Full Fabric Sensing Network with Large Deformation for Continuous Detection of Skin Temperature

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Abstract:

Electronic textiles accomplished by incorporation of electronics into textile substrate are indispensable parts for large-area wearable applications. This paper presents a full fabric-based temperature sensor network comprised of discrete fabric temperature sensors and elastic fabric circuit board (FCB). The fabric temperature sensor made by integrating a continuous metal fiber into woven structure has an enhanced sensitivity (0.0039°C^{-1}), high accuracy (error: ±0.2°C), superior resolution (0.05°C), short response time, as well as almost no hysteresis, which has far exceeded those of metal-coated thin films and composite materials in terms of combination of the properties. Due to large-deformation capability of the FCB, the packaged assembly could maintain electrical integrity with a maximum strain of 40%, and withstand a fatigue life of at least 10,000 cycles at 30% strain, suggesting great promise for next-to-skin electronics. To demonstrate its applicability, a smart garment integrated the assembly has been used for in-situ detection of skin temperature during respiration.

Keywords: fabric temperature sensors, fabric sensing network, electronic textiles, skin temperature

1. Introduction

Electronics integrated into textiles with the characteristics of extreme flexibility, large deformation, and permeability are indispensable parts for large-area next-to-skin electronics[1-4], where it requires the devices are capable of compliant interaction with zoetic, soft, three-dimensionally curved, and dynamic human skins[5-11] with an average surface area as large as to 2 m^2[12-14]. Electronic textiles that are accomplished by incorporating electronic functions into a mechanically compliant and porous textile substrate are hence of great importance to advance skin-conforming electronics[15-17], potentially opening up an enormous range of applications such as healthcare or physiological monitoring[15, 18-22], sophisticated soft robotics[14, 23-28], as well as artificial skin-like materials[20, 29-31].

Skin temperature, as a basic physiological parameter, often reflects human activities[32, 33] and health conditions[34-36]. Flexible temperature sensors have been investigated for continuous measurement of localized temperature variations of the human skin[33, 35, 37], in which many efforts concentrate on metal particles on thin films and temperature-sensitive conductive composites[38-40]. The former thin metal films, created by heterogeneously implementing metal particles[41-46], like platinum (Pt), nickel, and gold, on sheet-like thin films[47-52], such as polydimethylsiloxane and polyimide, operate based on their resistive change with variation of the temperature[42, 43, 53-58], resulting in high accuracy (±0.3°C)[59-64], superior resolution (0.03°C)[46], and short response time (<80ms)[53, 62]. The sensitivity of the metallic thin films, nevertheless, is reduced compared with theoretical values of their corresponding bulk metals[42, 62, 65], possibly because of electron scattering at grain boundary[56], deposition condition, as well as adhesion layers[42, 62]. Additionally, the used thin films are not suitable for a long-time intimate contact with human skins, although some are satisfactory in the stretching capability. Oppositely, conductive composites were formed by dispersing conductive fillers, including carbon-based materials[66], conductive polymers, and metallic particles[67], into amorphous[34, 53, 54] or semi-crystalline polymers, such as polyethylene oxide and polyethylene adipate[33, 43, 46, 68], achieving orders-of-magnitude changes in electrical resistance with a small temperature variation due to considerable volume expansion of the polymer matrix[67, 69]. Such polymeric sensors, however, usually suffer large error (accuracy: ±2.7°C), severe hysteresis, slow response time, as well as irreproducibility caused by morphological change of the conductive network[33, 69-71]. Furthermore, their temperature measurement range is very narrow from 35°C to 42°C[68], often forbidding their applications for wide-scale temperature sensing in healthcare and medical fields[33, 72].

To address the critical issues abovementioned, we make novel all-fabric based flexible temperature sensors by integrating free-standing metal conductors in the fiber form into textile substrates. When compared with the reported thin metal films, the sensitivity could be enhanced with the pure bulk metals; the flexible, stretchable and permeable textile substrate could softly interface with non-planar skin surface with different gesture and motion for continuous measurement in minimal user awareness[53, 55, 65, 73, 74]. Differently from the polymeric temperature sensors, the use of resistive metal fibers as the temperature sensing element significantly improves the accuracy, resolution, and is capable of detecting the temperature signals without hysteresis in a broad temperature measuring range. In this paper, we firstly report the mechanically flexible fabric temperature sensor by weaving individual Pt fibers with uniform cross-sectional features at a micrometer scale into textile structures, which is a general technique for the construction of smart textiles[75, 76]. The fabricated temperature sensor has a sensitivity of 0.0039°C^{-1}, which is same as to the sensitive value of the pure bulk Pt and could satisfy different demands in various temperature sensing circumstances, a remarkable accuracy (error: ±0.2°C), superior resolution (0.05°C), short response time, as well as low hysteresis in cyclic conditions. Those results suggest that the fabric temperature sensor could successfully detect human skin temperature. To scale up sensor distribution and achieve large-area coverage for spatial temperature measurement, we further demonstrate a mechanically compliant fabric sensing network by linking the discrete temperature sensors with elastic fabric circuit board (FCB) in a simple fabrication process, which facilitates a high-level integration, low-cost and large-scale comfortably wearable textile platform. Owing to the non-planar structure of the conductive tracks in the FCB, a maximum stretchability of 40% strain was achieved without degrading the device performance. The whole assembly could also withstand more than 10,000 stretching cycles at 30% strain, which enables the fabric sensing network for highly deformable and durable skin-mounted electronics[77, 78]. The high stretchability and better cyclic durability presents an important step toward the realization of implantable and wearable devices that are sensitive, cyclically stable, processable, and can be unobtrusively attached to the skin for physiological signal monitoring. Finally, we investigate the performance of the fabric sensing network for real-time detection of skin temperature, indicating considerable promise for development of wearable health monitoring devices over long periods of time in a practical and noninvasive modality.

2. Fabric Temperature Sensor

A fabric temperature sensor is produced by integrating a continuous metal fiber into a woven-structured fabric composed of inherently non-conductive yarns through a conventional weaving technology by using a semi-automatic weaving machine (Model: SGA598, Jiangyin Tongyuan Textile Machinery Co., Ltd., China). The resulting fabric temperature sensor operates based on the change in resistance of the metal fiber upon varying the temperature in an almost linear relation, expressed by $R=R_0\times(1+\alpha(T-T_0))$, where R and R_0 are resistances of the metal fiber at temperature T and reference temperature T_0, respectively; α is temperature coefficient of resistance (TCR). As the environmental temperature increases, the resistance of the fabric temperature sensor rises and usually has a positive temperature coefficient. Figure 1 shows schematic diagram and scanning electron microscopy (SEM), respectively, of one typical resulting sample, which consists of two sets of fibers, i.e., the metal fiber Pt (from Shanghai Shenjie Instrument Co., Ltd., China) in an organized floating pattern in the fabric, where natural cotton yarns (280 Denier, from Hangzhou Zhangfu Textile Co., Ltd., China) as both transverse (along the width) and longitudinal (along the length) elements are inter-crossed at more or less right angles to each other. The continuous metal fiber, as another transverse part, is primarily interlaced with the longitudinal yarns and their interlacement results in a coherent and stable assembly (figure 1a).

The free-standing metal fiber (Young's modulus: 169 GPa, Poisson's ratio: 0.38), as shown in figure 1b, with smooth surface and circular-like cross section of 20-μm diameter, though it is expensive and does not have the highest temperature coefficient of resistance (3.92×10^{-3}℃$^{-1}$), was employed as temperature-sensitive material owing to its desirable thermal properties and linearity between electrical resistance-temperature relation; its high antioxidation so that it is unnecessary to protect the metal fiber from the chemical or environmental attacks, without the risk of reducing its electrical performance for practical applications[79, 80]; acceptable bending ($\pi d^4 E/64 \approx 1.33\times10^{-3}$ N.mm^2) and torsional rigidities (πd^4 G/ $32 \approx 9.58\times10^{-4}$ N.mm^2) as well as mechanical robustness (breaking tensile strength: ~20 cN) so that it could be deformed substantially to the crimped configurations and remains intact after being incorporated into the woven structure (figure 1c).

The fabric temperature sensor is designed with a serpentine metal electrode for increment of initial resistance. The sensing area is 10 mm×10 mm with an initial resistance of ~60 Ω and an average total length of the metal fiber is about 150 mm; the spacing between each line is ~800 μm. The thickness of the woven fabric is 686 μm; the weight is 160 g/m^2; and the density is 20 threads per centimeter in both horizontal and vertical directions. From the front side, the metal fiber continues over three under one longitudinal yarn (figure 1c), achieving a sufficient contact area between the sensitive element and the arbitrary curvilinear bodies, meanwhile without irritating to the human skin for a long-term use. The metal fiber, however, passes over one under three warp yarns on the opposite side (figure 1d), performing like any soft and breathable garment in a noninvasive nature.

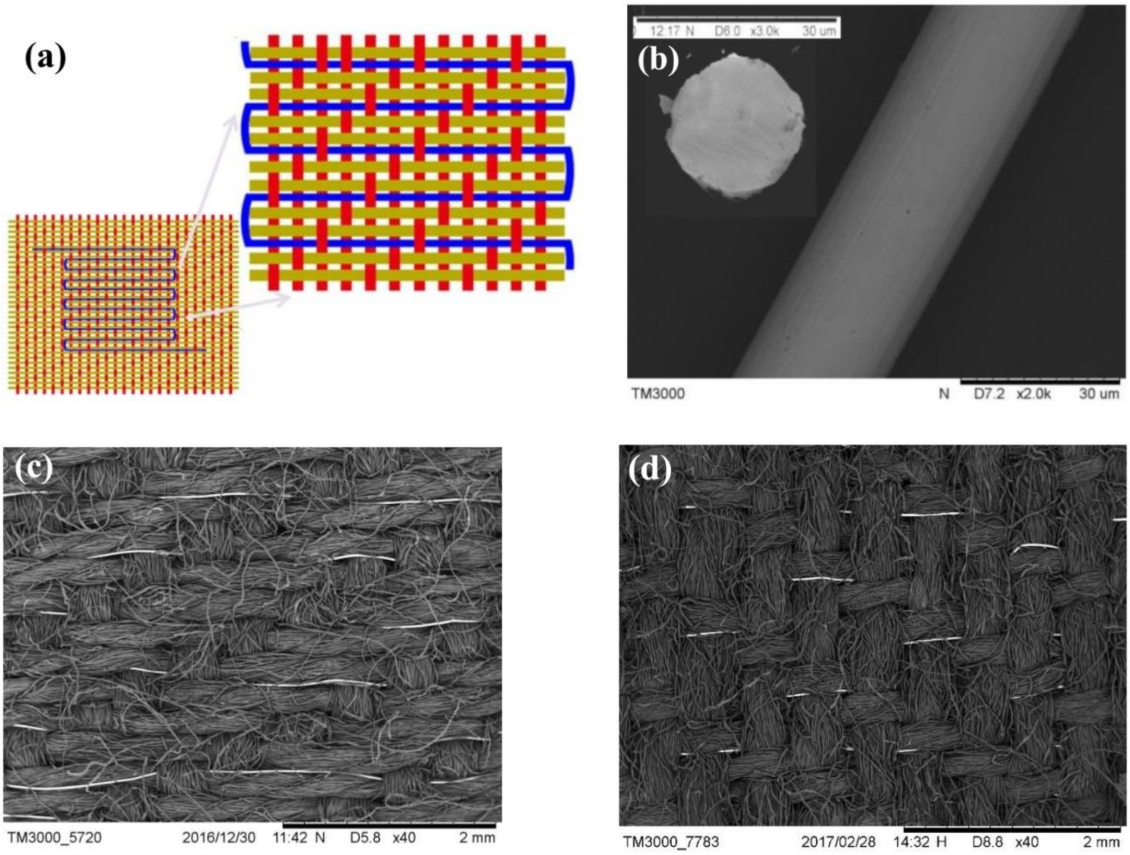

Figure 1. Structure of fabric temperature sensor. (a) Schematic diagram of the woven temperature sensor. (b) SEM images of the metal fiber. (c-d) Front-side and backside views of the woven temperature sensor.

Sensitive performance of the fabric temperature sensor was firstly examined by putting one resultant sample into a temperature-controlled oil bath, where the temperature ranges from 25°C to 45°C, which is suitable for the human body temperature[81, 82]. The electrical resistance was recorded and acquired at each temperature step for two consecutive temperature sweeps by Agilent 3458, which is interfaced with a computer[33, 53, 65, 83]. Figure 2a-b plots the typical resistance-temperature relation of the free-standing metal fiber and the fabric temperature sensor. The initial resistances are different due to the length variation, however, their electrical resistances rise almost linearly in average by 1.08 times in accordance with the increment of temperatures from 25°C to 45°C, whose slopes represent their TCR, a constant value of $3.92\times10^{-3}℃^{-1}$. Experimental data demonstrates that the temperature-resistivity charactersistics of the fabric temperature sensor remain at a level same to those of the free-standing metal fiber since the function mechanism of the fabric sensor is based on the changes of the metal resistance with subject to the temperature variation. It is noted that the sensitivity of the fabric temperature sensor is greater than that of thin film temperature sensors ($2.8\times10^{-3}℃^{-1}$)[84], due to no efffects of electron scattering at grain boundary in films[42, 56, 85]. In addition, the slopes of the data for both heating and cooling processes were exactly the same, suggesting no slight hysteresis between the data measured from the heating part and those measured from the cooling part of the cycle.

The accuracy of the fabric temperature sensor is also characterized by placing a reference sensor, i.e., Pt-100 resistor with ±0.03°C accuracy[86], during the measurement. Figure 2c shows the measured temperature error from 28°C to 45°C after one-point calibration at 28°C. It can be observed that an inaccuracy of ±0.1°C is obtained from 37°C to 39°C (±0.2°C from 28°C to 45°C), which is well within the specification (ASTM E1112-00: the maximum error tolerance for human body temperature monitoring[35]) indicated with black line. The fabric temperature sensor is hence suitable for biomedical applications to accurately detect human skin temperature.

More interestingly, the fabric temperature sensor has the ability to detect very minute temperature changes. The sensor’s response to extremely small changes in temperature was investigated by collecting resistance-temperature curves around 35°C. As plotted in figure 2d, the fabricated sensor could measure the temperature change as low to 0.05°C, which is promising in the precise thermometry of the human skin for providing relevant information about personal health.

The time constant, i.e., the time required for the sensor output to achieve 63.2% of its final value when subjected to a step change in surrounding temperature, is used to identify the sensor’s response[87]. Response time was characterized by plunging the fabric sensor from air at ~20°C into oil bath with ~50°C, where the sensor was exposed to a sudden change in temperature. The resistance of the sensor, however, gradually rises, resulting in an exponential transient. As illustrated in figure 2e-f, the typical response time of the free-standing Pt metal fiber is 0.50 s; the fabric sensor is 0.77 s due to larger volume of the metal fiber with a serpentine shape in the fabric construction. However, the response rate of the fabric sensor is much faster than that of the traditional Pt thermometer, whose response time was calculated as 3.30 s because of the negative effect from the protection sheath. The nursing time, therefore, can be saved when apply this sensor to clinic[53].

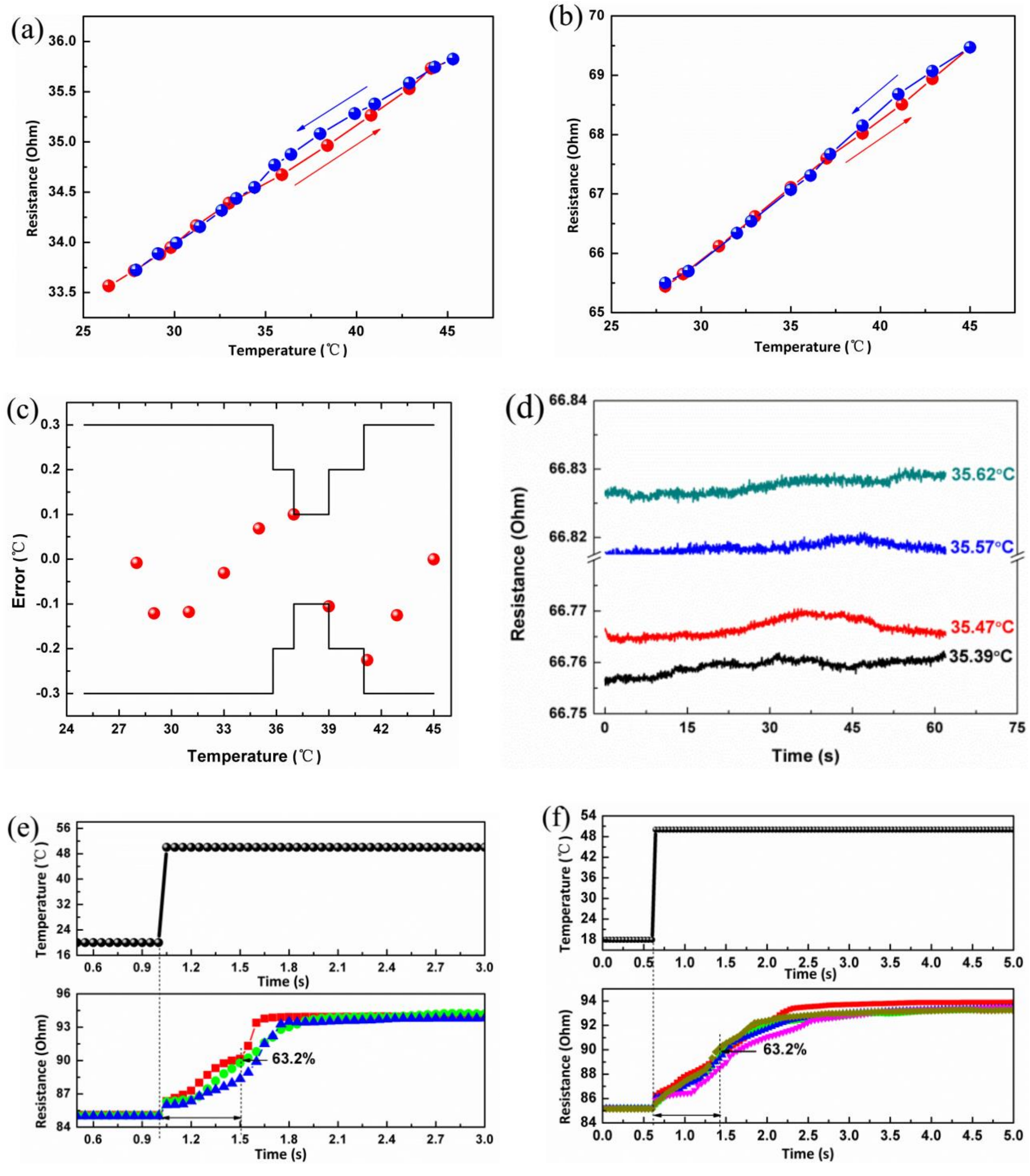

Figure 2. Performance of the fabric temperature sensor in oil bath. (a-b) Resistance-temperature relation of the metal fiber and the fabric sensor. (c) Measured inaccuracy after one-point calibration. (d) Measured resistance over an extremely small temperature range. (e-f) Response time of the metal fiber and the fabric temperature sensor.

Considering wearable condition, we further assessed the rate of change in resistance of the fabric sensor while placing it on a digital hot plate with temperature ranging from 25℃ to 45°C[88]. Figure 3a presents the influence of the temperature on the resistance of the fabric sensor when the sample intimately contacts the heating source in single-side condition. The resistance increases by 1.08 times when the temperature rises from 25°C to 45°C, calculating the TCR value is $3.92\times10^{-3}℃^{-1}$, same with the conditions in oil bath. Figure 3b further indicates that the fabric temperature sensor owns consistent trends and has the exactly same TCR in the conditions of oil bath and single-side contact with the heating source. The response rate of the fabric temperature sensor, however, became slower in single-side contact. As shown in figure 3c, the constant time is 1.70 s when investigated on the hotplate stage from 25°C to 50°C, suggesting that the application conditions contribute a lot to the response time of the fabric sensor[89]. As illustrated in figure 3d, in turbulent liquid, the sensor surface could intimately contact with the liquid media so that the surface contact could be easily maximized and heat could transfer easily to the sensing element, thereby yielding a faster response time; on hotplate stage, whereas, due to the non-planar of the fabric structure, the curved fabric sensor can not fully match the geometry of the flat mounting area, thus, the surface contact is not sufficient for fast response. Hence, the response of the fabric sensor depends on the environment in which the sensor is operated. Exact conditions of the test must be specified together with the time constant when apply a temperature sensor to an application[90].

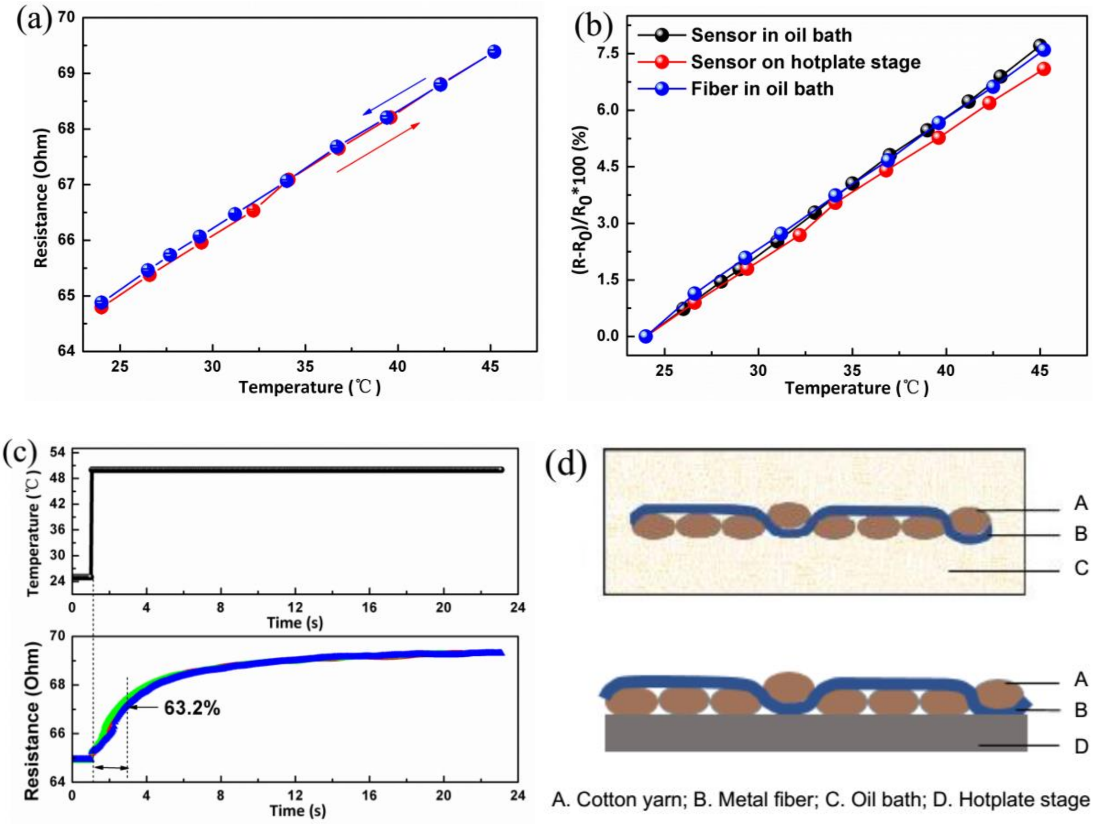

Figure 3. Performance of the fabric temperature sensor on hotplate stage. (a) Resistance-temperature relation of the fabric sensor. (b) Relative resistance changes of the metal fiber and the sensor in different conditions. (c) Response time of the fabric sensor. (d) Fabric sensor in different conditions.

3. Fabric Temperature Sensing Network

To the best of our knowledge, the performance of the present fabric temperature sensor has far exceeded those of previously reported metal-coated thin films and other organic materials in terms of combination of sensitivity, accuracy, resolution, measurement range, three-dimensional deformability, as well as permeability. Those distinctive features make the fabric sensor particularly suitable for next-to-skin electronic devices. As a demonstration, we have fabricated a flexible and stretchable integrated platform of temperature sensors as a wearable assembly to be used for in-situ detection of temperature distribution of the human skin by using 'island-bridge' strategy for stretchable electronics[91-93]. In the fabric sensing network, seven temperature sensor elements distributed on selected locations of the human skin referring to ISO 9886:2004 (ergonomies-evaluation of thermal strain by physiologieal measurement), as illustrated in figure 4a, were mechanically and electrically connected by conductive tracks of a FCB[94, 95]. Figure 4b presents main structure for the fabric sensing network. The first step involves weaving a jacquard pattern on a computerized weaving machine to define wiring layout of the FCB corresponding to predetermined locations of the seven independent sensor elements. The FCB was created by incorporating silver nano-particles coated polyurethane yarns (Young's modulus: 0.531 GPa, tensile stress: 159.2 MPa with 30% strain), as the conductive tracks, into an elastic woven substrate (figure 4c). The second procedure is the implementation of the sensors on the corresponding locations of the undeformed woven FCB in a precision fashion, so that the temperature sensors form checkerboard patterns[96]. Third, the sensor electrodes were physically linked by the conductive tracks through electrical connections for transmission of electrical signals to outer circuits. Here, a piece of woven fabric was bonded around the connected region, enhancing mechanical robustness of the electrical contact through reducing possible strain in the contact area when the whole assembly was stretched by an external force[97, 98]. The final step was to connect the other ends of the conductive tracks in the woven FCB to outer circuits by means of bonding selected interposers to the conductive tracks with a thin layer of woven fabric to stiffen the connected region.

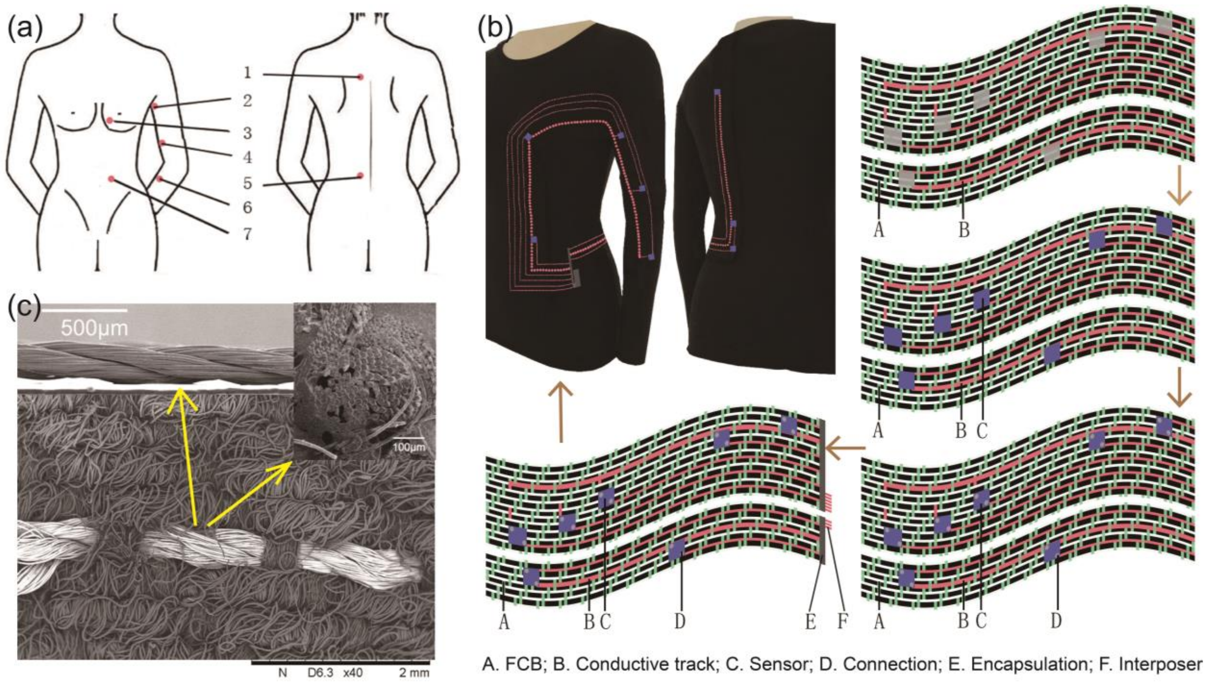

Figure 4. Fabric temperature sensing network. (a) Location of measuring sites. 1-scapula; 2-armpit; 3-upper chest; 4-upper arm; 5-paravertebral; 6-lower arm; 7-abdomen; (b) Structure of the fabric sensing network; (c) SEM image of the conductive track in the FCB.

The performance of the fabric temperature sensing network was characterized before application. The FCB consisting of an array of conductive tracks (resistance: 3Ω.cm) could maintain electrical integrity within 40% strain, where 20%-30% strain is a mean elongation ratio of the human skin, as plotted in figure 5a. After fabrication, the electrical resistance of one sensor element was firstly monitored when it was unidirectionally stretched from 0% to 30% strain at 25°C. Figure 5b demonstrates the resistance maintains stable when the fabric sensing network is stretched from 0% to 30%. Meanwhile, the resistance-temperature relation was investigated too with different strain. Under axial stretching of 0%, 15%, and 30%, the packaged fabric sensing arrays exhibit a stable resistance-temperature relation without any noticeable degradation in sensitivity as clearly seen in figure 5c, suggesting that stretching effect on temperature read-out of the sensor array is negligible. To evaluate the effect of repetitive mechanical deformation, the fabric temperature sensing network was subjected to cyclic stretching and their initial electrical resistance at 25°C was evaluated with 10,000 stretching cycles at 30% strain.

Figure 5d presents a little slight variation in electrical resistance from 71.5 Ω to 72.5 Ω after cyclic stretching[85]. These results clearly suggest that our fabricated temperature sensor on the stretchable substrate is very stable under repetitive axial stretching[99].

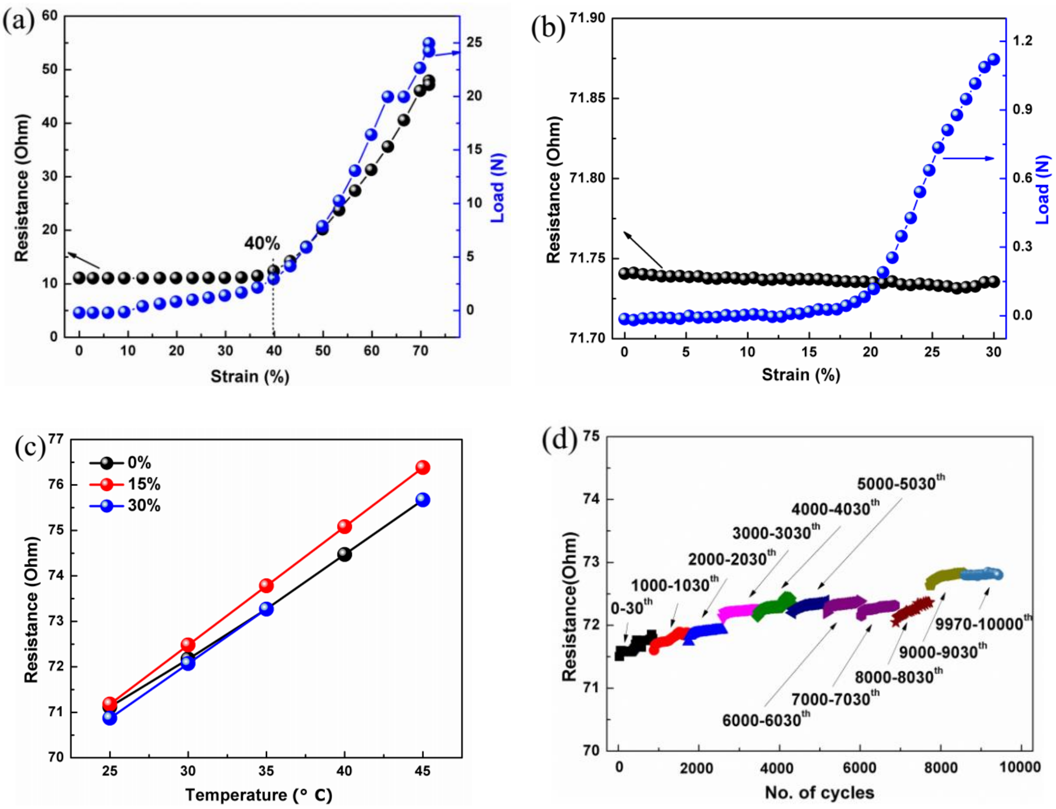

Figure 5. Performance of the fabric sensing network. (a) Resistance-strain relation of the FCB. (b) Resistance-strain relation of the fabric sensing network. (c) Resistance-temperature relation of the fabric sensing network at different strain. (d) Resistance of the fabric sensing network as a function of stretching cycles under 30% strain.

4. Precise Measurement of Skin Temperature

In order to investigate the applicability of the fabric temperature sensing network, we integrate the packaged assembly into a garment for real-time monitoring skin temperature in different locations of a young and healthy female subject during respiration (figure 4). The sensitive apparel directly contacts non-flat human skins to sense the physiological temperature changes in the selected regions during respiration, without causing physical damage to the skin or restricting movement of the human tissue. Before measurement, the temperature of the sensor was calibrated by using a non-contact infrared digital thermometer (Berrcom JXB-182, China). All of the seven temperature sensor cells on the array are functional and the temperature gradients have been measured successfully. The packaged fabric sensing network showed excellent reliability during measurement as all the sensor assembly functioned well without any mechanical and electrical failure and received acceptable electrical signals.

Figure 6a and 7a exhibits the temperature mapping sensed by the fabric sensor array with respect to eupnea and deep breathing, respectively. The skin temperature differs on separate places of the human body, displaying higher values at the location closest to armpit and lower values at the regions of upper arm and abdomen with a range from 33°C to 36°C. Figure 6 and 7 further plots temperature change over time in the seven selected areas of the subject during normal respiration and deep breath, respectively. It is firstly noted that the skin surface temperature always rises with breathing in, and then drops with breathing out. The whole unit period is approximately 5 s and 10 s for one normal and deep breath, respectively, which is consistent with the time used by the subject. Additionally, the temperature responses in the seven areas during deep breath are greater than those in their corresponding parts during eupnea, which is reasonable due to faster speed of the blood flow during deep breath[100]. Interestingly, we also discovered that there are several differences in the reading-out temperatures depending on varied positions, for instance, the temperature responses of the sensors near the abdomen, armpit, and upper chest regions were greater than those of the sensors near the other selected locations of the subject's body during deep breath. Similar phenomenon exists during normal respiration, too. We infer that the possible reason is attributed to different blood flow speed caused by the motion of the mitochondria in different locations of the human body. The details of this work will be reported separately in the near future.

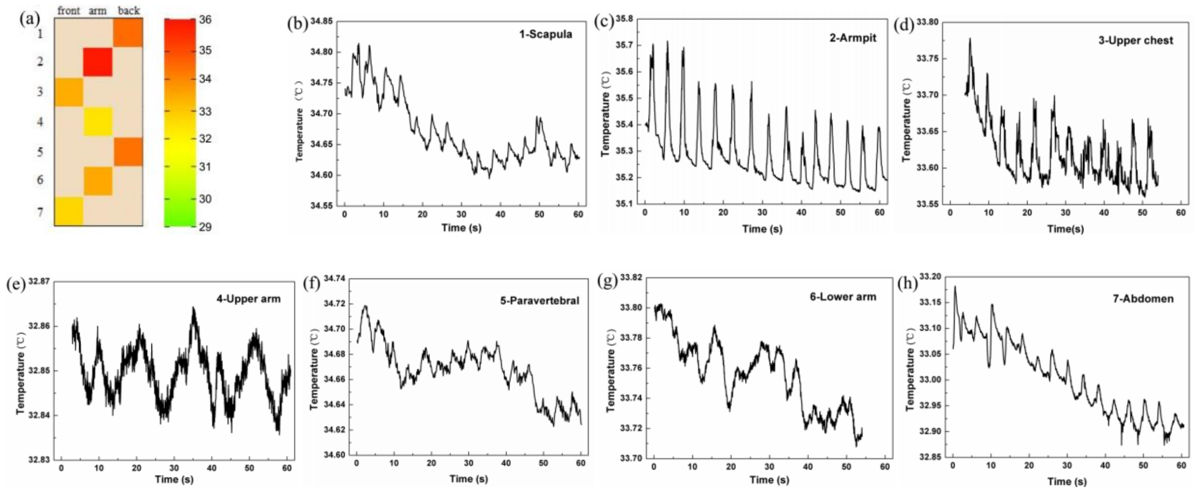

Figure 6. (a)Measured spatial distributions of tempreature and temporal distributions of tempreature during normal respiration at (b) scapula; (c) armpit; (d) upper chest; (e) upper arm; (f) paravertebral; (g) lower arm; (h) abdomen

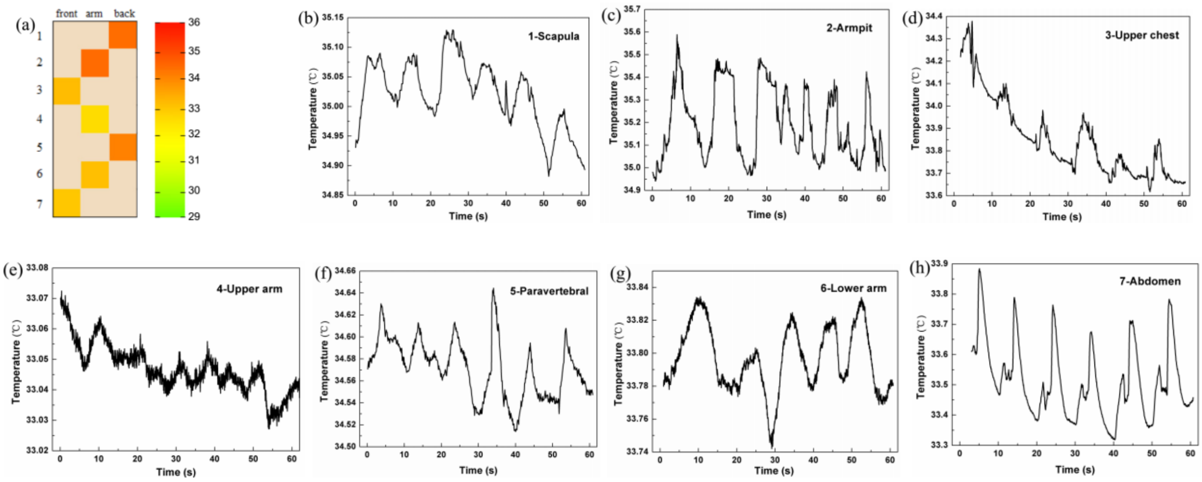

Figure 7. (a)Measured spatial distributions of tempreature and temporal distributions of tempreature during deep breath at (b) scapula; (c) armpit; (d) upper chest; (e) upper arm; (f) paravertebral; (g) lower arm; (h) abdomen

5. Conclusion

In this paper, we have reported the design, fabrication and characterization of largely deformable fabric temperature sensing network made by linking the newly developed textile temperature sensors through novel elastic FCBs. The resultant textile platform assembly exhibits stable temperature-sensitivity ($3.92\times10^{-3}℃^{-1}$), high accuracy (error: ±0.2°C), remarkable resolution (0.05°C), short response time, very low hysteresis in cyclic conditions, electrical stability with an average strain of 40%, as well as extraordinary fatigue life (greater than 10,000 cycles at 30% strain). In combination, the fabric temperature-sensing network provides the best performance for wearable electronic applications when compared with previously reported thin films and conductive polymers. The fabric sensing network with excellent flexibility, high three-dimensional deformability, superior breathability and durability for long-term use, hence, could be attached conformably on a highly curved surface without any physical damage. We have further shown the feasibility of application of the fabric sensing network in smart temperature-sensitive apparel for in-situ measurement during respiration. This precise temperature sensing capability of the fabric sensor array demonstrates its potential to be applied in human–machine interfaces, prosthetics, and wearable skin electronics for monitoring of skin temperature variation during daily activities.

6. Experimental Section

Fabrication of Fabric Temperature Sensor: An effective area with serpentine patterns of the metal fiber was first determined with consideration of the initial resistance and requirements for the circuits. A continuous Pt fiber was woven in an organized floating pattern into the fabric composed of cotton yarns as both transverse and longitudinal elements by using a semi-automatic weaving machine.

Fabrication of Fabric Sensing Network: A circuit diagram was first designed with consideration of discrete temperature sensors and data ports. Silver nano-particles coated polyurethane yarns, as conductive tracks, were incorporated into an elastic woven fabric in a jacquard pattern on a computerized weaving machine to define wiring layouts of the FCB. The temperature sensors were then adhered on the corresponding locations of the woven substrate with their electrodes linked by the conductive tracks. The other ends of the conductive tracks were connected to the outer circuits through bonding selected interposers to the assembly.

Characterization of Fabric Temperature Sensor: Morphological observation of the resultant sample was conducted on a scanning electron microscope. The relative resistance change of the fabric sensor with different temperature was investigated under different conditions. Both temperature controlled oil bath and digital hot plate were used to adjust the temperature ranging from 25°C to 45°C. The resistance of the fabric sensor was recorded and acquired continuously by Agilent 34970A, which was interfaced with a computer. The electrical resistance was monitored when the samples underwent different temperatures in both oil bath and hotplate stage.

Characterization of Fabric Sensing Network: The relative resistance change of the fabric sensing network with applied strain was investigated under unidirectional tensile test performed on an Universal Strength Testing Machine (Model: YG(B)026G-500), where the sample was fixed to the top and bottom clamps with gauge length of 5 cm. The tensile speed was 200 mm/min. The interposers of the fabric sensing network were connected to Agilent 34970A interfaced with a computer. The electrical resistance was monitored when the samples were stretched unidirectionally. For the fatigue test, each cycle corresponded to a strain of 30% and then returned to the original state with a tensile speed of 500 mm/min.

Temperature Detection during Respiration: The smart apparel integrated fabric sensing network was worn on a young and healthy female subject, where the sensors on the selected locations intimately contact the human skin. Before measurement, informed signed consent was obtained from the subject and the temperature of the sensor was calibrated by using a non-contact infrared digital thermometer (Berrcom JXB-182, China). The temperature in different positions of the subject was detected in real time during normal respiration and deep breath, respectively.

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