Simultaneously encapsulation and formation of PDMS-MWCNTs composites for multi-directional microchannel force sensors

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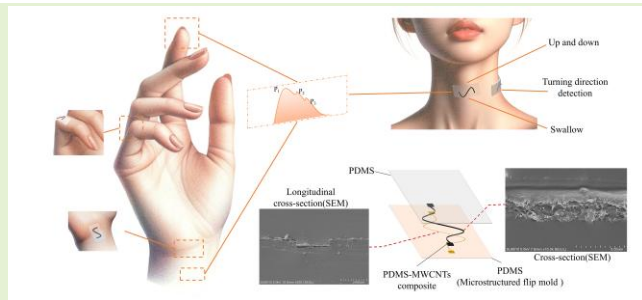

***Abstract*—Microchannel force sensors have good stretching characteristics, and have garnered a lot of interest in the research area of health monitoring and human movement identification. However, there are still existing a number of problems for such microchannel-based force sensors, such as costly and time-consuming manufacturing procedures, layer mechanical mismatches, and poor instability. Here, we propose a flexible microchannel-based PDMS-MWCNTs composite sensor with high sensitivity and directional stretching response. MWCNTs are inserted into microchannels using the self-diffusion approach, and a unique encapsulating process has been demonstrated that combines MWCNTs with PDMS to create a composite that maximizes interlayer mechanical compatibility. When compared to traditional encapsulation techniques, the novel encapsulating approach tenfold boosts the sensors' sensitivity within the same pressure detection range. In the range of 0-100 kPa, the sensitivity is up to 0.0433 kPa^{-1}, detecting pressures as low as 11.9 pa, while the gauge factor is as high as 18.1. The results demonstrate that the proposed microchannel force sensor has significant promise for the future in the field of motion detection, health monitoring, etc.**

***Index Terms*—Microchannel force sensors, Strain sensors, Conductive composites, Motion recognition.**

I. Introduction

Conventional rigid sensors fail to satisfy the demands of contemporary medical and health monitoring since they are large, difficult to bend, poorly portable, and have low wearer comfort. As rehabilitation medicine and intelligent health monitoring technologies advance quickly, there's an increasing demand for flexible and wearable electronic devices [1-3]. Skin attachable sensors have attracted attention for their excellent commensurability and ability to provide various biomechanical information [4-6]. Among them, microchannel sensors are widely used in strain and pressure scenarios due to the superior advantages of the conductivity and deformability, with conductive liquid integrated into microfluidic channel, bringing new functionalities of microchannel [7,8]. Munirathinam designs a flexible microfluidic channel sensor that injects Galinstan liquid metal alloy through the microchannels of a polydimethylsiloxane (PDMS) substrate for wireless power transmission and sensing [9]. Moreover, researchers are now exploring different microchannel structure for analysis, aiming to improve the stability and sensitivity of microchannel sensors in various directions of forces, including bending and pressing, which makes the microchannel sensors highly competent in human motion detection [10-20]. Ryu introduced liquid metal eutectic gallium indium embedded into wavy-shaped microchannel elastomeric matrix to achieve microchannel flexible strain sensor [22], which can restrain the viscoelasticity of elastomer effectively and improve hysteresis performance from 6.79% to 1.02%. And more studies have focused on improving directional response capabilities. Zhang develop a method to pattern the liquid metal onto the soft elastomer via soft lithographic process for fabrication of microfluidic channel sensors, which realized multidirectional detecting [21]. Additionally, a serpentine strain sensor based on multi-walled carbon nanotubes (MWCNTs) on a polydimethylsiloxane (PDMS) substrate was successfully created by X. Fu et al. The sensors responded differently to measurements of longitudinal and transverse strain: resistance increased wave-like under longitudinal strain, but resistance changed linearly under transverse strain [23]. Different channel structures have a dramatic effect on the sensor's detection capability. Nevertheless, fabrication of structurally precise microchannels

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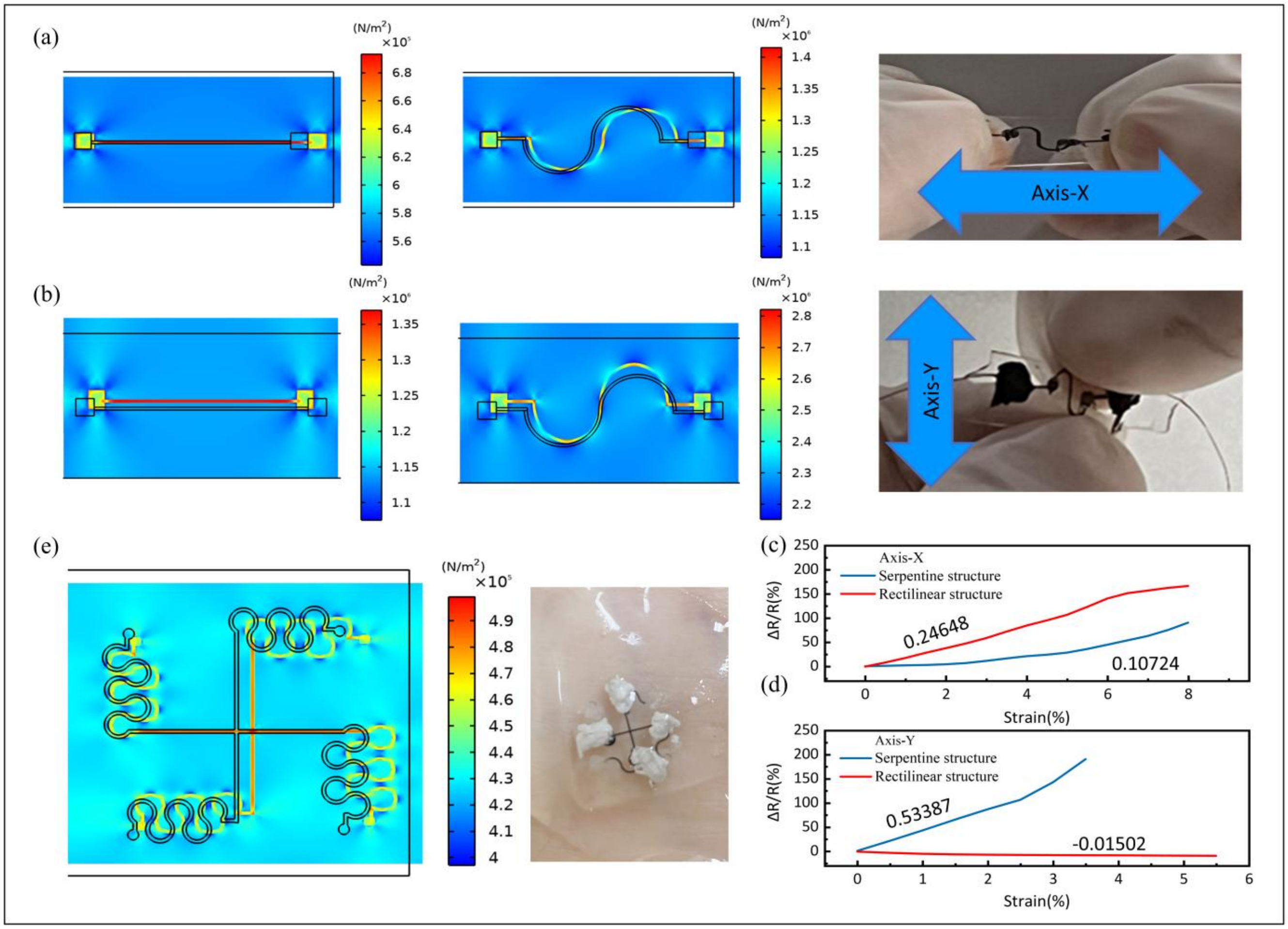

Fig. 1. Mechanical analysis of different shapes of microchannels (a) Mechanical simulation results of rectilinear and serpentine microchannels upon X-direction stretching. (b) Mechanical simulation results of rectilinear and serpentine microchannels upon Y-direction stretching. (c) Experimental results of rectilinear and serpentine microchannels upon stretching in the X-direction. (d) Experimental results of rectilinear and serpentine microchannels upon stretching in the Y-direction. (e) Mechanical simulation results of structurally optimized microchannel arrays upon stretching in the X direction and sensors fabricated by the structure.

and injection of conductive liquids into them leads to complexity of the microchannel fabrication process and instability of performance, which have limited its use [24-29]. Therefore, fabricating a microchannel sensor with simple fabrication, low cost, and stable performance is an urgent challenge.

Diffusing the conductive liquid in open channels rather than injecting it into pipelines can be an effective way addressing the above issues. Liu mimicked the water transport mechanism of Hogweed [30], such plant has a multiscale laminar structure in the orifice region that allows it to transport water and nutrients without the aid of external energy. In this way he delivered multi-walled carbon nanotube (MWCNTs) dispersion into the microchannel, which is a simple and low-cost way to transport conductive liquids in comparison. But there are still problems with the fabrication procedure. It does not solve the problem of mechanical mismatch between the different materials and layers after open channel encapsulation. Air still exists within the microchannel after encapsulation, and the poor layer-to-layer bonding leads to splitting of the material within the channel when it deforms asynchronously with the substrate, so that the layers can easily delaminate or separate from each other under complex mechanical deformation conditions, which greatly affect the performance of the sensor.

Here we self-diffused conductive dispersions in microchannels and proposed a novel encapsulation method to simply fabricate microchannel PDMS-MWCNTs composite sensors. Self-diffusion process transported MWCNTs to the channel by imitating Hogweed self-diffusion theory and the MWCNTs layer is attached to the bottom of the channel after diffusion. However, such layer of MWCNTs is not evenly distributed in channels with depths ranging from several micrometers to tens of micrometers. Especially using the conventional encapsulation method, which results in poor consistency and stability for sensing forces in various directions. The novel encapsulation thoroughly combines the internal MWCNTs in the channel with the PDMS flexible substrate, increasing the sensitivity of the microchannel sensor while improving its stretching response. Through surface morphology analysis and experimentation, the encapsulation method allows MWCNTs to form a stable PDMS-MWCNTs

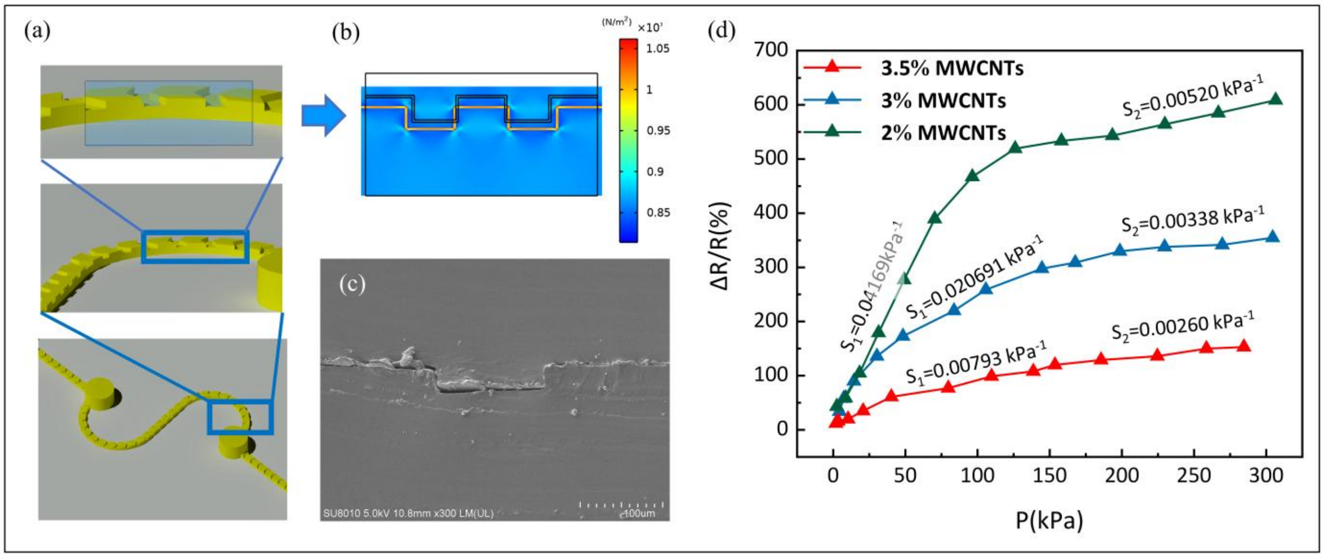

Fig. 2. Mechanical analysis of piezoresistive characteristics of sensors (a) Schematic diagram of microchannel lateral cross-section. (b) Mechanical simulation results of sensor microchannel lateral cross-section under pressure. (c) SEM (Scanning Electron Microscope) image of the microchannel lateral cross-section section. (d) Comparation of piezoresistive performance of sensors with 2, 3, 3.5wt% MWCNTs, hexane for encapsulation.

composite in a self-diffusion channel, greatly eliminating micro vacancies in the channel and bonding it tightly to the substrate, which utmost eliminating mechanical mismatches. The simplification and low cost of the fabrication method is also suitable for mass production of the proposed sensors. Compared to typical encapsulation methods, microchannel PDMS-MWCNTs composite sensors are 10 times more sensitive over the same pressure detection range (0-100 kPa), and the sensitivity was up to 0.0433 kPa^{-1}, while the gauge factor was as high as 18.1, detecting pressures as low as 11.9 pa. Exhibiting a recovery time of 6ms and a response time as low as 5ms. Furthermore, theoretical analysis and experimental tests show that the microchannel PDMS-MWCNTs composite sensors has great sensitivity and multi-directional response of stretching through simple geometric arrangement, we apply them to the hand joints, wrist and neck surfaces, they can accurately recognize various hand gestures and neck movement directions, and have great potential for human motion detection.

II. Principle and Fabrication

A. Design of the shape of microchannel

The performance of the microchannel sensor is largely determined by its channel structure design, particularly when responding to tensile strain. We designed and fabricated substrates with different channel shapes to test mechanical response, starting with the two most basic geometric units. Firstly, linear channels exhibited directional responses to lateral strains, and we tested strain response practically and mechanical simulations for this unusual phenomenon. When linear channel faced to lateral strains in Y-direction, the result of simulation shows that substrate tended to contract in X-direction and simultaneously squeeze the channel due to the mechanical properties of the soft silicone rubber material. As microchannels had a significantly high aspect ratio, linear channels exhibited more deformation when being stretched and showing directional sensitivity to strain forces (Fig. 1a, b). The phenomena are further explained by the experimental results, which match with the simulations results (Fig. 1c, d). However, for the linear shape microchannel PDMS-MWCNTs composite sensors, it's direction of location had a direct impact on the experimental results, affecting the stability of detecting strains in a specific direction. In contrast, serpentine channels, with their symmetric curved structure, exhibited significant counteract effects in deformation when subjected to strains in two directions (Fig. 1a, b), ensuring consistence and stability in response to strains, also consistent with experimental results (Fig. 1c, d). Conclusively, the performance of linear channels is limited by the placement location, although they have high sensitivity to strain response in a specific direction. For overcoming such limitation, a sensing array was designed in the experiments to combine multiple linear channels to compensate for the lack of spatial coverage and directional response of a single channel. Meanwhile, serpentine structure was used as a conductive channel connecting the microfluidic sensing arrays, in terms of its extensibility. By mechanical simulation of the optimized structure, the results verified the specific response of the two linear channels to different directional strains, and the serpentine structure has a small deformation under stretching (Fig. 1e), the optimized microfluidic sensor was suitable for testing the wrist twisting.

Inspired by the unique phenomenon of directional liquid transport at the peristome region of Hogweed, we imitated the microstructure of the peristome region to control the diffusion of different concentrations of multi-walled carbon nanotube ethanol solutions in microchannel. We attempted microchannels with various microstructural features according to self-diffusion theory (Supplementary Fig.8). Based on the experiment results, we constructed double-layered arrow-shaped structures within the width of 60 μm channels (Supplementary Fig.9) to transport liquids by capillary forces in the direction of the arrow. (Fig. 2a). Compared to other

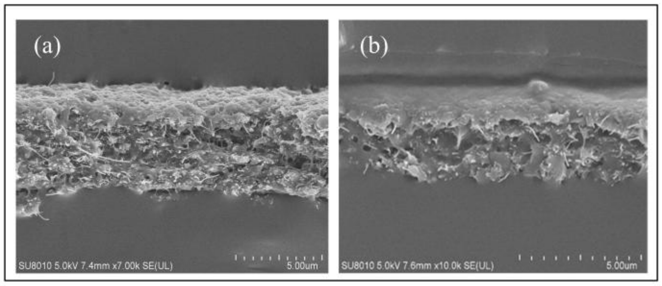

Fig. 3. Surface morphology of sensors cross section (a) SEM image of surface on the microchannel cross-section (without hexane). b SEM image of surface on the microchannel cross-section (with hexane).

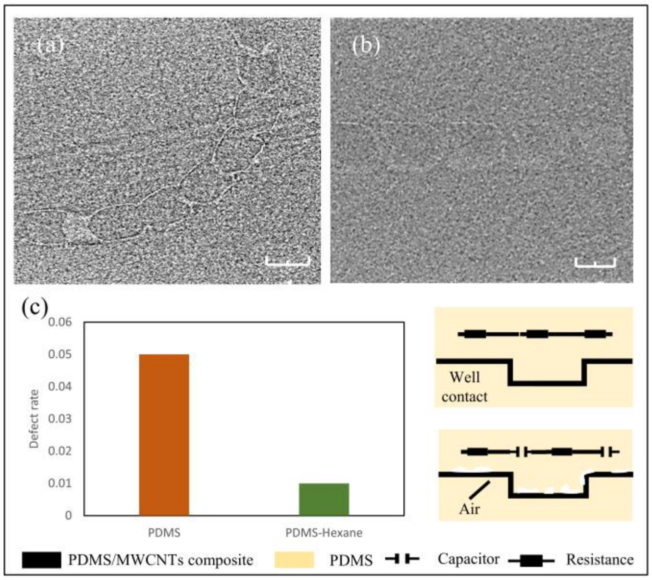

Fig. 4. Microchannel morphology and defect rate (a) CT (Computed tomography) image of microchannel (without hexane). (b) CT image of microchannel (with hexane). (c) Schematic diagram of the conductive mechanism and defect rate of different encapsulation methods.

flexible microchannel sensors fabricated using multi-walled carbon nanotubes, microchannel PDMS-MWCNTs composite sensors exhibits an increasing resistance response when faced to pressure. Mechanical simulations were taken to illustrated the piezoresistive character of microchannel sensors. When no pre-pressure is applied to the sensor, the lateral cross-section of channel exhibits a standard stepped shape (Fig. 2c). When pressure loaded to the sensor's surface, the simulation result of the inside deformation of the lateral cross-section indicates that the stepped microstructure deforms in two directions: the region in the vertical direction where force loaded is compressed, while the region around the loaded area is stretched due to squeeze coming from the pressure point (Fig. 2b). With both types of deformation occurring simultaneously, we performed mechanical simulations and combined them with practical test to verify which deformation dominated the response to pressure. Simulation results indicated that stretching deformation had a greater influence when loaded, and the thickness of the carbon nanotube layer on the surface of the channel was below 4 μm (Supplementary Fig.1(b)), the influence of compressive deformation when loaded was negligible by comparison. Thus, when subjected to pressure, microchannel PDMS-MWCNTs composite sensors exhibited an increase in resistance. We also took three mass fractions of

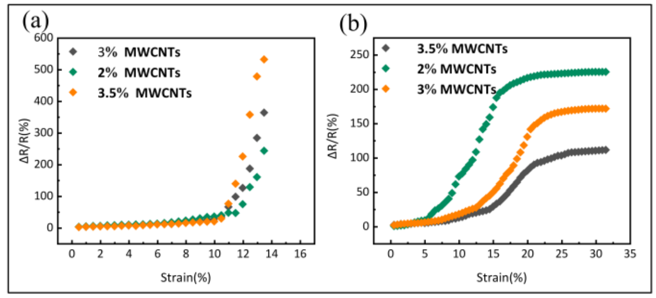

Fig. 5. Gauge factor of sensors with different encapsulation method and MWCNTs concentration (a) Comparation of strain performance of sensors with 2, 3, 3.5wt% MWCNTs, no hexane for fabrication. (b) Comparation of strain performance with 2, 3, 3.5wt% MWCNTs, hexane for fabrication.

MWCNTs dispersion to fabricate the microchannel sensors, and tested the piezoresistive response. According to the results, the sensors' piezoresistive response is constant throughout a range of MWCNTs concentrations, with sensitivity increasing with decreasing concentration (Fig. 2d).

B. Design of microchannel PDMS-MWCNTs composite sensor

To improve the stretching stability and sensitivity of the microchannel sensor, we proposed a totally new encapsulation method. After self-diffusion, the ethanol in the dispersion solution rapidly evaporated at room temperature and leaving an extremely thin layer of carbon nanotubes on the microchannel surface. Although the thickness of the layer is below 4μm, microscale and nanoscale vacancies formed within the layer during ethanol evaporation (Supplementary Fig.1(a)). We performed a CT (Computed tomography) scan image of the whole sensor for obtaining the defect rate due to the two encapsulation methods (Fig. 4c). The precise defect rates of both sensors were analyzed using the same size of sensor and the results are shown in Supplementary Fig.6. And compared the microchannel sensors inner surface with different encapsulation, method of using PDMS for encapsulation created many defects and vacancies in the microchannels, whereas the PDMS-Hexane encapsulated sensor almost eliminated the vacancies in the channels (Fig. 4a, b). Spin-coating PDMS directly on the surface of the unencapsulated microchannels cannot eliminate these vacancies, even if the minimum 10:1 ratio of A and B in PDMS. Moreover, after spin-coating a mixture of PDMS and Hexane and then waiting for curing, the Hexane in the PDMS evaporates and the MWCNTs in the channel combines strongly with the PDMS and adheres to the substrate. To prove such theory, we also obtained electron microscope images of the cross-section of sensors encapsulated with both methods (Fig. 3a-b). The figures show that PDMS mixed with Hexane can enter and combine with MWCNTs layer, whereas another encapsulation method cannot enter the channel completely. When subjected to stresses, the mechanical mismatch with the irregularly distributed bubbles inside can result in a significant decrease in device uniformity because the MWCNTs layer at the bottom of the channel is not firmly bound to the PDMS in the upper and bottom layers. Furthermore, as the carbon nanotube layer attached on the surface has no stretching properties, if it's not tightly integrated with the PDMS, which

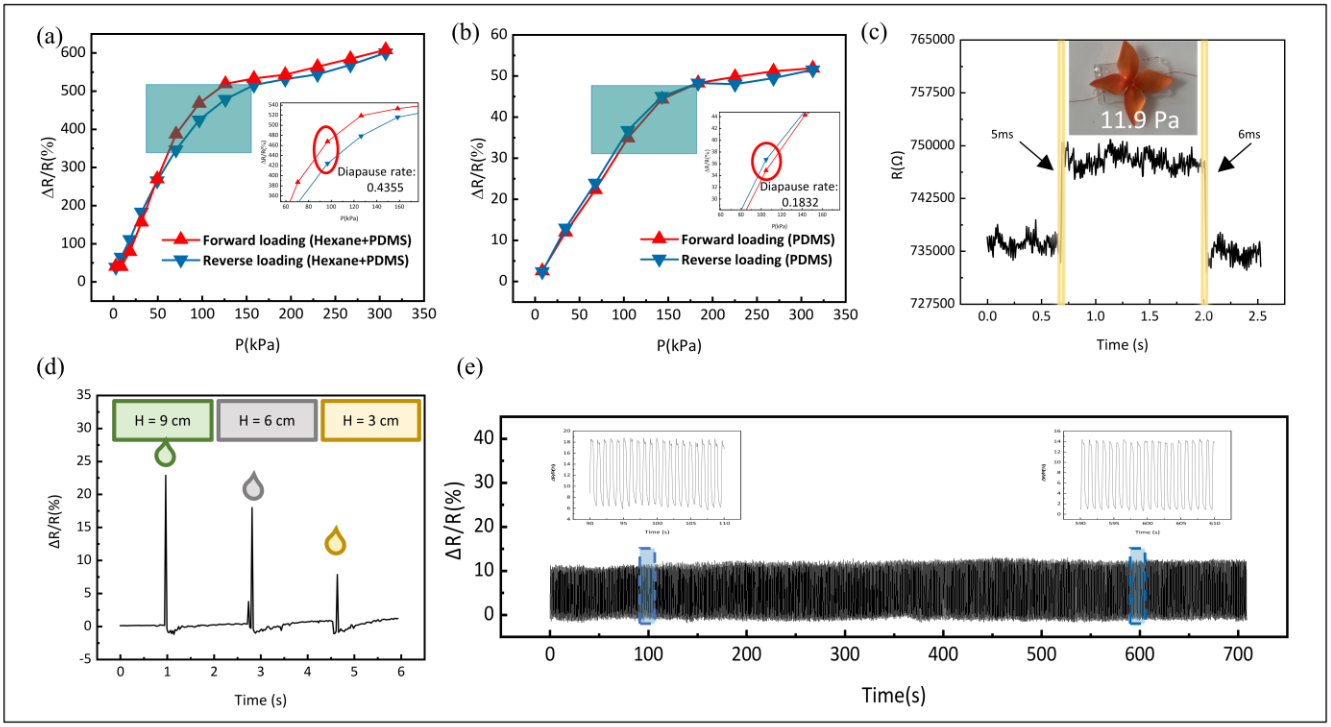

Fig. 6. Mechanical performance of sensors (a) Sensitivity and hysteresis rate of sensors using hexane, 2% MWCNTs. (b) Sensitivity and hysteresis rate of sensors without using hexane, 2% MWCNTs. (c) Minimum limit and the response and recovery time. (d) Experimental results of falling water drops from different heights. (e) Long-term loading/unloading cycle experimental results.

has difficulties to follow the deformation of the flexible substrate after the channel is stretched. And even appearing cracks in nanotube layers during stretching, means that the deformation of substrate and MWCNTs layer to be asynchronous, which reduces the stability of the sensor (Supplementary Fig.10). However, adding Hexane to PDMS, which can significantly reduce the viscosity of PDMS, allowing it to enter into the carbon nanotube layer during the spin-coating process and fill the vacancies of the layer. To further demonstrate the effect on performance of the above microscopic phenomena, we took three mass fractions of MWCNTs dispersion and two encapsulation methods to fabricate the sensors, and tested the strain response. In the strain response test, the addition of Hexane to the package makes the sensor show good stretching characteristics, the gauge factor of the PDMS-Hexane sensor was 18.1 (strain range of 5%-15%, Fig. 5b), while the PDMS-only packaged sensor shows a jump in resistance under a very small deformation, which also proves that cracks appear in the MWCNTs layer during the stretching process and affect the stretching response (Fig. 5a).

C. Fabrication of Microchannel Molds

We designed a three-dimensional model of the template using AutoCAD. The width of the channel was set to 60 μm and the depth was set to 50-80 μm. Arrow-shaped protrusions and indentations were connected to form the channel (depth difference of 30 μm), and the length of each arrow in the channel was 100 μm. The serpentine structure consists of a circle with a radius of 3.2 mm intercepting two semicircles and joining them together, with a linear channel of 5 mm at each end. A 2 × 2 mm square groove was set at the end of the channel for fluid storage and connection of wires (Supplementary Fig.4). The model data were downloaded to a 3D printer (P150, BMF, China) and a high-precision rigid template was fabricated using light-curing resin (Yellow-30 UR, BMF, China). The printed molds were soaked in anhydrous ethanol for 5 minutes to remove uncured resin from the surface. The molds were then ultrasonically cleaned in isopropanol for 15 minutes and washed with deionized water to remove any remaining reagents. Finally, the mold surface was blown dry with nitrogen and coated with a hydrophobic agent (propane).

D. Fabrication of Microchannel PDMS-MWCNTs Composite Sensor

PDMS (DC184, SYLGARD, China) substrates were prepared in a 10:1 ratio, degassed under vacuum and poured onto the surface of the mold. It was then cured at 80°C for 2 hours. After the PDMS was fully cured, the film was removed and processed with oxygen plasma for 5 min. Using a micropipette, 3μL of MWCNTs-dispersed ethanol (2wt%, XFNANO, China) was dropped onto the groove on one side of the channel to allow the ink to self-diffuse within the channel. A 0.1 mm enameled wire was used as the external wire of the sensor, and a conductive silver paste was used to connect the grooves on the surface of the film to the wire. The sensor was then placed at 80°C for 0.5 hours until the silver paste was fully cured to ensure a tight connection between the wire and the substrate. PDMS and hexane (97%, Aladdin, China) were mixed in a 1:1 weight ratio and the mixture were poured onto the surface of the film to cover the surface microchannels and electrode. After settling for 15 minutes, the assembly was placed at 80°C for 45 minutes, and finally, PDMS prepared at

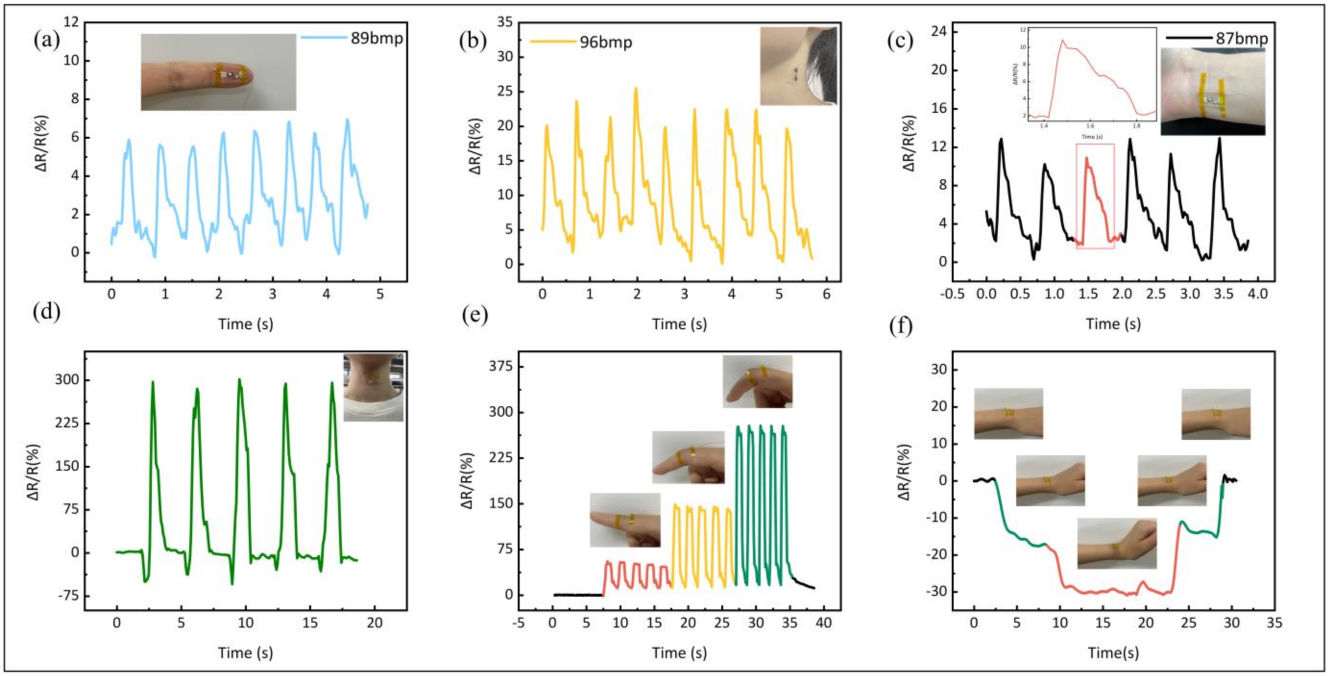

Fig. 7. Physiological signal recognition (a) Finger pulse. (b) Carotid pulse. (c) Wrist pulse. (d) Detection of swallowing. (e) Detection of finger bending angles on the knuckle. (f) Detection of wrist bending.

a ratio of 10:1 was spin-coated onto the sensor surface and exposed for 2 hours at 80°C. This step was repeated twice to complete the encapsulation of the sensor (Supplementary Fig.2).

E. Experimental Platform

The pull-compression force meters are set at a suitable height and the sensors are placed underneath or beside them. A three-axis micro motorized stage was used to set step displacements up to a maximum displacement value of 25 mm and a maximum velocity of not more than 2.5 mm/s. The force range of the pull-compression force gauge was -10 to 10 N, and the flat square pressure probe with an area of 2 x 4 mm was used as the interface. The probe applies a pressure of 0-1250 kPa to the sensor, and a Keysight 34460A digital multimeter is used to record changes in sensor resistance. A two-wire measurement method was used for better real-time performance, with a maximum reading speed of 300 S/s. LabVIEW software was set up to change the position of the pull-compression force meters in order to set the pressure and record the change in sensor resistance.

With the STM32 (STM32F103, STMicroelectronics, Italy) and an AD (Analog to Digital) converter module (AD7606, CREDIT, China), multiple sensor signals can be acquired simultaneously, with a maximum sampling rate of 1000 Hz per channel. the sensor is connected with a reference resistor and is supplied with a voltage of 5V. After the voltage division calculation, the resistance change of the sensor is obtained. The sensors were applied to the skin surface of the participant, and the participant's forearms and body were kept at rest to minimize environmental disturbances.

A 3 x 3 x 2 cm^3 plastic box full with water has the sensor attached to the bottom. To test the response of the water droplets falling at different heights, a 0.2 ml pipette is used to drop a quantifiable amount of liquid from different heights.

III. Results and Discussion

A. Performance

We emphatically compared the sensitivity and hysteresis of microchannel sensors fabricated with 2wt% MWCNTs using PDMS and PDMS-Hexane encapsulation technologies. The results show that for sensors with different encapsulation methods, although they have similar range of pressure detection and pressure thresholds in the saturation area, their sensitivities differ significantly. Compared to PDMS, PDMS-hexane has more than ten times of sensitivity for the same detection pressure range (Fig. 6a-b). The sensitivity of the PDMS-hexane sensor reached 0.0433 kPa-1 in the range of 0-100 kPa, confirming the sensor's ability to detect subtle signals and can detect pressures as low as 11.9 Pa. We also used petals to apply a small amount of tension in order to measure the sensor's response time. The results demonstrated the sensor's capacity to respond quickly to tiny signals, with a reaction time of 5ms and a recovery time of 6ms (Fig. 6c). Additionally, it may react instantly to water droplets dropping at various heights (Fig. 6d). Additionally, we tested the sensor's stability under repeated pressure loads. After 500 cycles of 5 kPa loading and unloading, the sensor demonstrated good stability (Fig. 6e). We also present a comparison between the performance of similar wearable devices with respect to the piezoresistive and tensile response characteristics of the sensors provided to verify that the encapsulation method enhances the sensor's performance (Supplementary Fig.5).

B. Physiological Signal Detection

Real-time physiological signals are monitored, including strain-based signals from joint motions and pressure-based signals from pulses. To detect pulse wave signals, sensors are

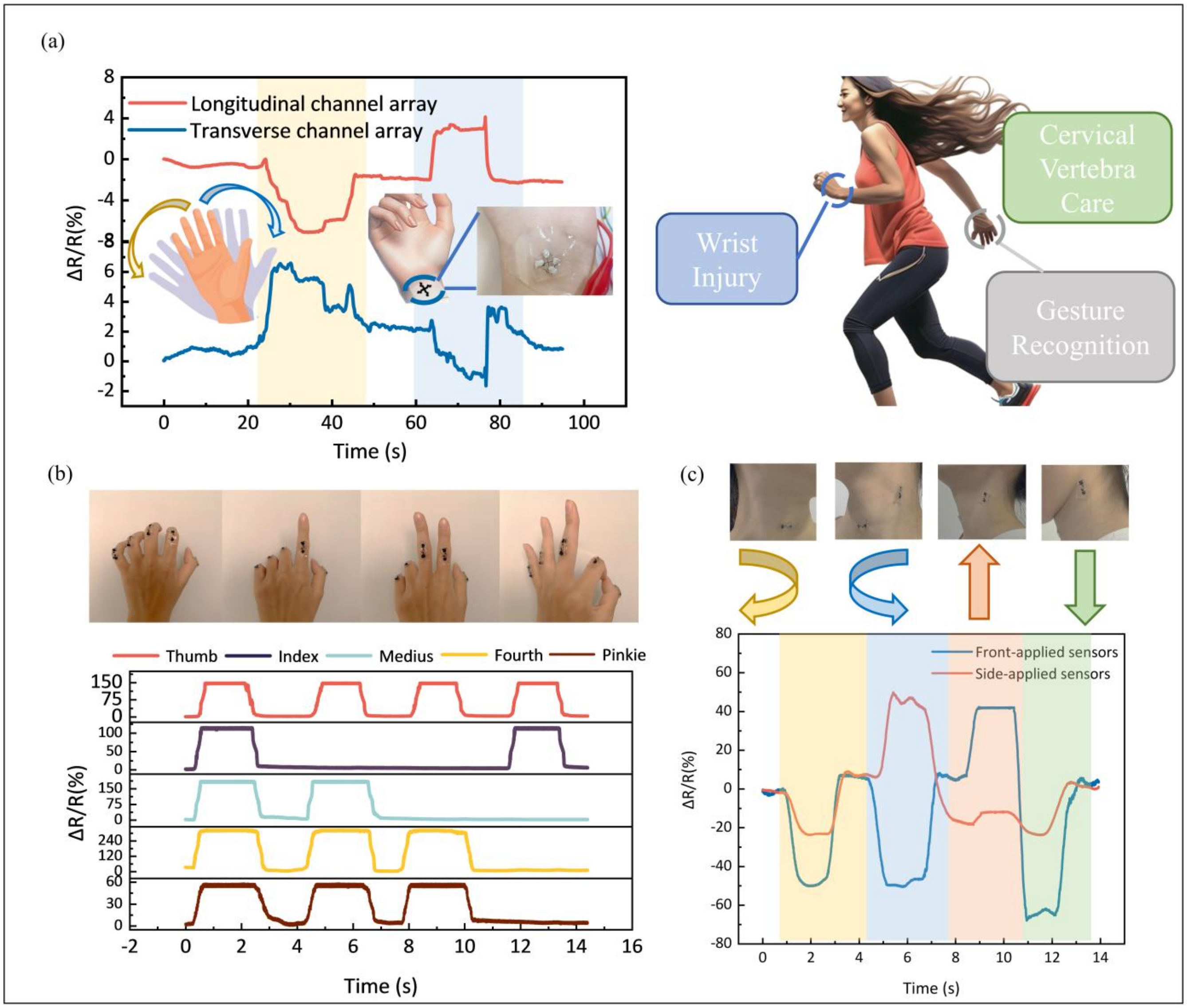

Fig. 8. Human motion recognition (a) Recognition of wrist twist and diagram of the experimental procedure. (b) Recognition of hand gesture. (c) Recognition of neck movement gesture.

placed to the skin surface of the wrists, fingertips and neck. By analyzing the data gathered, it is possible to clearly view the three stages of pulse waves in various body parts (Fig. 7a, b, c). Furthermore, the start and finish of the swallowing movement can be also identified when the sensor is positioned on the front of the neck (Fig. 7d). Unlike the finger joints (Fig. 7e), which have a restricted range of motion (90°), the wrist joint movements are more complex, include twisting from side to side and rotating up and down. Therefore, wrist motion cannot be accurately recognized by sensors detecting stretch forces alone. Microchannel sensors can be used to detect simple twisting and rotating motions, as shown by Fig. 7f, which shows how to use the sensor to monitor compressive forces when the wrist is elevated.

C. Motion Recognition

In daily life, gesture recognition plays an essential role as a crucial component of nonverbal communication. Recognition of gestures including detection of fingers with wrist movements, by applying the sensor to the surface of the wrist and finger joints. Initially, the wrist was twisted horizontally to make a 'goodbye' gesture, and the left-middle region of the wrist was chosen as the location to place the microchannel sensor. The sensor after optimizing with two crossed linear channel sensing arrays can detect the direction of wrist twisting. Based on the experimental results, it is concluded that the responses of the two linear sensors in the horizontal and vertical positions are opposite during a single wrist twist, which is consistent with the actual movement (Fig. 8a). Additionally, five serpentine microchannel sensors are attached to the joints of five fingers, and different hand gestures are represented by the degree of finger bending. The results, as shown in Fig. 8b, indicate that the sensors can accurately recognize various hand gestures.

In the field of cervical rehabilitation medicine, accurate cervical position diagnosis is crucial. When the serpentine microchannel sensors are attached to the front and side of the neck, as shown in Fig. 8c, they are used to detect four movements: turning the head left or right, and turning the head up or down. The results show that sensors attached to the side of the neck can accurately detect head turning based on their response to stretching and compression, while sensors on the front of the neck can accurately detect motions of up and down. Combining data from these two sensors enables comprehensive monitoring of neck movements.

D. Discussion

Traditional microchannel sensors depend on the good fluidity of piezoresistive liquids in the channel to achieve stretching, but the problems of leakage, poor consistency and cumbersome fabrication process are still not well solved. Microchannel sensors with non-injected fluid either suffer from debonding/delamination of the sensor interlayer or the existence of air vacancies in the channel that cannot be eliminated. We propose a new encapsulation method by combining PDMS with MWCNTs inside the channel to form a composite and minimize mechanical mismatches and achieved strong adhesion between the different layers of the sensor, while significantly improving sensing performance. As expected, close connections with the elimination of air vacancies significantly improved the signal fidelity of the sensor under high pressure and strain conditions. The gauge factor can reach 18.1, and the sensitivity can reach 0.0433 kPa^{-1} in the 0-100 kPa range, detecting pressures as low as 11.9 pa. The sensors show broad potential for real-world applications, such as wearable health monitoring devices, robotic tactile sensors, and human-machine interfaces. However, some challenges may arise during deployment. A primary challenge is the inability to fully decouple pressure and stress effects, which can affect the accuracy of the sensors in complex stress environments.

In the published article by Hassan et al., a Hilbert-designed printed sensor by mimicking fern leaves, has sensing properties in terms of fast response time, enhanced detection range (5–100 ppm), and high directional selectivity [31]. Sharma et al. introduced an all-directional strain-insensitive stretchable e-glove, which has a ripple-like meandering sensing area and interconnections meant to stretch in response to the applied deformation [32]. The above strain sensors using different fractal patterns have shown good orientation selectivity, but the problem of separating pressure and strain has not been solved. To address this issue, the patterned approach described in this paper can also be utilized. Microchannels can be printed on three-dimensional cylindrical surfaces and integrated with planar sensing arrays to enhance multi-directional sensing and force decoupling capabilities.

IV. Conclusion

To sum up, this work suggests a flexible strain sensor with outstanding performance, a straightforward and affordable procedure, and the ability to distinguish between various directional strains. Mechanical analysis was done on the microchannel sensors' conductive mechanism and how they responded to pressure. Additionally, the design of the microchannel structure was optimized using mechanical simulation of various shapes of microchannels to increase the viability of the sensor in application scenarios. Lastly, a new encapsulation method is proposed that makes use of multi-walled carbon nanotubes (MWCNTs) and polydimethylsiloxane (PDMS) to create composites in microchannels. Through experimentation and surface morphology analysis, this approach bonds the MWCNTs to the substrate tightly and removes the mechanical mismatch between the layers to the greatest extent possible. The sensor's exceptional durability and biocompatibility allow it to be used safely and reliably for the monitoring of physiological signals both within and outside the body. Consequently, it may result in fresh advancements and uses in the field of health and medical monitoring.

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