

A Machine-Fabricated 3D Honeycomb-Structured Flame-Retardant Triboelectric Fabric for Fire Escape and Rescue

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Fire disaster is one of the most common hazards that threaten public safety and social development: how to improve the fire escape and rescue capacity remains a huge challenge. Here, a 3D honeycomb-structured woven fabric triboelectric nanogenerator (F-TENG) based on a flame-retardant wrapping yarn is developed. The wrapping yarn is fabricated through a continuous hollow spindle fancy twister technology, which is compatible with traditional textile production processes. The resulting 3D F-TENG can be used in smart carpets as a self-powered escape and rescue system that can precisely locate the survivor position and point out the escape route to timely assist victim search and rescuing. As interior decoration, the unique design of the honeycomb weaving structure endows the F-TENG fabric with an excellent noise-reduction ability. In addition, combining with its good machine washability, air permeability, flame-retardency, durability, and repeatability features, the 3D F-TENG may have great potential applications in fire rescue and wearable sensors as well as smart home decoration.

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Fire accidents have become one of the common catastrophes that can cause serious personal burn injuries and devastating damages, threatening public safety and property. The World Fire Statistics 2019 show an average of 3.8 million fires per year from 1993 to 2017, resulting in at least 1 million deaths.^[1] Numerous fire cases indicate that improving the people's fire escape ability and materials' flameretardant ability are significant to reduce casualties. In a fire accident, most of the rescue electronics were out of service due to power interruption. Therefore, selfpowered fire-rescue electronics with flameretardant function are urgently needed. In this context, a triboelectric nanogenerator (TENG) with the capability of mechanical energy harvesting and self-powered sensing can exactly solve aforementioned problems.^[2] In addition, considering other

functions, i.e., decoration and acoustic absorption, textile fibers with flame-retardant function would be ideal materials for fire rescue sensors.

Textiles, widely used in daily life, can be classified into industrial, decorative, and apparel textiles according to their applications.^[3] Among them, decorative textiles are mainly used indoors, such as in houses, hotels, theaters, schools, hospitals, etc. These decorative textiles have lots of features such as noise reduction,^[4] lightweight,^[5] breathability,^[6] washability,^[7] adjustability,^[8] flexibility,^[9] and other additional functional performance.^[10] Therefore, compared with the film or strip electronic devices,^[11] decorative textiles would be a better choice for indoor energy harvesting or signal monitoring.^[12]

So far, considerable research has been conducted on textile TENGs,^[13] however, several critical issues that hinder their further applicability still need to be resolved.^[14] First, for fabric triboelectric nanogenerators (F-TENGs) that are manufactured by dip coating of functional materials on the entire fabric, the fabric is usually of high hardness and extremely poor permeability, which severely affect their wearing comfort.^[15] Second, multilayer-structured F-TENGs have typically been prepared via complicated procedures, resulting in the devices being bulky and rigid,^[16] which is neither propitious to harvest energy from the subtle movements of the human body in routine life, nor suitable for soft sensing and detection.^[17] In this concern, fabricating the F-TENG by weaving machine from continuous TENG yarn which could guarantee its permeability, flexibility,





and comfort is important to solve the aforementioned problems.^[18] However, the recently reported fiber (yarn)-shaped TENG usually has a short length, hefty diameter, and uneven fineness, which are inappropriate for fabric processing technology and directly affect the efficiency of weaving and fabric styles.^[19] Furthermore, the research on F-TENG which has special functionalities such as flame-retardant performance, noise-reduction ability, and better permeability is still lacking. Therefore, manipulation of the yarn spinning protocol to obtain yarns with even fineness and small diameter as well as design of fabric structure will be very significant for functional F-TENGs.^[20]

Here, for the first time, a 3D F-TENG with honeycomb structure is weaved by the flame-retardant continuously spun yarn to address the aforementioned challenges. An extremely durable and sustainable full-fiber flame-retardant single-electrode triboelectric yarn (FRTY) is spun by a scalable hollow spinning fancy twister technology. The effects of processing parameters on the yarn quality are systematically explored, and the FRTY's flame retardancy, mechanical washability, and mechanical properties are studied. Moreover, a mechanical constitutive model that fully considers the structure distribution and nonlinear mechanical behavior of the FRTY has been proposed, which is of giant value for better understanding the mechanical behavior of intelligent yarns and guiding the design of new intelligent varns. Owing to the aforementioned excellent performance, the 3D F-TENG of a honeycomb structure is weaved by the FRTYs after structural design. Based on the material and 3D structural characteristics of the F-TENG, it not only has a functionality of flame retardancy, but also can be used for vibration and noise reduction, which would enable a safer, quieter, and more comfortable indoor environment. More importantly, a selfpowered escape and rescue system which can precisely locate people's position and assist survivors searching and rescuing is established based on this 3D F-TENG carpet. This system can be used for real-time route guiding to help evacuees under extreme fire conditions as well. The 3D F-TENG made from FRTY would open up a new door for the F-TENG in the field of smart decoration.

As schematically represented in Figure 1a, an ultralong FRTY was initially prepared by continuous and scalable-production spinning technology.^[21] In consideration of the yarn's versatility in the textile industry, the FRTY can be weaved in diversified smart textiles for self-powered energy harvesting and sensing system. Here, a 3D honeycomb-structured F-TENG was weaved by taking the continuous FRTY as the warp and weft yarns (Figure 1a). Consequently, the prepared single-electrode mode 3D F-TENG can be utilized to establish a smart carpet for escape and rescue system, as presented in Figure 1b. This 3D F-TENG system has four functions of flame retardancy, real-time route guidance, precise rescue location, and noise reduction. First, the 3D F-TENG has a flameretardant property which is attributed to the basic performance of the FRTY; second, the 3D F-TENG acts as a self-powered escape and rescue system for pinpointing the locations of the survivor, which is essential for timely searching and rescuing



Figure 1. Schematic illustration of the 3D F-TENG and smart carpet. a) Schematic of the fabricating process of the flexible 3D F-TENG. b) Schematic of the 3D-F-TENG-based intelligent carpet, which has four functions of flame retardancy, precise rescue location, real-time route guidance, and noise reduction. c) Photograph of the prepared 3D F-TENG.





victim; third, it could work as a real-time route guiding device that can help evacuees make right escape route decision under extreme fire conditions. Fourth, the 3D structured fabric has a function of shock absorption and noise reduction, which could bring comfort to the indoor environment (Figure 1b). The morphology of the 3D F-TENG is shown in Figure 1c, which demonstrates its full-fiber and flexible performance with a concave–convex honeycomb-like structure.

As a raw material and fabric component, FRTY has a significant impact on the preparation and performance of the flame-retardant 3D F-TENG. Here, the FRTY is prepared for the first time by a hollow spindle fancy twister, which is an industrial spinning machine for fabrication and mass production of fancy yarns (**Figure 2**a and Movie S1 and Figures S1 and S2 (Supporting Information)). The core–sheath-structured FRTY is fabricated through wrapping the polyimide yarn with a fineness of 32s over the surface of the conductive core yarn (Figure 2a), which is abbreviated as PI-32s FRTY. It can be seen that the core varn is consistently guided and fed by a tension controller and three sets of positive rollers. These sets of rollers and wrap point controllers (Figure 2b) can effectively control the feeding speed of the core yarn and protect them from being affected by the wrapped yarn. The sheath varn wraps the core varn at the upper end of the hollow core spindle. It is worth mentioning that under the condition of high-speed wrapping, an air ring is formed. And, the air ring is small when the yarn is unwinding near the upper end of the bobbin and becomes larger near the lower end. As the size of the air ring has a great influence on the wrapping effect of the core-sheath yarn, it is necessary to adjust appropriate twist and speed for the processing of high-quality yarn (Figure 2c,d).



Figure 2. Fabrication and evolution of the full-fiber flame-retardant single-electrode triboelectric yarn (FRTY). a) Schematic illustration of continuous hollow spindle fancy twister technology. b) Photograph of core yarn controlling device. c,d) Device and schematic diagram of the yarn wrapping area. e) Pictures of FRTYs by the blackboard method to characterize the yarn quality. f) The weight of the FRTYs by a quantitative test method to characterize the yarn fineness and uniformity.

For the core-shell-structured FRTY, the high coverage rate of the flame-retardant sheath yarn to the conductive core yarn not only prevents the TENG from leakage current, but also enables the composite yarn a better flame-retardant performance. Therefore, adjusting the proper spinning process parameters such as hollow twist and hollow speed to maximize shell yarn coverage is important for the performance of FRTY. Accordingly, the hollow twist from 650 to 1250 T m^{-1} and the hollow speed from 2000 to 4500 rpm (Figure 2e and Figure S3 (Supporting Information)) were manipulated to obtain the FRTY with high coverage. The subjective and objective evaluation methods are used to analyze the varn quality for exploring the optimal processing conditions for FRTY. When the FRTYs are spun at a low setting twist or high spindle speed, the phenomenon of core grinning and shell sparse can be clearly observed by using the blackboard method to characterize the quality FRTY, (Figure 2e-i).^[22] On the contrary, under the setting parameters of high twist or low spindle speed, the FRTY is easy to form regular thick knots (Figure 2e-ii). These drawbacks will impact the FRTY performance and cause defects and complications in textile weaving. By adjusting these spinning parameters, the most suitable processing parameters of 3000 rpm and 1050 T m⁻¹ were obtained, in which conditions, the FRTY revealed good uniformity with no thick knots and grinning (Figure 2e-iii). The quantitative test method is also used to characterize the fineness and uniformity of the FRTY. A 10 m PI-60s FRTY (PI yarn with a count of 60s was used as the sheath yarn to fabricate the FRTY) is subjected to equal-length cutting and weighing tests, and the results indicate that the continuous yarn has excellent uniformity in fineness.^[23] The average weight of the FRTY with 166.67 mm length is only 0.0138 g, which indicates that the fineness of the FRTY is as low as 82.80 tex with a yarn diameter of only 445 µm (Figure 2f and Figures S4 and S5 (Supporting Information)). By utilizing the optimized spinning parameters after the aforementioned analysis, the cooperations of collection rollers and other accessories are adjusted properly to continuously and proportionally produce high-quality FRTY (Figure S2, Supporting Information).

The physical and mechanical properties of the FRTY decide its subsequent use and performance in weaved fabric. For comparison, PI yarn with a count of 32s as well as polyester/ cotton (T/C) blended yarn with a count of 32s were used as the sheath yarn to fabricate the TENG yarn, i.e., PI-32s FRTY and T/C-32s TENG. As shown in Table S1 (Supporting Information), the average fineness of the PI-60s FRTY, PI-32s FRTY, and T/C-32s TENG are 82.80, 133.14 and 131.52 tex, respectively. By manipulating the spinning parameters, the sheath yarns are well wrapped around the conductive yarn to form a core–sheath structure, which can be seen from the radial and cross-sectional views (**Figure 3**a and Figure S5 (Supporting Information)).

Furthermore, the mechanical properties of these TENG yarns are experimentally and theoretically studied (Figure 3b,c and Figure S6 (Supporting Information)). For the wearable fabrics in human daily motion or decorate textiles in carpet, the deformation strain of the fabric is generally within 5%. Hence, the mechanical performance of the TENG yarns in the strain range of 5% is theoretically discussed by comparing with the experimental results. In the theoretical models, a spring with elastic modulus of E_1 is used to express the mechanical performance

of the sheath yarn as it is a spring structure from the morphological aspect. As for the core conductive yarn silver-plated nylon filament, it can be seen from the mechanical curve that it has both viscosity and elasticity during stretching.^[24] Therefore, the Voigt–Kelvin model, in which another spring with elastic modulus of E_2 and the stick pot 2 with coefficient of viscosity η_2 are connected in parallel, is used to express the mechanical behavior.^[3] Due to the interaction between the core layer and the sheath layer, the sticky pot 1 with coefficient of viscosity of η_1 was further introduced to optimize the mechanical model of the composite yarn, therefore, a four-element model is established according to the mechanical performance of each component yarn, as shown in Figure 3b.

As shown in the stress–strain curves (Figure 3c) of composite yarns with three different sheath yarns, the PI composite yarn has a higher modulus than the T/C composite yarn, and the strength of the PI-60s FRTY is higher than the PI-32s FRTY. Moreover, the four-element mechanical model was used to theoretically analyze the mechanical curves of three composite yarns, and all the fitting correlations were greater than 0.99, indicating that the four-element model can accurately describe the mechanical behavior of the composite yarn. This mechanical model can provide theoretical guidance for the viscoelastic energy and mechanical loss caused by the plastic deformation of composite yarns.

As for the raw material of 3D F-TENG which can be used for self-powered fire escaping and reusing system, the FRTY not only has a functionality of flame-retardant but also a good performance of energy output. The operating mechanism of the FRTY is single-electrode mode, in which the PI yarn works as dielectrics and the conductive yarn functions as a conductive electrode. As for the FRTY for fire escape and rescue, the survivor who acts as the other electrode is mobile that the singleelectrode mode is more suitable for energy harvesting and tactile sensing. Taking a skin as a contact object, the working mechanism^[25] of the single-electrode FRTY is schematically shown in Figure 3d. When the skin contacts with the FRTY, negative triboelectric charges are gained by the FRTY owing to the stronger capability to obtain negative charges of the PI varn (Figure 3d-i). Once relative separation occurs, the negative charges from the exterior of the FRTY seduce positive charges, leading to the flow of instantaneous electrons from electrode to the earth (Figure 3d-ii). Once the skin is completely apart from the FRTY, the electrons in FRTY are balanced, resulting in no electron flow (Figure 3d-iii). When the skin approaches the FRTY again, opposite electron flow emerges from the ground to electrode till skin has intimate contact with the FRTY again (Figure 3d-iv). Hence, by repeating the touch and separation progress, an alternating electricity output of the FRTY will be produced. The potential distributions of the FRTY during touching and separating states are simulated by COMSOL.^[26] As illustrated in Figure 3e, an obvious negative potential is observed on the surface of PI yarn after separation from contacting, which is consistent with the aforementioned analyzed working principle.

To test the flame retardancy, the TENG yarn is ignited for 1 s to test its combustion performance by using the 45° flame retardancy test method (Figure 3f). Figure 3g,h and Figure S7 (Supporting Information) show that the T/C-32s TENG burns www.advancedsciencenews.com

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Figure 3. Performance of the FRTY. a) SEM images of the TENG yarns (scale bar, 500 μ m), which are the T/C- 32s, PI-32s, and PI-60s. b) Illustration of the rheological models for describing nonlinear mechanical behavior of TENG yarns (note: σ refers to the stress on the TENG yarn, ε refers to the strain of the TENG yarn, E_1 and E_2 refer to the elastic modulus of springs representing the sheath and the core, and η_1 and η_2 refer to the viscous coefficients of the dashpots representing the sheath and the core, respectively). c) A comparison of the experimentally derived stress-strain curves of the TENG yarns with results predicted by the model provides the predictions to the experimental results. d) Schematics of the working principle for the FRTY. e) Potential distributions at the different states simulated by COMSOL. f) Flame-retardant performance test: g) T/C- 32s TENG continues to burn to ashes after the test, h) PI-32s FRTY remains stable in appearance, and i) only slight degradation in the electrical output performance after the test. j) Short-circuit current of the TENG yarns with different materials, frequencies, and lengths. k) The capacitor charging ability of the PI-32s FRTY measured with different external load resistances under 1 Hz frequency and 30 N force. l) The current and peak power of the PI-32s FRTY measured with different external load resistances under 1 Hz frequency and 30 N force.



out quickly, whereas the PI-60s FRTY (5–20 yarns) remained unaffected in appearance after the test. The current output of FRTY before and after the flame retardancy test was furtherly tested. As shown in Figure 3i, only slight deprivation in the electrical output performance was observed after the test, which shows that the FRTY can be used even in a fire disaster.

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The electrical output performances of PI-60s FRTY, PI-32s FRTY, and T/C-32s TENG are investigated and compared. The output performance of PI-60s FRTY is the highest (Figure 3j) compared with the other two yarns-sheathed FRTY, which is because of a high electron affinity potential energy of PI compared to T/C materials as well as the smaller thickness of PI-60s than PI-32s.^[27] The output performance of PI-60s FRTY with different lengths (5-25 cm) is characterized under 1 Hz condition (Figure 3j and Figure S8 (Supporting Information)). As predicted, the output performance of the FRTY rises with length increment. Herein, the FRTY is performed at small mechanical frequencies spanning from 1 to 2.5 Hz (Figure 3i and Figure S8 (Supporting Information)), which is similar to that of human motion. As can be seen from Figure 3k, a range of capacitors from 0.1 to 4.7 µF were used to investigate the charging behavior of FRTY.^[28] It shows that as the capacitance increases, a slower charging velocity can be found. For instance, when charging a 0.1 µF capacitor, it takes 16 s to reach a voltage of 6.0 V under the testing conditions of 1 Hz frequency and 30 N force. As shown in Figure 3l, the FRTY complies with Ohm's law, so the current decreases when the applied external resistances increase. The output power can be computed by $W = I^2 R$, where I represents the output current through the external circuit while *R* represents the loading resistance.^[29] The output power W reaches the largest value of 73.55 μ W m⁻¹ immediately once the external load resistance is around 1000 M Ω .

To evaluate the washability, the PI-60s FRTY is washed by laundering machine following AATCC test method 135.^[30] The detailed washing process can be seen in the Experimental Section. Scanning electron microscopy (SEM) images of the unwashed PI-60s FRTY after 1, 3, and 5 times of regular washing are presented in Figure S9 (Supporting Information), respectively. The yarn is sturdy and robust as no grinning was noticed even after 5 times of washing. However, a little increased hairiness of yarn appeared. Thereafter, it can be assumed that a small decrease in I_{sc} is primarily owing to the hairiness amount upon repeating washes, leading to a higher sheath yarn's thickness. Based on the superior output signals of the FRTY, it can be used not only as an energy harvesting yarn, but also as a sensor to identify and detect normal fabric constitutes (Figure S10, Supporting Information).

This yarn (**Figure 4**a) with unlimited length, good flexibility can satisfy various mechanical requirements of weaving (knitted machine, weaved machine, etc.) and processing conditions (Figure S11 and Movie S2, Supporting Information), e.g., the strength requirements of the yarn under high-speed winder or warp finishing process, the fineness requirements of yarn under the loom weaving process, the continuity of the yarn for large-scale fabrics preparation, the adaptability of weft in different fabric structure, the friction of mechanical beating on warp yarns, and self-adjusting ability after getting off the weaving machine (Figure 4b). Five kinds of flame-retardant F-TENGs (Figure 4c,d and Figure S12 (Supporting Information)) with different weave structures are mass-produced by a weaving machine. The fabrics are prepared by interweaving the warp and weft FRTYs according to the designed fabric pattern (Figures S11 and S12, Supporting Information).

As the properties of air permeability and thickness have a significant influence on the comfort of the electronic textiles, the thickness and breathability of these F-TENGs are tested (Figure S13, Supporting Information). As shown in Figure 4e, honeycomb fabrics have the largest thickness due to their concave-convex and porous structure, followed by twill and plain fabrics. However, the large thickness does not restrict their air permeability at all because of their unique 3D structural design. Conversely, the honeycomb fabric also has the highest air permeability (1043.36 mm s⁻¹) in these fabrics. Washability and flame-retardant properties of the F-TENGs are also good (Figures S14 and S15 and Table S2, Supporting Information). Moreover, the electrical output performance of the flameretardant F-TENGs with different structures, areas, and external pressures is tested (Figure 4f,g and Figure S16 (Supporting Information)). The fabrics with different structures can be used in different application scenarios according to their different output performances (Figures S17 and S18, Supporting Information). The order of electrical output (V_{oc} , I_{sc} , Q_{sc}) is: twill weave > honeycomb weave > plain weave. The reason for the unequal electrical outputs in these fabrics (made from the same yarn with the same area) is because of the difference in fabric structure parameters. It can be verified by the unequal density of the warp and weft yarns. As the order of the warp and weft varn density is twill weave > honeycomb weave > plain weave, this result is consistent with the electrical outputs. Therefore, the density of warp and weft yarns can be used to control the charge output of the fabric per unit area.

In the process of fabric structure design, to facilitate the understanding of the interweaving of warp and weft on the fabric, the lifting plan is used to design the fabric in advance. As shown in Figure 4h-i, in the lifting plan, each warp and weft interweave forms a single interlacing point, which is mainly manifested as alternating forks and blanks. The forks represent the warp interlacing points (the warp varn is on the fabric surface, and the weft yarn is under the fabric surface in the small unit of warp and weft interweaving), and the blank represents the weft interlacing point (weft yarn is on the fabric surface, and the warp yarn is under the fabric surface), and the connection of more than three identical warps or weft interlacing points is called floating line. Here, the derivative structure (honeycomb structure) and the other four structures are designed through the lifting plan. It can be seen from Figure 4h-ii that there are continuous warp interlacing points or continuous weft interlacing points between each of the two points of AB, BC, CD, and DA, hence the fabric surface forms long warp (weft) floating lines. The interlaced weft interlacing points and warp interlacing points between AC and BD are relatively tight. As the yarn is continuous during the fabric forming process, the yarn of long floating line will be pulled by the same yarn which has the interlacing point, resulting in the formation of protrusions at the position of the long floating line and the formation of a depression structure in the tight interlacing point area. In this way, the entire fabric surface is circulated to form a 3D concave-convex honeycomb-like fabric structure (Figure S17b,







Figure 4. Schematic and performance of the F-TENG based on FRTY. a) Photograph of the FRTY. b) Photograph of the process for fabricating a 3D F-TENG. c,d) Photographs of the F-TENG. e) Breathability and thickness of the F-TENGs with different structures. f) Short-circuit current of the F-TENGs with different structures. g) The open-circuit voltage of the 3D F-TENG with different areas. h) Lifting plan and schematic illustration of the 3D F-TENG. i) Comparison of the thickness of 3D F-TENG and plain F-TENG. j) Comparison of noise reduction of 3D F-TENG and plain F-TENG.

Supporting Information), which makes it thicker than the plain fabric (Figure 4i).

In addition to flame-retardant performance, the 3D honeycomb-structured F-TENG also has potential applications in carpets for noise reduction, because of its unique porous structure. As shown in Figure 4j and Movie S3 (Supporting Information), when the key from the same altitude is falling onto the surface of the plain fabric and 3D structural fabric on the floor, noise reduction by these fabrics is investigated. Compared with blank contrast (the indoor noise, 46.1 dB), almost no enhancement in noise (46.2 dB) is observed when the key is falling onto the 3D F-TENG fabrics, indicating



better noise-reduction capability than the floor (95.9 dB) and plain fabric (57.6 dB).

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In most situations, fire escape is not easy, especially for indoor public places. Once a fire occurs, the electricity is likely to collapse. Subsequently, people face difficulty in identifying safe escape instructions and cannot determine the direction of the correct escape route, which may cause unnecessary injuries and/ or deaths. At the same time, due to the large number of rooms at such places, it is difficult for rescuers to figure out the victim's location if the traditional sensors stop working. Therefore, it is of great significance to identify the escape route in time and transmit the precise rescue location signal quickly. As depicted in Figure 5a, while someone taps the TENG carpet, the 3D F-TENG will produce an apparent output signal. By using a multichannel data collecting method, real-time voltage data of every 3D F-TENG unit can be measured simultaneously (Figure S19, Supporting Information). Following signal processing, the rescue location can be real-time represented on the rescue terminal.

Due to the excellent flame-retardant property and selfpowered sensing, the as-prepared 3D structural fabric can be used in emergency route guiding and rescuing under fire conditions (Figure 5b). As shown in Figure 5c and Movie S4 (Supporting Information), for those who cannot escape on time, they can tap the nearest carpet for help, and generate emergency signals by contacting and separating the palm with the carpet, and sending accurate real-time location, which is convenient for rescuers to search and rescue. Furthermore, every step of people walking or running can generate energy by contact-separation with the 3D F-TENG carpet, which is sufficient to drive the signal lights connected with the carpet in front of people, and the direction to escape is displayed during the fire or other situations (Movie S5, Supporting Information). The shortest escape path can be selected through the real-time direction arrow guidance (Figure 5d and Movie S6 (Supporting Information)). Once these decorative textiles have the function of energy harvesting, signal indicating, and rescues signal transmitting under the extreme situation, they will provide effective solutions for public safety and other issues.

In summary, a 3D full-fiber F-TENG with functions of flame-retardant, noise reduction, and self-powered escape



Figure 5. Application of the 3D F-TENG in a self-powered escape and rescue system. a) Scheme of the 3D-F-TENG-based self-powered escape and rescue system. b) Demonstration of the self-powered escape and rescue system. c) Photograph of the real-time precise rescue location display of the self-powered precise rescue location system. d) Photograph of the indicator lights for route guidance system powered by the 3D F-TENG.





and rescuing system, is successfully fabricated. Attributed to excellent flame-retardant properties of polyimide yarn, the 3D F-TENG which is weaved from the FRTY can be used in fire searching and rescuing. The unique design of the honeycomb weaving structure endows the fabric an excellent noise-reduction ability. Moreover, the 3D F-TENG can be utilized indoors as a self-powered escape and rescue system that can precisely locate the survivor position to timely assist victim searching and rescuing. The FRTY is compatible with textile processing technology and is able to mass-produce on a large scale. Besides, the FRTY can withstand standard mechanical test, permeability test, flammability test, and machine-washed test, and shows a good level of durability and repeatability. This continuously scalable manufacturing technology and 3D F-TENG design provide an efficient and commercial processing route for energy harvesting and emergency signal transmission under the extreme fire condition.

Experimental Section

Materials: Polyimide yarns (yarn numbers are 32s and 60s) were purchased from Aoshen Co., Ltd., China. Polyester/cotton blended yarn (yarn number is 32s) was bought from the Alibaba website. Conductive silver yarns were purchased from Qingdao Zhiyuan Xiangyu Functional Fabric Co., Ltd., China.

Preparation of the PI (T/C)-TENG: First, the yarn required for the sheath layer was transferred from commercial bobbin to the hollow yarn bobbin (dedicated to the QFB730K empty core fancy twisting machine) through a yarn pressing machine (QFB650). Second, the hollow yarn bobbin was mounted on the empty core fancy twisting machine. Finally, as shown in Figure 1, the core yarn was placed as required, and the machine could be turned on after setting reasonable process parameters. Here, cotton yarns and polyimide yarns were used as the sheath yarn.

Fabrication of the F-TENGs: The F-TENG was woven by the semiautomatic weaving sample machine (SGA598, Jiangyin Tongyuan Textile Machinery Co., Ltd.). First, the yarns were arranged and warped on the loom to prepare the warp yarns; second, the TENG yarn was wrapped around the shuttle to wait for use; finally, the fabric structure diagram was typed into the control panel of the loom machine (Figure S11, Supporting Information) and weaving process started.

Measurement and Characterization: The morphologies of the hybrid yarns and the surface morphologies of fiber webs were analyzed by SEM (TM3000, Hitachi Group-Japan). The mechanical properties of the yarn were tested on a yarn strength elongation tester (XL-1A, Shanghai Xinxian Instrument Co., Ltd.). The testing sample yarn clamped at the crosshead with a gauge length of 20 mm. The crosshead speed was 20 mm min⁻¹. The YG381 blackboard yarn examining machine and YG086C measuring reel were used for yarn evenness. The fabric flammability tester (YG815D-II) was used to test the yarn sample (T/C-32s TENG and PI-32s FRTY) and the F-TENG's flammability in reference to GB/T 14644-1993. The yarn (the yarn sample was cut and fixed in a shelf) and fabric samples were put into a laundry bag, the whole bag was put into a commercial laundering machine to perform delicate machine washing tests according to AATCC Test Method 135-2017. The fabric thickness (according to GB/T3820-1997) and air permeability (according to ASTM-D 737:1996) were tested by digital thickness gauge for textile (YG141D-11) and air permeability tester (YG461E) (Wenzhou Fangyuan Instrument Co., Ltd.), separately. Combustion property was investigated by a cone calorimeter (6810, Suzhou Vouch Testing Technology, Suzhou, China) according to ISO5660-1 standard. Limiting oxygen index value was characterized by oxygen index meter (5801A, Suzhou Vouch Testing Technology, Suzhou, China) according to GB/T 5454. The voltage, current, and charge quantity of the yarns were recorded by an electrometer (Keithley 6514). Yarns of different lengths were pasted on the paper to test the TENG electrical properties (unless otherwise specified, the test length of the TENG yarn was 25 cm).

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

bioenergy harvesting devices, emergency guidance and signal transmission, flame-retardant triboelectric fabrics, self-powered sensors

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