Conductive Composite Fiber with Customizable Functionalities for Energy Harvesting and Electronic Textiles

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ABSTRACT : Fiber-based triboelectric nanogenerator (F-TENG) is an important technology for smart wearables, where conductive materials and triboelectric materials are two essential components for F-TENG. However, the different physicochemical properties between conductive metal materials and organic triboelectric materials often lead to interfacial failure problems, which is a great challenge for fabricating high-performance and stable F-TENGs. Herein, we designed a new conductive composite fiber (CCF) with customizable functionalities based on a core-spun yarn coating approach, which was applicable for a fiber based TENG (CCF-TENG). By combing a core-spun method and a coating approach, triboelectric materials could be better incorporated on the surface of conductive fibers with the staple fibers to form a new composite structure with enhanced interfacial properties. The applicability of method has been studied using different conductive, staple fibers and coating materials as well as different CCF diameters. As a demonstration, the open-circuit voltage and power density of CCF-TENG reached 117 V and 213 mW/m^2 respectively. Moreover, a 2D fabric TENG was woven and used as a wearable sensor for motion detection. This work provided a new method for 1D composite fibers with customizable functionalities for the applications in smart wearables.

KEYWORDS: Conductive composite fiber; Triboelectric nanogenerator; Core-spun yarn; Self-powered system; Smart electronic textiles

1. Introduction

Wearable systems as next-generation electronic equipment are combined with modern advanced technologies such as big data and Internet of Things (IoTs) for applying in all aspects of life, including health monitoring, smart devices, e-skin,[1-4] and tactile electronics [5-7]. However, these high-tech systems are primarily driven by some energy storage devices such as commercial lithium-ion batteries (LIBs) which are not eco-friendly.[8-9] Triboelectric nanogenerator (TENG), composed of conductive electrode and triboelectric material, has been explored as a new technology for a self-powered and sustainable system, which can harvest and convert mechanical energy from ambient into electricity via coupling induction of triboelectrification and electrostatic effect.[10-12] One-dimensional fiber-shaped TENG (F-TENG) is a type of TENGs composed of 1D fibers with small diameters to be applied in the electronic textiles or smart textiles, [13-17] which has attracted more and more attentions recently. Based on the advantages of lightweight and flexibility as well as knittability, [18-22] 1D F-TENG can be coped with various deformations including bending, knotting and twisting.[23] More importantly, the F-TENG can be woven into fabric or integrated with other devices as electronic textiles or wearable electronics, which can perform as a kind of breathable, comfortable, lightweight and washable sensors to meet the demand of human wearable applications.[24-25]

For the 1D fibers in F-TENGs, a coaxial structure or a core-shell structure is widely utilized because of its good performance under various deformations including bending and stretching.[25-27] Metal material with lots of free electrons, occupies an essential role in TENG, because it has excellent conductivity to serve as an electrode. [28] In a typical coaxial structure, conductive material as electrode is covered by organic triboelectric material such as polydimethylsiloxane (PDMS) to generate electricity via contact and

separation between two different triboelectric materials.[29-30] However, it is considerably difficult for the assembly of conductive materials and triboelectric materials as a functional and structural integrity.[31-32] Due to their different physicochemical properties such as physical modulus and chemical compatibility, interfacial failure between the two components is a common phenonmenon in these kinds of 1D fibers. In the previous researches, many works studied the fabrication of fiber-based TENGs, including coating triboelectric materials on carbon nanotube layer or stainless steel, [29-30, 24, 33] or convolving a metal wire or a carbon nanotube (CNT) layer on silicone rubber wire. [25, 34-35] These researches achieved various types of fiber-based TENG. However, due to different physicochemical properties of metal materials and organic triboelectric materials mentioned above, the compatibility of their interfacial regions would be weak and thus influence the performance and stability of TENGs. [36] Therefore, fabrication of 1D fibers with customizable functionalities and structural integrity is still a difficult challenge.

Core spun yarn is a type of composite yarn that consists of two components mainly with a filament as the core and staple fibers as the sheath.[37-39] The staple fibers in the outer layer of the core spun yarn tightly wrap and protect the inner filament.[40-41] Through a proper design of core filament and sheath fibers, the structure and properties of yarn can be optimized to obtain a yarn with the advantages of high strength and multifunction as well as wearing comfort.[42] More encouragingly, as the sheath layer, staple fibers including cotton fiber and other natural fibers possess high compatibility and strong capacity to adsorb various types of organic solutions (e.g. triboelectric materials) via capillary action and siphon action,[43-44] which implies a potential to solve the challenges mentioned above. In this way, the core can be designed as a conductive metal fiber serving as an electrode, and the triboelectric materials can thus effectively and tightly bond on the metal fiber with the assist of the staple fibers in the sheath layer,

forming a structural integrity composed of triboelectric material, metal material and staple fibers with enhanced interfacial compatibility.

Herein, a new conductive composite fiber (CCF) with customizable functionalities was proposed based on a core-spun yarn coating approach, which was applicable for a fiber based TENG (CCF-TENG). To address the challenges mentioned above, the CCF was fabricated using a core-spun spinning method and a surface coating approach, in which conductive fibers as core were wrapped by staple fibers as sheath and were coated by triboelectric materials with desired triboelectric properties. Through the staple fibers, triboelectric materials would be better incorporated on the surface of conductive fibers to form a new composite structure with enhanced interfacial properties. The proposed method also enabled the flexibility in selection of various kinds of materials with customized triboelectric functionalities for the optimization of CCFs, such as polydimethylsiloxane (PDMS), thermoplastic polyurethane (TPU), cellulose, nylon, polyvinyl chloride (PVC) and polyvinylidene difluoride (PVDF). The CCFs with opposite polarity were combined as a triboelectric nanogenerator (CCF-TENG), and the open-circuit voltage and power density of CCF-TENG reached 117 V and 213 mW/m^2 respectively. Moreover, the CCFs were further woven into 2D energy fabric for serving as wearable sensor for motion detection. The design and fabrication method of CCFs will provide a useful guide for the fabrication of 1D composite fibers with customizable functionalities for the applications in energy harvesting and smart wearables.

2. Results and Discussion

2.1 Fabrication and characterization of the CCFs

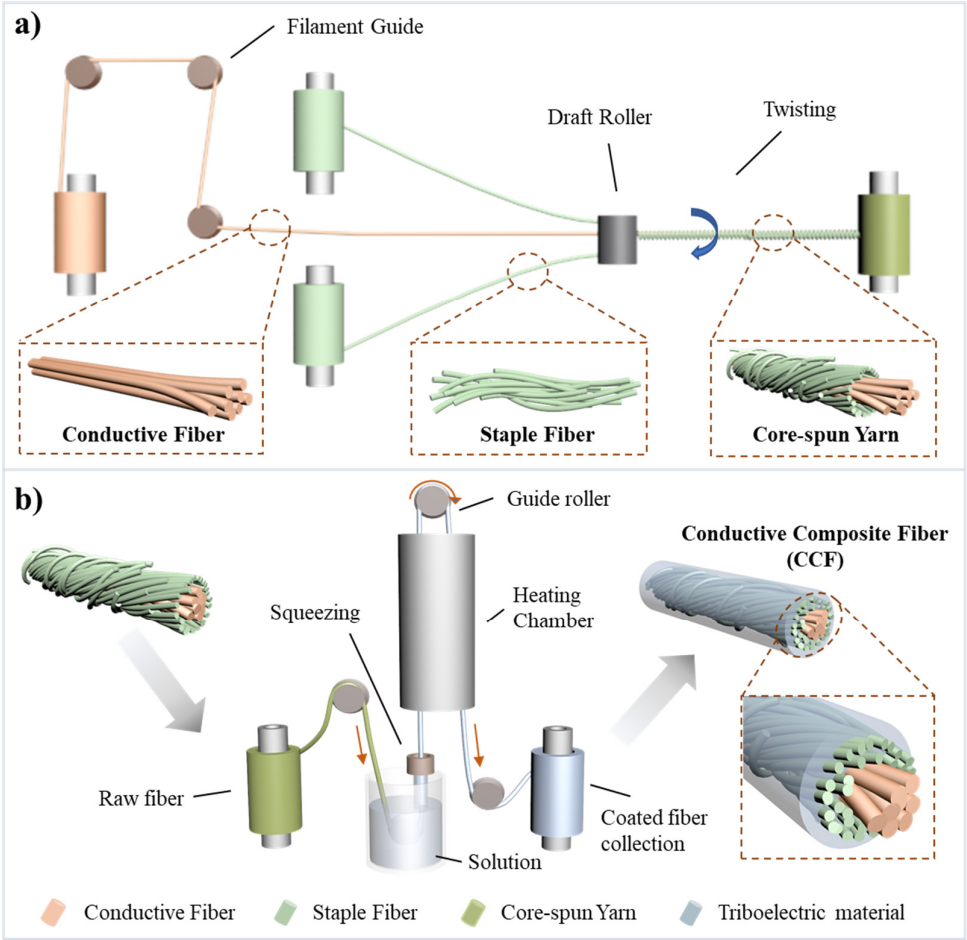

Figure 1. Fabrication method of a) yarn spinning for core-spun yarn and b) yarn coating for CCFs.

The proposed method for fabrication of conductive composite fibers (CCFs) is to combine a core-spun spinning method with a coating approach. The detailed method is schematically illustrated in Fig. 1. First, conductive fiber used as a 1D flexible electrode was spun with the staple fibers using a core-spun spinning method, leading to the fabrication of a core-spun yarn in which the staple sheath fibers tightly wrapped on the conductive fiber, as shown in Fig. 1a. Next, a desired triboelectric material such as electronegative material or electropositive material was employed for surface coating of core-spun yarn. Here staple fibers absorbed the triboelectric component during the coating process, and thus the absorbed solution was highly retained on the surface of

core-spun yarn/conductive fiber to generate the CCF with coaxial composite structure, as shown in Fig. 1b. The employment of wrapping staple fibers contributed to form a good transition interface with enhanced compatibility. Therefore, CCF with enhanced interfacial compatibility and customized triboelectric properties could be obtained.

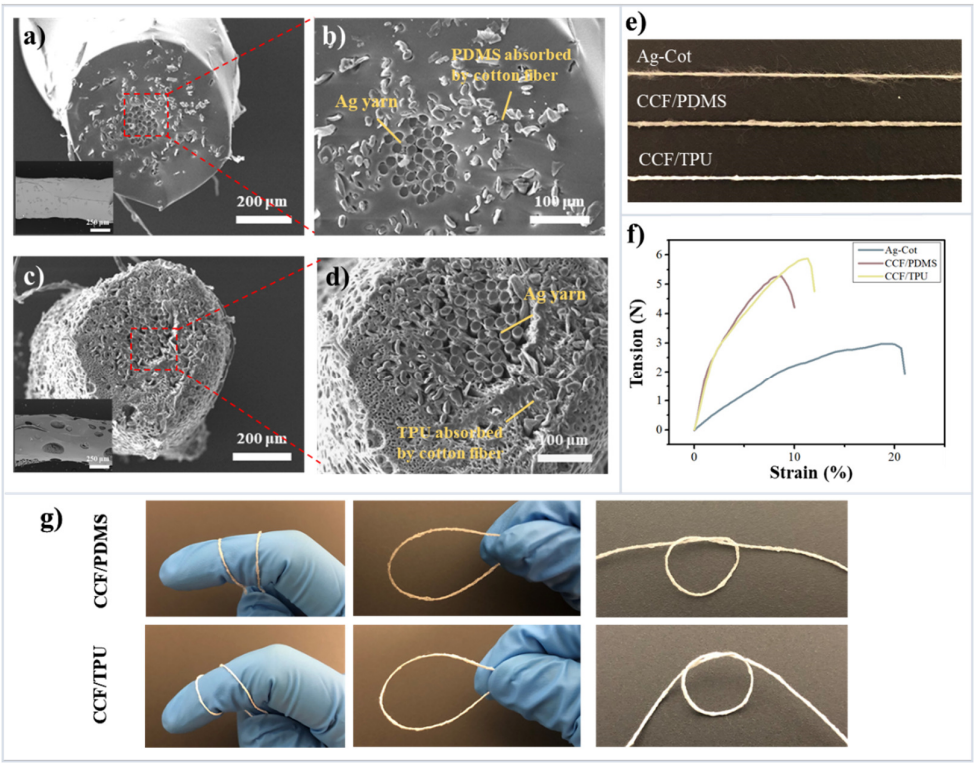

Figure 2. SEM images of the cross section of a-b) CCF/PDMS and c-d) CCF/TPU, inset of a) is the surface of CCF/PDMS and inset of c) is the surface of CCF/TPU. e) The digital photographs of Ag-Cot, CCF/PDMS and CCF/TPU. f) The strain-tension curve of yarns before and after coating. g) The photographic images of CCFs with different folded shapes.

To demonstrate the feasibility of our method, widely used PDMS and Ag yarn was selected as the coating triboelectric material and conductive fiber respectively for making the CCFs. In the conventional method, the pristine Ag yarn is directly coated with PDMS. Due to their different physicochemical properties, uneven and incompatible coating will normally appear (Fig. S1a-d), which affected the

performance of TENG. In our proposed method, staple fibers such as cotton fibers present the characteristics of large surface area and strong adsorption to organic solutions[43-44], which will wrap on the Ag yarn to form a core-spun yarn defined as Ag-Cot, as shown in Fig. 1a. The Ag yarn passes the filament guide and then enters the draft rollers together with cotton staple fibers. The cotton staple fibers were applied as the staple sheath that twisted around the Ag yarn to prepare Ag-Cot, as shown in Fig. S2 in supporting information. Subsequently, PDMS were coated on the Ag-Cot using the dip-coating method, as shown in Fig. 1b. The Ag-Cot went into the PDMS solution with guide rollers. The excess solution of yarn was squeezed and PDMS was cured in the heating chambers. Finally, the PDMS coated Ag-Cot is collected as CCF/PDMS with a total diameter of 0.66 mm. Ag yarn diameter was about 0.11 mm, and the coated thickness on the surface of Ag was about 0.55 mm. The coaxial composite structure was clearly observed in SEM images in Fig.2a-b and Fig. S1c-d. PDMS tightly encapsulated on the conductive fibers' surface via the absorption of cotton staple fibers and the continuous surface was presented in the inset of Fig. 2a.

Besides PDMS, other triboelectric material such as TPU is also applicable for Ag-Cot. Similarly, Ag-Cot could also be coated with TPU solution in a similar way shown in Fig. 1b, which is labeled as CCF/TPU. TPU closely wrapped along the Ag yarn via the cotton staple fibers, forming the CCF/TPU with a total diameter of 0.66 mm and the coated thickness of 0.55 mm, as demonstrated in SEM images in Fig. 2c-d. Fig. 2e illustrated the digital photographs of Ag-Cot, CCF/PDMS and CCF/TPU, respectively. In addition, their mechanical strengths were also measured and evaluated. As shown in Fig. 2f, both CCF/PDMS and CCF/TPU have exhibited an enhanced strength as compared to Ag-Cot. The fabrication of CCFs is scalable and they contained all the properties of commercial fibers, such as flexibility and softness, and were able to be folded into various shapes by bending and twisting, as shown in Fig. 2g. Finally, the

CCF/PDMS and CCF/TPU samples were wrapped on a plate individually with an effective area of 9 cm^2 to fabricate CCF-TENG for further evaluation, as shown in Fig. S3.

2.2 Working mechanism of the CCF-TENG.

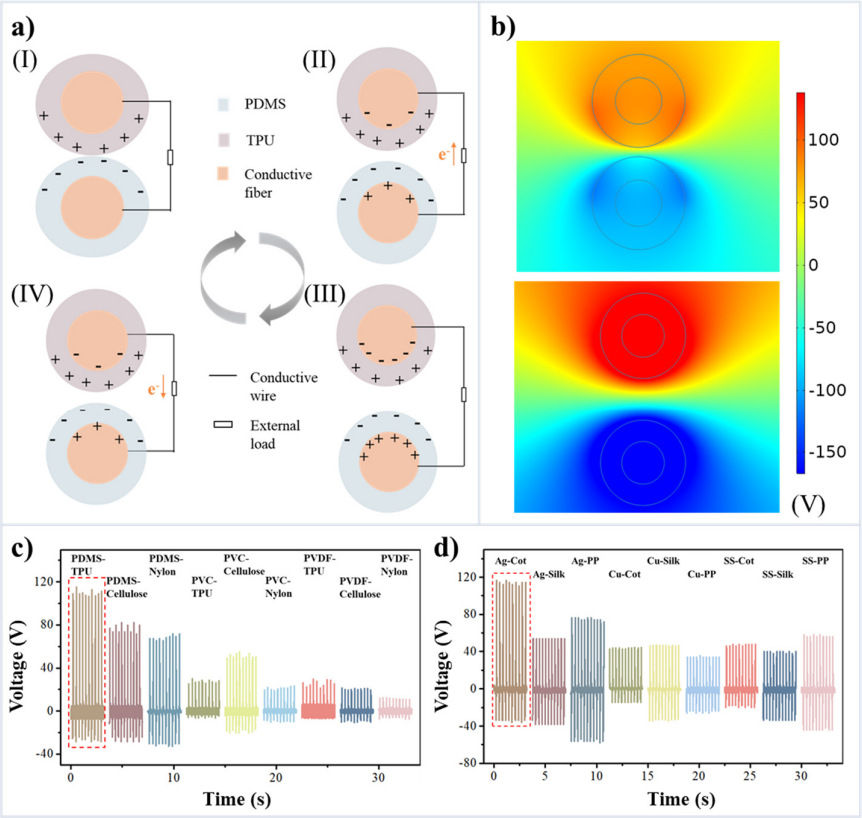

Figure 3. a) (I-IV) The schematic diagrams of working mechanism of CCF-TENG by contact and separation mode. b) Simulation results of electrical potential distribution by COMSOL software. c) Open-circuit voltage signals of CCFs with Ag-Cot coated with different kinds of triboelectric materials. d) Open-circuit voltage signals of CCFs with different conductive and staple fiber materials coated with PDMS and TPU.

The operating principle of CCF-TENG was schematically illuminated in Fig. 3a, which exhibited the process of electron transfer by contact and separation mode. CCF-TENG plates were subject to a periodic external force. Firstly, in the initial state (Fig. 3a, I), the CCF/PDMS and CCF/TPU contacted together under an action of force. The

positive charges and negative charges were produced on the surface of TPU and PDMS, respectively. There were no electrons transfer. When the external force was withdrawn and these two fibers were separated from each other (Fig. 3a, II), the gap between two fibers was generated and the potential difference was produced, which resulted in that the electrons were transferred through external load from the bottom electrode to the top, and the electrical current was produced. Once the CCF/PDMS and CCF/TPU were separated completely and the gap was maximum (Fig. 3a, III), there was an electrostatic equilibrium, and no electrons were moving. When the external force was applied again, the electrostatic equilibrium was broken and a new potential difference was generated between these two fibers. The electrons were flowed again from the opposite direction (Fig. 3a, IV). After the composited fibers were contacted totally (Fig. 3a, I), the electrostatic equilibrium was achieved again and the electrons stopped moving. During the process of contact and separation of CCF/PDMS and CCF/TPU under an impact force, the electrons flowed between bottom and top electrodes continuously. The electric potential distribution of the separating state of the CCF-TENG was also simulated using COMSOL software to show the electricity generating process, as shown in Fig. 3b.

2.3 Material studies of CCFs

CCF is composed of three components of conductive fiber, staple fibers and triboelectric coating materials. For the study of coating materials, various kinds of triboelectric materials were incorporated on the conductive fiber based on the core-spun yarn coating method, including polydimethylsiloxane (PDMS), thermoplastic polyurethane (TPU), cellulose, nylon, polyvinyl chloride (PVC) and polyvinylidene difluoride (PVDF), to fabricated CCFs. In order for efficient evaluation of the performance, the CCFs were wrapped on a plate individually with an effective area of

9 cm^2 to form the CCF-TENG, which was impacted with an external force of 200 N at a frequency of 3.3 Hz. The structure of CCF-TENG was exhibited in Fig. S4 and the performance of the coating materials was measured and shown in Fig 3c. It can be noted that each pair of materials showed different electric performance and the pair of PDMS-TPU (i.e. CCF/PDMS via CCF/TPU) exhibited the highest output performance (116 V) that was superior to all other pairs of materials, which may be mainly ascribed to the strong ability of gaining and losing electrons based on the quantified triboelectric series and sequence[45-46], and the well wrapping of the PDMS and TPU on the surface of CCFs. Specifically, PDMS as the electronegative material showed better performance than PVC and PVDF, with PDMS-Cellulose and PDMS-Nylon of 82 V and 72 V respectively. By contrast, PVC and PVDF paired with electropositive materials exhibited lower voltage results, especially for PVDF with PVDF-TPU, PVDF-Cellulose and PVDF-Nylon of 28 V, 21 V and 12 V respectively. Moreover, for core-spun yarn, conductive fibers should have a good electric conductivity and flexibility, and staple fibers should have good spinnability and compatibility with triboelectric materials. Therefore, different kinds of metal fiber such as silver yarn (Ag), copper wire (Cu) and stainless steel wire (SS) were also adopted as conductive fibers, and nature fibers such as cotton and silk or synthetic fibers such as polypropylene (PP) were used as staple fibers. Fig. 3d showed the electric performance of CCFs with different conductive fibers and staple sheath fibers, all coated with the PDMS and TPU that were identified with the best performance in Fig. 3c. It can be noted that Ag yarn as the core showed a higher performance than Cu and SS wires. Ag-Cot presented the highest output performance (117 V) among all core-spun yarn materials, followed by Ag-PP (76 V). When the staple sheath was cotton fiber, the voltage performance was 45 V for Cu-Cot and 48 V for SS-Cot. Silk fibers exhibited a similar performance when paired with Ag yarn, Cu and SS wires, which were 54 V for Ag-Silk, 46 V for Cu-Silk and 40 V for SS-Silk.

Consequently, the proposed method combining a core-spun method and a coating approach is applicable for various kinds of conductive fibers, staple fibers and triboelectric coating materials. Moreover, CCF/PMDS and CCF/TPU with Ag yarn and cotton staple fibers presented the best performance.

2.4 The output performance of the CCF-TENG

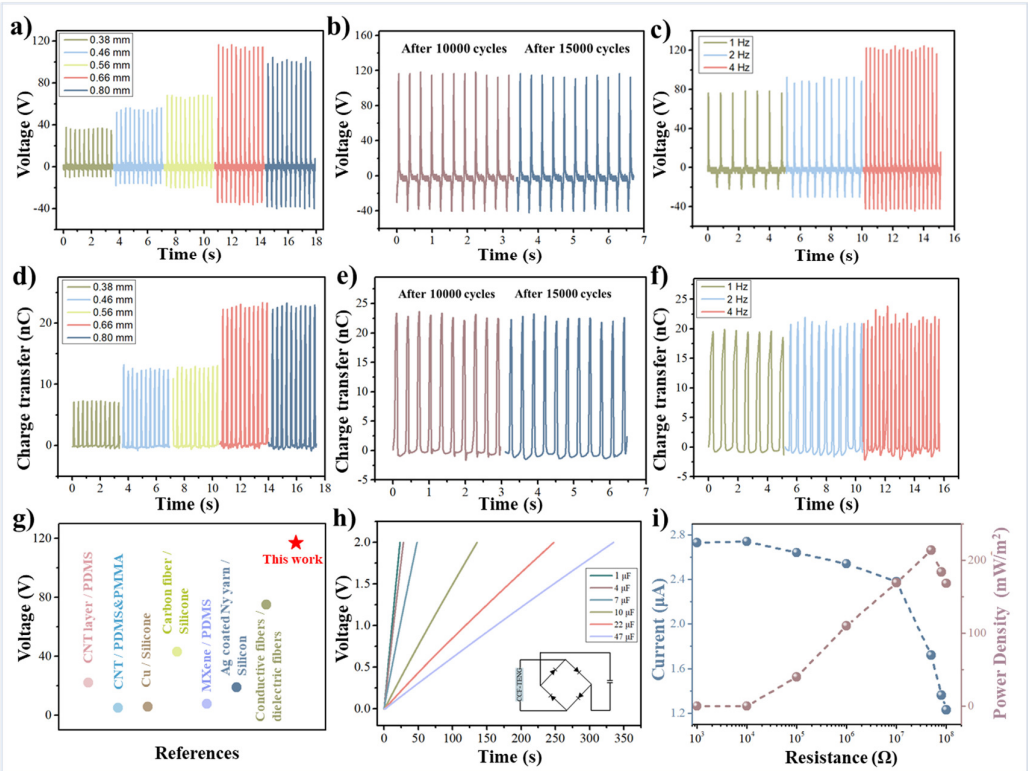

Figure 4. The open-circuit voltage results of a) CCF-TENG with different diameters, b) CCF-TENG for stability test and c) CCF-TENG at different frequencies from 1 to 4 Hz. The short-circuit charge transfer of d) CCF-TENG with different diameters, e) for stability test and f) at different frequencies. g) Comparison of voltage for CCF-TENG and previous similar reports. h) The voltage-time curve of CCF-TENG for charging different capacitors. i) The current and power density curve of CCF-TENG at different resistances.

In order to characterize the triboelectric performance of CCF-TENG, CCF/PDMS and CCF/TPU were wrapped around a plate respectively with the effective area of 9 cm^2 to fabricate a CCF-TNEG which were then contacted and separated completely

under an impact force of 200 N at a frequency of 3.3 Hz. The open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) as well as short-circuit charge transfer (Q_{sc}) were measured and collected. To study the influence of CCF diameter, the performance of CCF-TENG prepared with different diameters from 0.38 to 0.80 mm was also fabricated and investigated, as demonstrated in Fig. 4a, 4d and Fig. S5a. The diameter was depended on the coating amount of PDMS or TPU. Comparing with other diameters, the CCFs with 0.66 mm obtained the highest and optimized performance with V_{oc} of 117 V and Q_{sc} of 23 nC as well as I_{sc} of 2.3 μA. Decrease of diameter could reduce coating uniformity and increase of diameter could reduce the electrostatic induction effect,[24] which influenced the output performance of CCFs. Therefore, the CCFs with 0.66 mm were utilized in the following performance evaluation.

The durability was an essential property for CCF-TENG, which would influence the further applications. The durability of CCF-TENG with 0.66 mm was tested for 15,000 cycles. As shown in Fig. 4b, the results of V_{oc} were nearly stable after 10,000 cycles and 15,000 cycles, with voltage of about 118 V and 117 V respectively. Similarly, the Q_{sc} and I_{sc} were almost steady with 23 nC and 2.3 μA after 10,000 cycles, 23 nC and 2.2 μA after 15,000 cycles, respectively, as illustrated in Fig. 4e and Fig. S5b. Moreover, the CCF-TENG was tested with the continuous impact force for 500 s and the V_{oc} was stable at 117 V, as shown in Fig. S6. In addition, the V_{oc} of the early and late four cycles were also exhibited in the insets of Fig. S6.

In addition, the performance of CCF-TENG was influenced by the frequency of external force. To determine the impact of frequency on performance, the CCF-TENG was evaluated at different frequencies from 1 Hz to 4 Hz under a fixed external force of 200 N, which was demonstrated in Fig. 4c, 4f and Fig. S5c. When the frequency was 1 Hz, the V_{oc}, Q_{sc} and I_{sc} were weak at 78 V, 19 nC and 1.2 μA separately. Once the frequency is increased from 2 Hz to 4 Hz, the performance was enhanced from 92 V to

124 V for V_{oc}, 21 nC to 24 nC for Q_{sc}, and 1.7 μA to 2.9 μA for I_{sc}. Therefore, the triboelectric performance of the CCF-TENG was affected by frequency and increased with frequency. Compared with other fiber-based TENGs' performance in previous research [20, 24-25, 28, 34, 47-48] (Fig. 4g and Table S1), CCF-TENG can reach better results in voltage and current as well as power density at a lower frequency.

Furthermore, the charging capacity of the CCF-TENG was also evaluated by using different capacitors, as shown in Fig. 4h. The charging rates of different capacitors were calculated as 64 mV/s for 1 μF, 55 mV/s for 4 μF, 35 mV/s for 7 μF, 14 mV/s for 10 μF, 8 mV/s for 22 μF and 6 mV/s for 47 μF. It was clearly shown that the capacitors could be charged by CCF-TENG and the charge rate was increased with the decrease of capacitance. Subsequently, the output power density of CCF-TENG was evaluated by connecting with different external load resistances from 1 KΩ to 100 M, as shown in Fig. 4i. It was illustrated that the current was decreased as the resistance increased, and the power density increased at 1 KΩ to 50 MΩ and then reduced at 50 MΩ to 100 MΩ. The maximum power density reached 213 mW/m^2 at the load resistance of 50 MΩ.

2.5 Wearable sensors

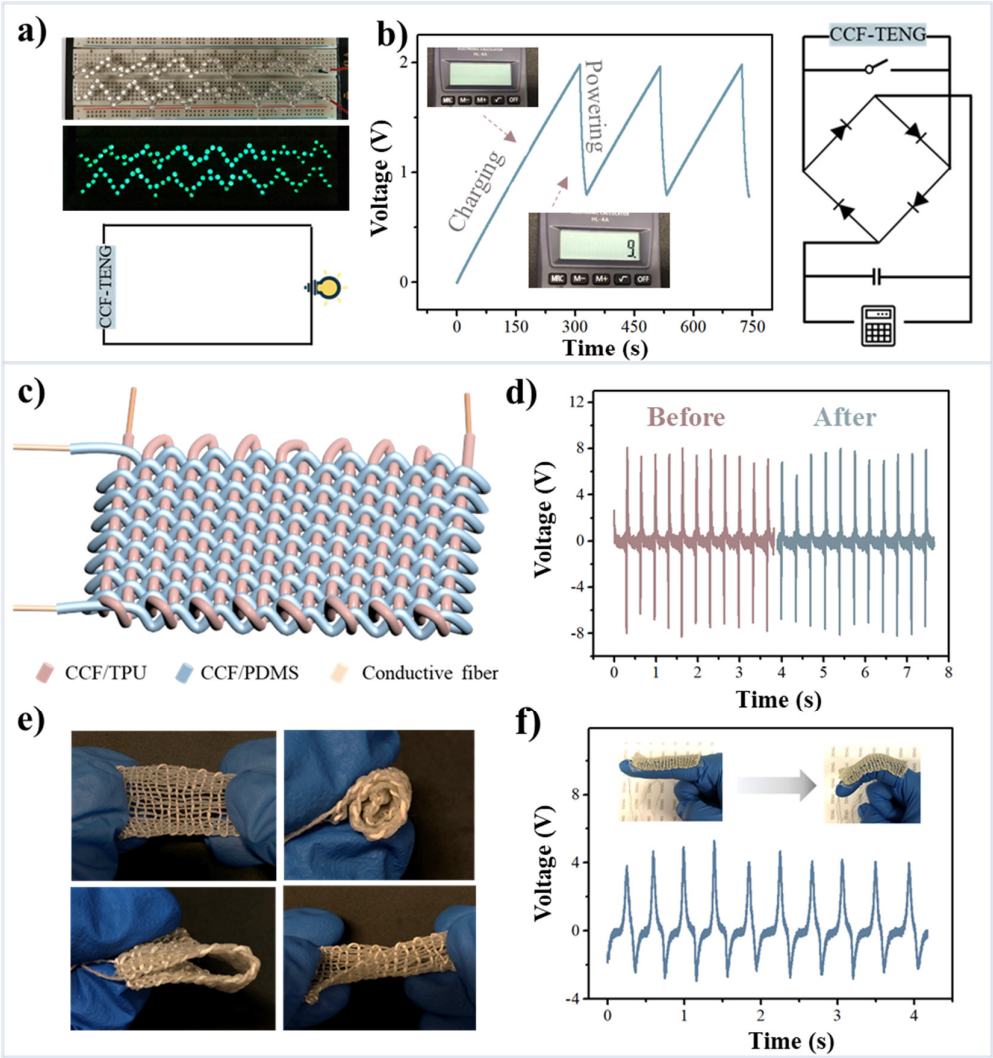

Figure 5. Applications of a CCF-TENG: a) Powering LEDs and the relevant circuit. b) Voltage curve and the electrical circuit of powering a calculator. c) The structural diagram of the CCF-TENG-based 2D fabric sensor. d) The output voltage of CCF-TENG-based 2D fabric sensor before and after washing. e) The photographic images of CCF-TENG-based 2D fabric sensor to show different folded shapes. f) The voltage signals of CCF-TENG-based 2D fabric sensor to monitor the motion of finger.

For the application of CCF-TENG, the CCF-TENG could light 115 green LEDs by applying the impact force of 200 N at a frequency of 3.3 Hz, which was exhibited in Fig. 5a and SI video-1. Moreover, a calculator as an electrical device could be powered by the CCF-TENG with 22 μF capacitor, as shown in Fig. 5b and SI video-2. The CCF-TENG was connected with a rectifier for electric current conversion. The capacitor was

charged to 2 V in 310 s. Subsequently, the calculator was connected with the capacitor and was driven continuously for 20 s. Then the capacitor was recharged to 2 V within 186 s and discharged again to power calculator. The process of charging and discharging could be continued periodically for 3 times, which also could prove the stability of CCF-TENG performance. Furthermore, based on the flexibility and softness, the CCFs could be fabricated as a 2D fabric to be applied as a wearable sensor. As illustrated in fig. 5c, the two composited fibers, CCF/PDMS and CCF/TPU, were woven to a 2D fabric with 10 cm^2 area by knitting approach. The electric performance of the fabric before and after washing was evaluated, as shown in Fig. 5d. Before washing, the CCF-TENG-based fabric was tested by tapping. Subsequently, this fabric was washed using detergent and dried in oven, which was repeated for three times. In Fig. 5d, the voltage of washed fabric was very close to that of unwashed fabric, demonstrating the good stability of the CCF-TENG after washing. In addition, the CCF-TENG-based 2D fabric was flexible and could be folded into different shapes, such as twist and roll as well as bend, as demonstrated in Fig. 5e. The mechanical properties of CCF-TENG based 2D fabric were tested, including compression and tensile performance, as illustrated in Fig. S7. The fabric sensor could be compressed 66% with 3 N load and was recovered after unloading (Fig. S7a). For the tensile performance, the load with 20 N was applied for the tensile strain of 10% (Fig. S7b). Both compressive and tensile tests were repeated for 8 cycles. Moreover, this fabric could be applied on a finger as a wearable sensor. Benefiting from the softness of this fabric sensor, it could be completely attached to the finger and the voltage was generated with the movement of finger, as demonstrated in Fig. 5f. The evaluated results verified that the CCF-TENG was applicable as a monitor to detect the human motion for the further application in electronic textiles.

3. Conclusion

In summary, this paper proposed a new conductive composite fiber (CCF) with customizable functionalities based on a core-spun yarn coating approach, which was applicable for a fiber based TENG (CCF-TENG). By combing a core-spun spinning method and a coating approach, triboelectric materials could be better incorporated on the surface of conductive fibers with the staple fibers to form a new composite structure with enhanced interfacial properties. The CCFs maintained the inherent properties of commercial yarns such as flexibility and knittability and could be folded into various shapes. The CCFs were wrapped on plates to form as CCF-TENG and the performance of CCF-TENG reached 117 V for open-circuit voltage and 213 mW/m^2 for power density. LEDs and calculator could also be driven by CCF-TENG. In addition, 2D energy fabric was woven by CCFs to form a CCF-TENG based fabric, which had good softness and washability to be applied as a device to detect the motion of fingers. Furthermore, the proposed method is applicable to various kinds of conductive core (e.g. silver yarn, copper wire and stainless steel wire), staple fibers (cotton, silk, polypropylene) and triboelectric materials including polydimethylsiloxane (PDMS), thermoplastic polyurethane (TPU), cellulose, nylon, polyvinyl chloride (PVC) and polyvinylidene difluoride (PVDF). It is believed that development of CCFs will provide a new method for 1D composite fibers with customizable functionalities for smart wearables.

4. Experimental section

4.1 Materials

Polydimethylsiloxane (SYLGARD™ 184 Silicone Elastomer kit) was purchased from Dow Corning Co., Ltd. Thermoplastic polyurethane (TPU) was purchased from BASF. Nylon and Polyvinyl chloride (PVC) were purchased from Sigma-Aldrich.

Polyvinylidene Fluoride (PVDF), cellulose, N,N-Dimethylformamide (DMF, ⩾99.8%, ACS reagent), formic acid (88-91%, ACS reagent), tetrahydrofuran (≥99.9%, ACS reagent) and acetone (≥99.5%, ACS reagent) were purchased from DIECKMANN. For the yarn material, commercial Ag-coated nylon yarn (Ag yarn, 100D) and stainless steel (SS) wire were purchased from Qingdao Hengtong X-Silver Speciality Textile Co., Ltd., China. Cotton staple fiber (Cot, 400 Tex), polypropylene staple fiber (PP, 400 Tex), and silk staple fiber (400 Tex) were purchased form Shandong Zhongxian Textile Technology Co., Ltd., China. Copper (Cu) wire was bought from Dongguan Yishengxing Copper and Aluminum Materials Co., Ltd., China.

4.2 The fabrication of core spun yarn

Ag-Cot yarn (Ag-Cot) was fabricated by using a core-spun spinning system. Cotton staple fibers and Ag yarn were used as a staple sheath and a core of the yarn, respectively. The Ag yarn passed the filament guide and then entered the draft rollers together with cotton staple fibers. The cotton staple fiber twisted around the Ag yarn through the draft rollers to prepare Ag-Cot, as shown in Fig. 1a. The twist was 300 T/m with a total draft of 14.7. The diameter of Ag-Cot was about 0.3 mm. The weight density of Ag-Cot was 0.41 mg/cm. Other core spun yarns, such as Ag-Silk, Ag-PP, Cu-Cot, Cu-Silk, Cu-PP, SS-Cot, SS-Silk and SS-PP, were prepared using the same method.

4.3 The fabrication of CCF-TENG

The as-prepared Ag-Cot core-spun yarn was coated by PDMS and TPU respectively. PDMS as electronegative material was prepared using elastomer and curing agent with the ratio of 10 to 1. PDMS covered on the surface of Ag-Cot by dip-coating method and was cured at 150 °C for 2 mins to fabricate a composite conductive yarn coated PDMS (CCF/PDMS). TPU as electropositive material was dissolved in DMF to form 40%

TPU solution. TPU solution was dip-coated onto the CCF and was dried at 25 ℃ to form a composite conductive fiber coated TPU (CCF/TPU). The total diameter for each fiber was controlled as 0.38-0.80 mm for the study of influence of CCF diameters. The unit weight of PDMS on each CCF was 0.78 mg/cm for 0.38 mm, 1.13 mg/cm for 0.46 mm, 1.51 mg/cm for 0.56 mm, 1.86 mg/cm for 0.66 mm, and 3.26 mg/cm for 0.80 mm. The unit weight of TPU on each CCF was 0.26 mg/cm for 0.38 mm, 0.27 mg/cm for 0.46 mm, 0.59 mg/cm for 0.56 mm, 1.12 mg/cm for 0.66 mm, and 1.31 mg/cm for 0.80 mm. Finally, CCF/PDMS and CCF/TPU were wrapped on a plate respectively with an effective area was 9 cm^2 to form a CCF-TENG.

For other functional materials, the coating method follows the same way. The cellulose was dissolved in DMS and acetone with the ratio of 4 to 6 for 12 h to fabricate cellulose solution. Nylon was dissolved in formic acid for nylon solution. PVDF solution was fabricated by dissolving PVDF in DMF and acetone with the ratio of 1 to 1. PVC solution was generated by dissolving PVC in tetrahydrofuran and DMS with the ratio of 3 to 7 at 40 ℃ for 6 h. The core-spun yarn was immersed in these solutions and was dried at room temperature for fabrication of CCF.

4.4 Characterization and measurements

A SEM of TESCAN VEGA3 was used to observe the surface and cross-section of fibers with 20 kV accelerating voltage for the electrons. The tensile and compressive testing were conducted using INSTRON. The performance of CCF-TENG was measured by an endurance testing machine (ZX-A03 from Zongxinagda Shenzhen) under the impact force of 200 N at the frequency of 3.3 Hz. The output voltage signal was collected by oscilloscope (Keysight Infiniivision DSOX3024T) and the short-circuit current and charge transfer were recorded by Keithley 6514 system electrometer of Tektronix, Inc. The 2D woven fabric was washed by detergent and cleaned by DI

water and was dried at 50°C. The steps were repeated for 3 times.

Supporting information

The photographic image and SEM image of PDMS directly coated conductive fiber and coated core-spun yarn (CCF/PDMS); the SEM images of the cross section and surface of core-spun yarn (Ag-Cot); photographic images of CCF-TENG wrapped on plate; the schematic diagram of CCF-TENG's structure; the short-circuit current of CCF-TENG with different diameters, the short-circuit current of CCF-TENG for stability test and the short-circuit current of CCF-TENG at different frequencies from 1 to 4 Hz; the stability test of CCF-TENG under the continuous impact for 500 s; Cyclic compressive load-strain curve and cyclic tensile load-strain curve of CCF-TENG based fabric for 8 cycles; comparison table of current F-TENG.

Lighting LEDs using the CCF-TENG.

Powering a calculator using the CCF-TENG.

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