Homogeneously and Gradient-Coated Conductive Smart Threads for Multidimensional Flexible Pressure-Sensing Devices

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Dear Sir/Madam,

We would like to submit our manuscript entitled “Homogeneously and Gradient-Coated Conductive Smart Threads for Multidimensional Flexible Pressure-Sensing Devices” with four figures and supporting information for publication in Advanced Functional Materials. In this paper, we prepare double-twisted smart threads (DTSTs), which comprise one gradient-coated and one homogeneously coated conductive thread and investigate their potential for application as flexible 1D, 2D, and 3D pressure-sensing devices.

We begin by reviewing the pressure-sensitive mechanism of conductive threads coated with single-walled carbon nanotubes (SWCNT) via macroscopic and microscopic aspects. We determine that homogeneously coated threads can be used to detect the intensity of the load applied while threads coated with a graded thickness can be used to detect the location of the load. By twisting the two threads together to produce a DTST, we achieve multidimensional, flexible pressure-sensing devices with high sensitivity (up to 1.56 %kpa), tunable resolution, efficient cycling resilience (>104 cycles), and a rapid response time to an applied load (2.5 Hz at least). In addition, the smart threads we built are simpler in structure and cheaper to produce than existing devices. Therefore, they have the potential to be developed for application as electronic skins.

We believe that this work fits within the scope of Advanced Functional Materials and that it will be of interest to your readership.

Thank you for your consideration, and we look forward to hearing from you soon.

Yours sincerely,

Gilles Lubineau
PI of COHMAS Lab. in KAUST
Fiber-based, flexible pressure-sensing systems have attracted more attention recently due to their promising application as electronic skins. Here, we report a new kind of flexible pressure-sensing device based on a polydimethylsiloxane membrane instrumented with double-twisted smart threads (DTSTs). Our DTSTs are made of two conductive threads obtained by coating cotton threads with carbon nanotubes. One thread is coated with a homogeneous thickness of single-walled carbon nanotubes (SWCNTs) to detect the intensity of an applied load and the other is coated with a graded thickness of SWCNTs to identify the position of the load along the thread. We systematically analyze the mechanism and capacity of DTSTs to accurately sense an applied load. Results demonstrate that the fabricated 1D, 2D, and 3D sensing devices can be used to predict both the intensity and the position of an applied load. Our sensors feature high sensitivity (between 0.1 % kPa ~ 1.56 % kPa) and tunable resolution, good cycling resilience (>10⁴ cycles), and a short response time (minimum 2.5 Hz). The strategy we present here is a viable alternative for the design of simple, low-cost pressure sensors.
Homogeneously and Gradient-Coated Conductive Smart Threads for Multidimensional Flexible Pressure-Sensing Devices

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1. Introduction

Flexible pressure-sensing systems, such as electronic skins (E-skins), have attracted
significant attention in recent years due to their promising applications to robotics and
medicine. [1-3] To date, sensing mechanisms have been based primarily on changes in
functional materials, such as metal, carbon, and semiconductor conductive membranes, [14-17]
spheres. [22]

Most of these technologies create E-skins with pixelated sensing arrays that can achieve
relatively high resolutions. [23] Each pixel is a small unit for sensing external stimuli, such as
pressure, temperature, humidity, and the presence of gases. [24, 25] However, these multiple-
pixel arrays require complicated electrode wirings, heavy recording and analysis of the raw
data, and complexities associated with applying the sensing voltage. Subsequently, these
arrays have a high cost, low yield, and large size and weight components; [26-28] thus, for their
practical application as E-skins, new sensing technology needs to be considered.

Fabric electronics based on a variety of functional fibers are very popular for their
application to the rapidly growing demand for portable and wearable consumer electronics. [29, 30]
Their excellent flexibility, high sustainability, light weight, and comfort have favored their
use in flexible circuits, [31] textile-like batteries or supercapacitors, [32] fiber-based solar cells
or nanogenerators, [33] woven organic light-emitting diodes, [34] and strain sensors. [35]
Although E-skins have also been successfully fabricated by crossing conductive fibers or tracks, their resolution is dependent on the density of the conductors in two directions (X-Y).

We were therefore challenged to produce a flexible pressure-sensing device that addresses current limitations to expand the suitability of their application. Here, we design a technique for creating multidimensional double-twisted smart threads (DTSTs) and demonstrate their superior performance compared to existing pressure-sensing devices.

First, conductive threads coated with a homogeneous thickness of single-walled carbon nanotubes (SWCNTs) or graded thicknesses of SWCNTs were prepared by a multiple dip-dry method (HTTs and GTTs, respectively). Threads were then double-twisted into the final smart threads to create DTSTs. The sensing mechanism and capacity of individual homogeneously and gradient-coated conductive threads are revealed in detail; the fabrication process for producing DTSTs is shown in Figure 1a and 1b.

Second, we investigated the feasibility of using these DTSTs as pressure-sensing devices by systematically comparing calculated and measured values of load intensity and location. To enhance their performance stability, DTSTs were embedded into a protective layer of ultrathin polydimethylsiloxane (PDMS) (total thickness = 400 µm). Results show that this kind of one-dimensional (1D) pressure-sensing device with four terminals can detect the intensity and location of an applied mechanical load with high sensitivity, excellent dynamic fatigue properties, and a short response time.

Third, to be fully applicable as E-skins, pressure-sensing devices should be able to sense an applied load in multiple dimensions. Therefore, we assembled these DTSTs into two- and three-dimensional (2D and 3D) flexible-sensing devices and evaluated their performance at different resolutions. Results indicate that these 2D and 3D devices have the potential to replace existing pressure-sensing devices, which comprise multiple-pixelated sensing units and terminal cables.
Finally, these DTSTs have a simpler structure, are cheaper to produce than existing devices, and are fully compatible with the industrial-scale manufacture of portable and wearable devices.

**Figure 1.** Fabrication of DTST. a) A schematic diagram illustrating the fabricating process of DTST and b) digital images of a HTT, a GTT, and a DTST. c) SEM images of graded-thickness SWCNT coatings on GTT at P3, P6, and P9. SEM images of d) a high-magnification image of the SWCNT coating and a lower magnification image of e) the homogeneous SWCNT coating on HTT before and after coating with PVA.
Figure 2. Characterization of conductive threads. a) Variation in resistance of conductive threads from HTT-1 to HTT-10; b) The piezoresistive effect in HTT-3, HTT-6, and HTT-9 conductive threads; SEM images of HTT-3 (unloaded/loaded) with c) corresponding cross-sectional images with finite element analysis and d) conductive networks of SWCNT on threads (dotted red lines). The scale bars are 20 µm and 1 µm for c) and d), respectively; e) LED blinking with the conductive thread as the switch. The thread fiber was prepared in SWCNT ink (12.5 mg/ml) only for the LED demonstration and a 1.23 kohm/2 cm was applied after drying.)
2. Results and discussion

2.1 Preparation, characterization, and the sensing mechanism of conductive threads

Preparation and characterization of conductive threads

SEM images detailing the morphology of the SWCNT coating at three selected positions (P3, P6, and P9) along GTTs are presented in Figure 1c. Although the thickness of the SWCNT coating on the threads increases, as might be expected with increasing dip-dry repetitions, the increase in thickness appears in variable increments: from 90-110 nm to 220-280 nm to 400-550 nm for P3, P6, and P9, respectively, as shown in Figure S5. In addition, as coating thickness on the threads increases, the space between the threads decreases (see Figure 1c). Similarly, SEM images in Figure 1d, illustrate the morphology of the homogenously distributed SWCNTs at a high magnification. Figure 1e illustrates that the surface of HTTs is much smoother after dipping in the PVA solution, confirming the existence of this insulating polymer coating.

Resistance of conductive fibers decreases with increasing dip-dry repetitions: from HTT-1 to HTT-10 the resistance decreases from 1.06 Mohm to 161 kohm, as seen in Figure 2a. Corresponding dip-dry treatments of HTT and GTT have comparable resistance values. These resistance values are indicative of the resistance gradient at each position along GTTs (from P1 to P10 of 3-mm-long threads).

The piezoresistive behavior of HTTs was further investigated using selected samples (i.e., HTT-3, HTT-6, and HTT-9) at a preload of 0.1 N, as shown in Figure 2b. We observe that all threads have decreasing electrical resistance with increasing mechanical strain. The change in electrical resistance is characterized by two main features. First, the intensity of the piezoresistive response is correlated with the initial electrical resistance of the thread. Specifically, when the strain is at 1.5 %, the variation in resistance (\(\Delta R/R_0 = (R_0 - R_L)/R_0\), where \(R_0\) and \(R_L\) are the resistances without and with applied load, respectively) is 45 % for HTT-3, 26 % for HTT-6, and 13 % for HTT-9. Second, the piezoresistive gauge factor is...
much higher at the beginning of the load and decreases until 0.4%. Both observations directly result from the sensing mechanisms described in the section below.

The sensing mechanism of SWCNT-coated threads

The large gauge factor of the piezoresistive behavior observed in Figure 2b results from two very different mechanisms: 1) a change in macroscopic resistance with densification of fibers, \( \Delta R\text{-desification} \) and 2) a change in macroscopic resistance with the intrinsic piezoresistive behavior of the SWCNT coating, \( \Delta R\text{-coating} \).\[^{36,37}\]

The first mechanism (\( \Delta R\text{-desification} \)) is related to the decrease in distance between fibers with increasing axial strain. Each thread comprises a large number of smaller fibers via spinning technology (Figure 1c). The space between fibers is reduced during stretching, which results in more fiber-to-fiber contacts and increases conductivity. This effect is less visible in threads as coating thickness increases (compare HTT-9 to HTT-6 and HTT-3 in Figure 2b); space between the threads is most evident with thinner coatings, such as for HTT-3. Figure 2c illustrates this change in morphology, indicating that stacking density has a strong dependency on strain; however, this mechanism becomes rapidly saturated with less of an affect above a macroscopic strain of 0.4%. The second mechanism (\( \Delta R\text{-coating} \)) is related to the piezoresistive effect of the conductive coating on thread fibers. According to previous reports, thread fibers normally present 6–8 % strain under stress before failure.\[^{38,39}\] This strain will cause the SWCNT conductive network on the surface of thread fibers to generate a piezoresistive effect, which can be confirmed via micromorphological variation in the SWCNTs on them, as shown in Figure 2d.\[^{40,41}\] Note that the SWCNTs used here were modified with a 2-4 nm coating of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT/PSS).\[^{42,43}\] Although PEDOT/PSS itself presents some intrinsic piezoresistive
behavior, previous work has verified that the majority of the piezoresistivity results from the change in distance between nanoparticles that takes place under a mechanical strain.\textsuperscript{[44]}

Moreover, these findings were further exhibited through a closed circuit (voltage = 3 V) containing a light-emitting diode (LED) and a conductive thread (length = 2 cm, total resistance = 1.23 kohm after drying). By applying a manual pressure to fibers of this thread with a glass slide, the LED light begins to blink (Figure 2e).

\textbf{Figure 3.} Characterization of the 1D flexible pressure-sensing device. a) A schematic illustration and mechanical circuit structure of the experimental setup for characterizing the sensing mechanism and digital image of a typical 1D pressure-sensing device based on DTST with a protective PDMS layer. b) Variation in resistance at different positions along HTTs under 500 Pa, 5 kPa, and 30 kPa applied loads, c) the relationship between variation in
resistance and an applied load on HTT-6, and d) predicted load values on HTTs. e) Variation in resistance at different positions under a 25 kPa applied load, f) the relationship between variation in resistance and load at different positions, and g) predicted position of loads along GTTs.

2.2 Preparation and sensing capacity of 1D flexible pressure-sensing device

A 1D flexible pressure-sensing device was fabricated using a 3-cm-long DTST into pre-cured ultrathin PDMS films (total thickness = 400 µm) as a protective layer, as shown in Figure 3a. We will reveal the “smart” features of DTST in a systematic manner by simultaneously mapping the response of HTTs and GTTs to an applied load. The related experimental setup can be seen in Figure 3a.

Figure 3b illustrates that the response of HTTs is nearly equivalent at all positions along the threads, independent of the intensity of the applied load (500 Pa, 5 kPa, or 30 kPa). This result was expected due to the homogeneous thickness of the SWCNT coating on these threads.

Figure 3c demonstrates that in HTTs, the relationship between an applied load and variation in resistance is nearly proportional at any one point (we used HTT-6 as an example). Specifically, variation in resistance occurs up to 3.9 % with a 2.5 kPa applied load, indicating that HTTs have a high sensitivity to pressure (up to 1.53 % kPa). Between 20 kPa and 50 kPa, sensitivity decreases to 0.1 % kPa, indicating that variation in stacking density and SWCNT alignment is reduced. This phenomenon is consistent with the large gauge factor of piezoresistive behavior shown in Figure 2b. Based on this curve, which we created from experimental results (defined as database-1), HTT has the capacity to estimate the value of an unknown applied load but not its location.

Next, we tested the efficiency of database-1 by comparing the real value of the load and the calculated value of the load, Figure 3d shows that these values are nearly identical between 0
kPa and 50 kPa. Therefore, HTT can be used to accurately measure the intensity of the applied force.

Figure 3e presents that under the same applied load (25 kPa), a gradient of variation in resistance occurs from 7.82 % (P1, the least conductive location) to 0.59 % (P10, the most conductive location). This confirms that this relationship discussed earlier with regard to individual HTTs with different thicknesses of SWCNT coatings (Figure 2b) also exists in threads with a graded SWCNT coating at relatively similar sizes.

Next, we built the complete database (database-2) from responses at each location (P1 to P10) to an increasing load. This database will be used later to reconstruct the exact position of the point of application of the load by direct comparison of the measurements to the recorded values. Figure 3f summarizes the results for an applied load ranging from 0 kPa to 50 kPa. All positions along the threads presented stable, gradual pressure and variation in resistance behavior. Figure 3g shows that the real position of the applied load along the thread can be discriminated accurately and effectively from P1 to P10 for a known applied load by reading its variation in resistance.

Therefore, DTST has the potential to integrate features from both GTTs and HTTs to become “smart” threads. The intensity and position of the load can be estimated easily and precisely: the intensity of the load can be recovered based on the variations in resistance by HTTs and once the intensity has been recovered, the location can be determined based on variations in resistance by GTTs.

The databases formulated here, detailing the sensing properties of HTTs and GTTs, were central to determining the practical applications of each and ultimately, how each will contribute to produce the overall efficiency of DTSTs as sensing devices.
2.3 Performance of the 1D flexible pressure-sensing device

Flexible pressure-sensing devices are required to be extremely durable. Thus, we tested the durability of our threads by testing their variation in resistance when subjected to a rapidly varying cyclical load (maximum load = 25 kPa, load frequency = 1 Hz). Figure S6a illustrates that throughout the cycling of HTT and GTT, high signal-to-noise ratios were well maintained with no noticeable drift after ten thousand cycles. This results from the excellent physical viscoelasticity of the PDMS membrane and great flexibility of the DTSTs.

Next, we considered the consistency and speed of HTTs to respond to an applied load, as shown in Figure S6b. We compared output resistance signals with the dynamic force inputs at different frequencies to find that the response remained very stable, up to frequencies as high as 2.5 Hz. In conclusion, DTSTs based on 1D pressure-sensing devices demonstrated excellent dynamic mechanical properties and efficient responses to an applied load, indicating that they are suitable for application to E-skin technology.
Figure 4. Multidimensional pressure-sensing devices. Digital images of a) a typical 2D pressure-sensing device (inset image shows its ability to stretch) and b) the device with two applied loads (the yellow arrow indicates the direction from P1 to P10.). c) The recorded variation in resistance with time of HTT and GTT threads in response to an applied load (curves have been shifted in the y direction so they do not overlap) and d) calculated positions of the applied loads. e) 3D map of calculated intensities and positions of applied loads and f) a digital image of a typical 3D pressure-sensing device with an applied load (resolution 3° = 4 mm, 2° and 4° = 3 mm, and 1° and 5° = 2 mm). The inset illustrates the distribution of DTSTs in the 3D device. g) The relationship between the calculated position and the real position of
DTSTs based on a 3D pressure-sensing device (due to the symmetry of the system, only half the length of the DTSTs was considered from position 1 to 5). All the scale bars are 1 cm.

2.4 Multidimensional pressure-sensing devices

To verify the pressure-sensing efficiency of DTSTs, a 2D pressure-sensing film was designed and fabricated by integrating five DTSTs (1#–5#) into two PDMS membranes in parallel. A photographic image of this device is presented in Figure 4a.

When two loads were simultaneously applied to this 2D sensor film (Figure 4b), the appropriate HTTs and GTTs responded to the strain with variable resistance (see Figure 4c). According to variations in resistance by HTTs, database-1 can be used to predict the intensity of applied loads. Specifically, 0 % (1#), 1.02 % (2#), 1.03 % (3#), 8.4 % (4#), and 8.1 % (5#) variations in resistance, corresponded to 0 kPa, 6.2 kPa, 4.5 kPa, 22.1 kPa, and 18.9 kPa load values, respectively. Next, variations in resistance by GTTs and database-2 can be used to calculate the locations of the loads along the threads. Results show that the position of the applied load between DTST 2# and 3# was at P7 and that between DTST 4# and 5# was at P3.

When the load is applied in between two threads (say threads i# and j#), we were able to more accurately define the location of the load in between the threads by using the following equation,

\[ D_{\text{real}} = \frac{P_j - P_i}{P_j + P_i} \times \frac{D_{\text{SUM}}}{2} \]

\(D_{\text{Real}}\) is the distance to the midline between the threads. \(D_{\text{SUM}}\) is the distance between DTST i# and j#. Pi and Pj are the loads detected by i# and j# respectively. When Pi = Pj, the load was applied equidistantly between DTST i# and j#. If Pi > Pj, the load was applied closer to DTST i#, and similarly if Pi < Pj, the load was applied closer to DTST j#. Figure 4d presents the
results graphically. We find that the position of the load was 2.6 mm from DTST 2 at P7 and 2.35 mm from DTST 4 at P3. These calculated values agree well with the real values. Figure 4e shows a 3D map of calculated load values and their positions.

One application for 3D flexible pressure-sensing devices as an E-skin is in robotic joints, such as elbows, knees, and ankles. The image in Figure 4f is a good example of this type of device, where five DTSTs with different resolutions, 2 mm (1st and 5th), 3 mm (2nd and 4th), 4 mm (3rd), are integrated into a semi-spherical PDMS membrane in parallel with 5 mm between each thread.

The calculated vs. real positions are summarized in Figure 4g. Although many of the calculated positions accurately reflected the real positions at several resolutions, some deviations can be observed. We believe that experimental error is responsible for these discrepancies.

In general, these kinds of DTSTs can be used to fabricate 2D and 3D pressure-sensing devices at several resolutions and to detect the intensity and position of an applied load accurately and effectively. These devices are an advancement to current pressure-sensing technologies.

3. Conclusion

We successfully developed a new kind of smart thread to integrate into the fabrication of multidimensional flexible pressure-sensing devices. By systematically analyzing the sensing mechanism of conductive threads, we found that our prepared 1D, 2D, and 3D sensing devices can be used to predict both the intensity and position of an applied load. These sensors have a high sensitivity (between 0.1 %kPa–1.56 %kPa) and accuracy, adjustable resolution, excellent dynamic fatigue properties (>10⁴ cycles), and short response time to mechanical stimuli (2.5 Hz minimum). In addition, these devices are simpler in structure
and cheaper to produce than existing devices. Further investigations are necessary to optimize the resistance gradient of GTTs for maximized sensitivity followed by practical application of these threads to portable and wearable devices like E-skins.

4. Experimental Section

4.1 Materials

We purchased PDMS (Sylgard® 184) with base and curing agent from Dow Corning Inc. SWCNT were purchased from Cheap Tubes, Inc. with an outer diameter of 1-2 nm, a length of 5-30 µm, and a purity over 95 wt.%. We obtained poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT/PSS) in an aqueous dispersion (1.3 wt. %, Clevios™ PH1000) from HC Starck, Inc. A poly(vinyl alcohol) dispersion (PVA, 30 wt. %, Kollicoat® SR 30D) was purchased from Sigma Aldrich and used to electrically insulate the threads. Commercial cotton threads (cotton balls) with an average diameter of 275 µm were purchased locally. Deionized (DI) water was used in all experimental processes.

4.2 Preparation of water-based SWCNT ink

A conductive solution was prepared using SWCNTs (200 mg), PEDOT/PSS aqueous dispersions PH1000 (10 g), and DI water (6 g). The effective concentration of SWCNTs in the final solution was 12.5 mg/mL. Next, this mixture was homogenized using a Brason 8510 bath sonicator (Thomas Scientific) for 1 h followed by the exfoliation of the SWCNTs through an ultrasonic processor (Cole-Parmer) at 20 kHz and 500 W for 40 min in an ice bath to prevent overheating and damage to the SWCNTs and PEDOT/PSS. This ink was then diluted in DI water to reach the desired concentration (1 mg/mL).
4.3 Preparation of GTTs, HTTs, and DTSTs

Pre-treatment of threads.

Cotton threads were first treated with an ethanol flame to eliminate extraneous fibers and then cleaned with acetone, ethanol, and DI water several times for 20 s.

Preparation of GTTs.

GTTs were fabricated using a multiple dip-dry method. In brief, using a 3-mm resolution, a cleaned 3-cm-long thread is divided into 10 portions referred to as P1, P2, …P10 (Figure S1). The thread is dipped into the prepared 1 mg/mL SWCNT ink for 10 s and then dried on a hot plate at 90 °C for 20 min. With each dip, the number of dipped portions increases by one; for example, the first dip-dry includes only P10 but the second includes P10 and P9 and so on, such that ultimately, P10 will be dip-dried ten times (for a total dip time of 100 s) and P1 will only be dip-dried once (for a total dip time of 10 s). A resolution of 2 mm or 4 mm corresponds to cleaned 2-cm or 4-cm threads, each fabricated by the same process.

Preparation of HTTs.

HTTs were also fabricated using a multiple dip-dry method. A clean 3-cm long thread was dipped entirely into the prepared SWCNT ink (1 mg/mL) for 10 s and then dried on a hot plate at 90 °C for 20 min. This thread was defined as HTT-1. Via the same method, another 3-cm-long cleaned thread was treated the same way twice (HTT-2) up to ten times (HTT-10). Therefore, each sequential thread is dipped for an additional 10 s, such that HTT-1 spends 10 s and HTT-10 spends 100 s being dipped. Next, HTTs were dipped into the prepared PVA solution (3 wt.%) for 10 s and dried on a hot plate at 90 °C for 20 min to dielectrically insulate them.

Preparation of DTST.

To produce DTSTs, one GTT and one HTT of similar length were twisted together by making three turns per 9 mm. The process for preparing DTSTs is shown in Figure 1a and 1b and in Figure S1 and S2.
4.4 Fabrication of flexible pressure-sensing devices

We produced 1D flexible pressure-sensing devices by embedding DTSTs into two pieces of pre-cured ultrathin PDMS membranes (base/curing agent = 20:1, cured at 80 °C for 30 min, 3 cm × 5 mm × 400 µm) and then thermally curing at 80 °C for 3 h. To fabricate 2D flexible pressure-sensing devices, DTSTs were integrated 5-mm apart in parallel into an ultrathin flat PDMS membrane and then thermally cured at 80 °C for 3 h. 3D flexible pressure-sensing devices were built by integrating the 2D DTSTs into a pre-cured semi-spherical PDMS membrane and then thermally curing at 80 °C for 3 h. Figure S3 depicts a typical DTST with a protective PDMS layer.

The ends of all GTTs and HTTs in all devices were bonded with copper wires using silver paste and then cured on a hot plate at 80 °C for 3 h. Typical examples of the multidimensional pressure-sensing devices are shown in Figure S4.

4.5 Characterization and measurements

The surface morphology and thickness of SWCNT on HTTs and GTTs and of the PVA coating on HTTs were examined by scanning electron microscopy (SEM, Quanta 600, FEI Company). An Agilent 34411A multimeter was used to measure the electrical response of conductive threads. A PC-controlled universal test machine (Instron 5944, 5-N load cell, 2-mm force tip diameter) with a PC-recordable multimeter (Agilent 34411A) was used to measure the electro-mechanical response under both continuous and dynamic cyclical loads.

Note that 1D and 2D flexible pressure-sensing devices were fixed on a very soft polyurethane sponge base (8-mm thick) to mimic skin, as would be the case for application as E-skins.
Supporting Information

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

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References


A typical double-twisted smart thread (DTST). One thread is coated with a homogeneous thickness of SWCNTs to detect the intensity of an applied load and the other is coated with a graded thickness of SWCNTs to identify the position of the load along the thread. The basic performance of each thread is also presented.
Supporting Information

**Homogeneously and Gradient-Coated Conductive Smart Threads for Multidimensional Flexible Pressure-Sensing Devices**

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Figure S1. A schematic diagram illustrating the distribution of SWCNT at different positions from P1 to P10 along 3-cm-long HTTs and GTTs with a resolution of 3 mm. Resolution can be controlled by the length of each portion.
Figure S2. Preparation of GTTs and HTTs. a) Raw materials including SWCNT ink (1 mg/ml) with its TEM images and cotton thread. b) Preparation of GTT-1 to GTT-10 with different repetitions of dip-drying. c) Preparation of HTT-1 to HTT-10 by the dip-dry method, where each dip consists of 10 s; the scale bar is 1 cm.
**Figure S3.** A typical DTST with a protective PDMS layer. The scale bars are 200 µm, 20 µm, and 20 µm, respectively. Note that in addition to the insulating PVA coating on the HTT there is also a PDMS layer between the HTT and the GTT, which effectively prevents the risk of a short circuit.
Figure S4. A schematic illustration and a typical multidimensional flexible pressure-sensing device (1D, 2D, and 3D). 400-µm-thick PDMS was used as a protective layer.
Figure S5. a) and b) SEM cross-sectional analysis at different magnifications for the thickness gradient of the SWCNT coating on a GTT at positions P9, P6, and P3. c) The thickness gradient of the SWCNT coating on a GTT. Bars are the average of five thickness measurements at a specific location; error bars show standard deviations in thickness at each location.
Figure S6. Performance of a 1D flexible pressure-sensing device. a) Dynamic fatigue properties of DTSTs (HTT and GTT) with PDMS as a protective layer under a 25 kPa load and a frequency of 1 Hz. b) Response to mechanical resistance by HTT-1 with PDMS as a protective layer under a 25 kPa load and at different frequencies (2.5 Hz, 1.7 Hz, and 0.8 Hz).
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