therefore, we need to consider the conditions as one of the design factors, and to verify that the structure of the sensor functions properly under these conditions. In this respect, to ensure the mechanical stability of the structure of the proposed sensors we used: 1) a special structure (Kirigami-serpentine combined form factor), 2) Ti with relatively high yield strength as an adhesion layer as well as a mechanical complementary layer, and 3) also, the electrodes for the sensor were located about 200 μm from the edge of substrate where strain and stress are maximized as illustrated in the Supplementary material Fig. S1b.

Fig. 4 shows the results of stretching experiment and the finite element method (FEM) for *x*-, *xy*-, and *z*-directions (at 30% strain). According to the results, the generated maximum stress by the structural strain of 30% is about 1.0 x 107 N/m^2 (very far below the upper limit of the transition from elastic to plastic deformation, $\sim$ 7.0 $\times$ 107 N/m^2).

As a result, the aforementioned considerations made a very large increase (in the *x*-direction, *y*-direction, or *xy*-direction) in the structure possible: Pt electrode damage commences at a strain of 90%, Au electrode damage commences at a strain of 120%, and structural damage commences at a strain of 175%, as described in Fig. 5(a) FEM simulation and Fig. 5(b) experimental representation. Furthermore, the design factors allow the structure to realize huge deformation along the *z*-direction: Pt electrode damage starts at a displacement of 18 mm, Au electrode damage start at a displacement of 22 mm, and structural damage starts at a displacement of 28.5 mm, depicted in Fig. 6(a) FEM simulation and Fig. 6(b) experimental representation.

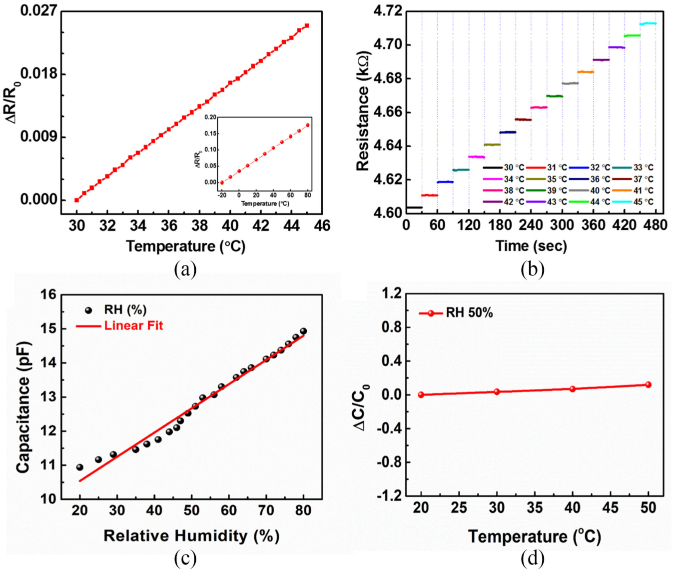
Here, we note that the deformations of a substrate and an electrode occur within the linear elastic region due to a specially designed structure despite its relatively huge displacement before damage is first started (beginning of Pt electrode damage). After the point, the deformations enter the nonlinear plastic region (or beyond the elastic limit). This is far below our goal (target strain for all directions: 30%) set by our condition; all deformations are located within the elastic region. Therefore, the structure can completely return to the initial state after



(a)

(b)

Fig. 6. (a) FEM simulation and (b) experimental representation of Pt electrode and substrate from beginning to damage in the *z*-direction, respectively.



(a) (b)

(c) (d)

Fig. 7. (a) Temperature sensor response at various temperature ranges from 30 °C to 46 °C (inset of the figure has a temperature range of −20 °C–80 °C). (b) Resistance response of the temperature sensor to temperature changes (30–45 °C) during a time interval of 30 s each. (c) Serpentine-based interdigitated humidity sensor response in the range of 20–80 RH (%). (d) Humidity sensor response under various temperatures (20 °C to 80 °C) at the same humidity environment (50%RH).

removal of the external load. These facts are in agreement with the results of our stretching and cyclic loading tests. The structural stress has little effect on the deformations of each electrode on the Kirigami–serpentine combined substrate; the maximum strain of the elements occurs only within 1%. The result is associated with the cyclic loading test up to 1500 cycles; mechanical and electrical characteristics are constant regardless of the amount of cyclic loading in the case of temperature, as shown in Supplementary material Fig. S2a. In the case of the humidity sensor, the cyclic stretching test has been performed for the constant humidity environment of 50% relative humidity (RH), for up to 1500 cycles, and the results show no significant effect during the experiment (Supplementary material Fig. S2b). From the outcome of these tests and analyses, we know that our Kirigami–serpentine combined substrate with considering additional design factors can guarantee and support mechanical and electrical stability under our working conditions for the wearable real-time health monitoring sensor.

D. Electrical Characteristics of Heterogeneous Sensors

Humid and temperature variation in the human body are clinically important vital signs. The thermoregulatory center in the hypothalamus of the brain simultaneously receives temperature information from the thermoreceptors in the human body. Abnormal thermoregulation occurs as hyperthermia (higher than 38 °C) or hypothermia (lower than 35 °C), which indicates potentially life-threatening events due to infection, inflammation, cachexia from malignancy or malnutrition, gastrointestinal hemorrhage, delirium, or endocrine dysfunction [36]–[38]. Extreme body temperatures over 45 °C or below 25 °C result in mortality in humans [39], [40]. The thermoregulatory system of humans is also an important part of homeostasis, which controls the heat loss in human skin such as convection, conduction, radiation, and evaporation. When the environmental temperature exceeds the skin temperature, the evaporation process in the human body will occur that causes the body temperature to rise and the heat loss by convection. In hot and cold conditions, the increment and decrement occurred in sweat productions of the human body, which indicate serious events that need to be monitored accordingly. Therefore, accurately measuring the body temperature and humid condition are critically important for disease diagnosis and monitoring. To achieve accurate detection of the thermoregulatory system of the human body, the entire surface of the sensing probe must be in direct contact with the skin. A heterogeneous structure of biomedical sensors enables us 1) to overcome attendant errors and 2) to extend the detectable area. Moreover, the stretchable platform covers a wide area of skin without separating from the skin. To realize a sensitive and stable temperature sensor, Pt was selected due to its high linear property of sensing with respect to the temperature. As we expected, the normalized response of the Pt thermometer to temperature changes from 30 to 46 °C shows stable linear characteristics as shown in Fig. 7(a). The normalized resistance has been defined as $\Delta R/R_0 = (R_0 - R)/R_0$, where R presents the measured resistance at various temperatures (−30 to 46 °C), and R_0 presents the reference resistance at a reference temperature (30 °C). In addition, to obtain the high sensitivity, the thermometer has been examined at a maximum temperature range from −20 to 80 °C and the results exhibit a linear behavior as described in the inset of Fig. 7(a). In addition, continuously monitoring the body temperature is critically important because each specific illness shows different patterns of body temperature throughout the day: 1) continuous fever (not fluctuating more than 1 °C in 24 hours): lobar pneumonia, typhoid, meningitis, urinary tract infection, or brucellosis; 2) intermittent fever (body temperature is only elevated at certain times of the day): malaria, kala-azar, pyaemia, or septicemia; and 3) remittent fever (fluctuates more than 1 °C in 24 h): infectious diseases [41], [42].

The patterns of change in body temperature provide diagnostic evidence for responding to specific illnesses and treatment effects. However, it is not easy or feasible for healthcare providers to monitor the variability of the body temperature for 24 h in clinical settings. Traditional body temperature monitoring is labor-intensive and time-delayed due to time-constrictive clinical environments. Therefore, real-time monitoring of body temperature with minimal operations is critically important, as is the aforementioned accuracy of the sensor. Fig. 7(b) shows real-time data of the temperature measured for 30 s at 1 °C intervals in a vacuum chamber where the temperature has been varied by the hot chunk controller. However, we note that a maximum error of 0.1% for the temperature sensor was present owing to impurities and defects in the fabrication process.

For remotely monitoring the human body trauma, the tragic movement of air/water molecules in the skin requires to monitor at the comfort and harsh zone for healthcare. The serpentine-shaped interdigitated humidity sensor exhibits a linear response at various humidity ranges from 20 to 80%RH as shown in Fig. 7(c). In addition, the homeostasis avenue in human body affects the thermoregulation system with gradually increasing and decreasing body temperature. Hence, to verify the sensing ability of the proposed humidity sensor, an examination was conducted under various temperatures range from 20 to 50 °C at the fixed RH of 50% [see Fig. 7(d)]. In addition, the temperature sensor response was measured at various relative humidity ranges from 30 to 80% at the fixed temperature of 50 °C, and the consequences show no significant effect during the experiment, depicted in the Supplementary material Fig. S3. The results support the heterogeneous structure of the humidity and temperature sensors, which shows accurate sensing of humidity and temperature at various temperature and humidity scales, respectively. In addition, the electrical properties of the temperature and humidity sensor exhibit linear and accurate behavior under various conditions, which allows the sensors to be used in the healthcare field.

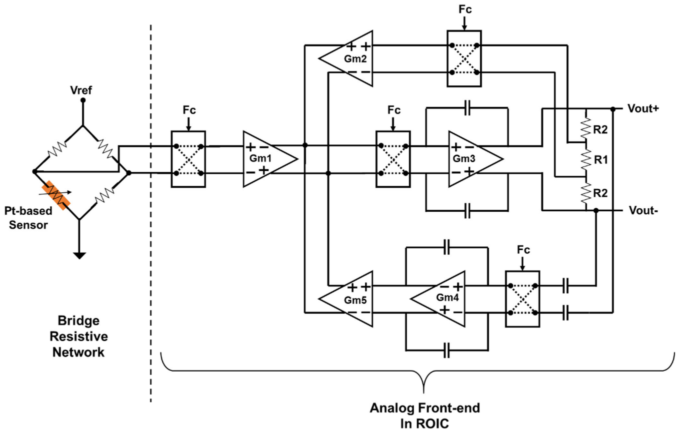


Fig. 8. Interfacing layout of the temperature sensor as the front-end chopping-stabilized amplifier.

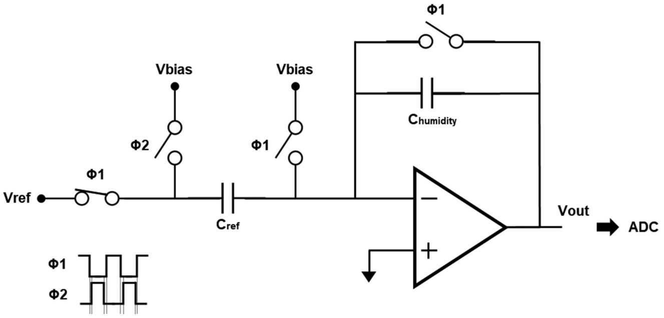


Fig. 9. Digitizing circuit diagram for the humidity sensor data.

E. Characterization and Real-Time Data Acquisition of the Smart Patch-Based Healthcare Device

The schematic flowchart of the entire system of the proposed biomedical emergency device is described in a detailed view in Supplementary material Fig. S4. In case of the temperature, sensor signals can be processed automatically by the system on a chip, which elaborates the sequential process in the following format: 1) First, the amplifier (AMP) has been customized to amplify the analog signals sensed from Pt temperature sensor. To suppress the offset and the flicker noise of the AMP, the chopping-stabilized amplifier with a two-stage amplifier is employed. With a ripple reduction loop of Gm4 and Gm5, the output voltage of the AMP becomes Vin × Gm1 / Gm2 × (R1 + 2 × R2)/R1 (see Fig. 8). 2) After amplifying, the signals then filtered to avoid the noises through low-pass filter and 3) then the signals being digitized from analog signals by using modified 16 bits delta-sigma Analog-to-Digital Converter (16b ADC) (Supplementary material Fig. S5). For the humidity sensor, a capacitance-to-voltage converter is adapted to generate a linear voltage signal proportional to the relative humidity (see Fig. 9).

The capacitance from the humidity sensor is compared with a reference capacitance (C_{ref}) and the capacitance variation from the relative humidity can be converted by an amplifier with a fixed ratio of $C_{\text{humidity}}/C_{\text{ref}}$. The signals are digitized in the same way as temperature sensor through a 16b ADC. In addition, the commercialized three-axis accelerometer has been selected for the motion detector and assembled in the medical device. As a final step, the multifunctional medical device data values in terms of temperature, humidity, and motion are calculated and transmitted to the mobile phone via low energy BLE module. Patients and their healthcare providers can monitor health conditions in real time with their smartphones as well as on the

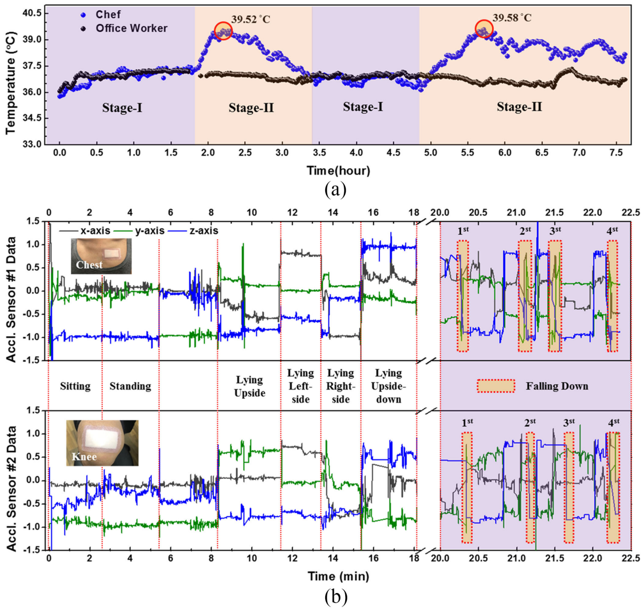


Fig. 10. (a) Graphical representation of real-time monitoring of the temperature sensor attached to selected subject's body during the experiment for 8 h. (b) Real-time monitoring of individual's activity with an emergency indication of falling down.

specific database server. Supplementary material Fig. S6 shows the custom-built Android application running on the smartphone that can display and analyze the real-time data stream of an individual's body temperature, humid, and motion with high accuracy and precision.

Fig. 10(a) displays the real-time monitoring temperature patterns collected during a representative experiment which are examined on two kinds of following subjects for 8 h approximately: 1) a normal routine person as an office worker and 2) an ordinary person as a chef (emergency case). In the case of a normal person, the real-time monitoring of the temperature sensor has been analyzed and the consequences show the stable response of temperature variations in the normal environment. The representative experiment has been examined in two stages for an emergency case with a one-time repetition: 1) when the chef is at a normal state (normal work routine) and 2) when the chef is cooking near to the fire. The graphical representation explained that when the chef is near to the fire for cooking, the slight changes can be visualized, which has been increased up to 39.52 °C and 39. 58 °C that indicates the emergency situations [see Fig. 10(a)]. By simultaneously monitoring the body temperature in severe and normal environments, it is possible to measure any emergency conditions instantaneously, whether a user is suffering from a high temperature or exposed to any hazardous environment.

With the addition of three-axis accelerometer sensor, the mobile health-care device creates a wide system to examine the motion of a human body in emergency cases for critical patients in hospitals under treatment. Two patch-based devices were employed to detect more accurate motion while attached on chest (sensor # 1) and knee (sensor # 2). The motion sensor captures various direction moments using a three-axis acceleration sensor. To demonstrate the potential of the motion sensor, consistent experiment with several motions (sit-to-stand-to-lay, walking, and falling down) was performed to observe the difference of the sensor data [see Fig. 10(b)]. This slight difference between the two devices can be found in falling down motions. The situation of falling down from a bed 80 cm above the ground only shows an abrupt change in both x-axis and z-axis, unlike other motions, as shown in Fig. 10(b). An emergency notification is received in 0.5–1 s when a user falls from a bed and collides with the ground. The device alerts care providers of the emergency, so they can quickly take the action necessary to treat patients. We believe that the proposed device with multiple properties of sensing the temperature, humid, and motion of the human body might be used in hospitals for critical patients and under-treatment children.

III. CONCLUSION

This new Kirigami-inspired stretchable heterogeneous sensor-based biomedical device exhibits high robustness performance, greater stretch-ability, higher electrical conductivity, and long-standing real-time monitoring. In addition, the mechanical stress and strain analysis of the nature-inspired Kirigami–serpentine heterogeneous sensors was verified through serial experimental and theoretical analysis and the results show that the unique of proposed sensors can accommodate higher deformability and stretch-ability under harsh environments. In terms of the electrical properties, the linearity and stable responses were acquired of the temperature and humidity sensors under different related scales. Furthermore, the proposed valuable design of a biomedical device that was being used for evaluating the temperature, humidity, and motion sensors data wirelessly has a worthy longstanding real-time monitoring ability of individual's health status, which can be visualized on a custom build android application using smart mobile and simultaneously record the monitoring data on a database server for a long time. Thus, the presented smart patch-based healthcare device can enable numerous new opportunities in the wearable electronic and biomedical field, as well as Internet-of-Things applications.

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