

Article

3D Stitching Double Weave Fabric-Based Elastic Triboelectric Nanogenerator for Energy Harvesting and Self-Powered Sensing

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Abstract: With the start of the intelligent age, textiles are no longer limited to safety protection, warmth, and aesthetic purposes. They have become intelligent textiles, which combine functionality, intelligence, and information technology to adapt to the era and enrich our lives, such as wearable textiles and energy harvesting electronics. However, the limited stretchable smart textiles and complex fabrication methods have largely hindered their development. Here, a mass-manufactured 3D stitching double weave fabric-based elastic triboelectric nanogenerator (3DWE-TENG) is developed. Based on its stable electrical output performances and rapid response to external tensile strain, it can be used for energy harvesting and self-powered sensing simultaneously through both the lining layer and the exterior layer. With an advanced 3D structural design and using the improved woven method, 3DWE-TENG can be stretched to 300% and achieves a stable mechanical structure, breathability, and excellent flexibility. Furthermore, it also has low costs, wearable comfortability, and high fabricating efficiency due to the mature woven technique and the common yarns used in the fabric. This work provides more opportunities for stretchable power sources and self-powered sensors with applications in wearable electronics.



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Keywords: triboelectric nanogenerators; stitching double weave; elastic fabric; energy harvesting; self-powered sensing

1. Introduction

Smart textiles enrich people's lives and adapt to the new information age. Wearable electronics are one of the directions in intelligent textiles, which has an urgent need for portable power resources. To this end, a triboelectric nanogenerator (TENG) [1–3] was developed, which could efficiently convert mechanical energy into electrical energy based on Maxwell displacement. As chemistry, physics, mechanical principles, and electronics have become involved, TENG has become a newly-developed interdisciplinary technology in energy and sensing applications [4–6].

TENG can collect low-frequency vibration mechanical energy in the environment and convert it into electrical energy [2,7,8], green energy resources for other nanodevices such as sensors and detectors. Mechanical energy is widespread [9] in people's daily lives, such as in wind, in water, the operation of an engine, human motion [10,11], heart rate [12,13], and blood flow. All of these could generate electricity through TENG.

As a new energy harvesting and self-powered sensing technology, TENG not only brings possibilities for the miniaturization of energy systems, but also provides an ideal sensing system for nanoelectronic or microelectronic devices that are completely wireless, bio-implanted, and have no need to manage for long periods or even a lifetime, which could be widely used in the fields of energy, power networks, the Internet of Things, the Internet, biomedicine, wireless communication, wireless sensing, and smart textiles [14–17].

Due to the excellent performances of textiles and TENG [18–22], textile-based TENG is qualified as having wearability, low costs, flexibility, being lightweight, and the ability of harvesting energy and self-powered sensing, which has drawn considerable attention from researchers from different fields. To this end, it has been widely applied in wearable electronics, smart clothes, personal healthcare, and human-machine interfaces [23,24]. With its development, the urgent demand for the comfortability, breathability, shape-adaptive, elasticity, and flexibility of textile-based TENG keeps increasing. Among these requirements, stretchability is largely desirable, owing to the complex mechanical deformations of wearable devices. As a consequence, stretchable textile-based TENGs with different structures have been reported, including stretchable yarn-based TENG and stretchable fabric-based TENG. However, they still face several challenges. First, some stretchable yarn-based TENGs are fabricated by winding the conductive yarn densely around the elastic core yarn, or by coating different electric materials and dielectric materials layer by layer on an elastic fiber or yarn [25–27]. Nevertheless, these fabricating methods largely inhibit their industrialization, due to their complex structure, limited lifetime, and mechanical instability. The coatings may fall off, which even affects the electrical outputs and their wearability during use. Second, stretchable knitting fabric-based TENG [28] has perfect stretchability but low elastic resilience, which is not friendly to structure stability and output stability. Furthermore, some knitting structures may have friction damage during contact-separate motion with materials that have rough surfaces, such as snags, pilling, and fuzzing problems, due to the loose structure. Third, some fabric-based TENGs achieve stretchability by sewing the fabric without wave-shaped elastic on the stretchable dielectric fabric [29–31], which could generate electricity during the stretching and releasing process. Or the energy harvesting threads could be sewn into a serpentine shape onto both sides of the elastic textile to fabricate a stretchable fabric-based TENG. These structures cannot be mass manufactured, which increases the fabricating costs and hinders their wide application.

Here, a mass-manufactured 3D stitching double weave fabric-based elastic triboelectric nanogenerator (3DWE-TENG) is presented, which is constructed from PA yarn with silver coating on the surface as the conducting electrode and PET multifilaments as the triboelectric material. In this work, the single electrode mode [32–40] is applied, in which only one electrode (PA conductive yarn) directly interacts with the triboelectric layer (PET multifilament). The PA conductive yarn acts as the electrode. The ground is just a reference electrode as a source for electrons. Based on its stable outputs and rapid response to external tensile strain, 3DWE-TENG could be used for energy harvesting and self-powered sensing simultaneously through both the lining layer and the exterior layer. Due to the mature woven technology, raw materials, and improved woven methods, it not only achieves high tensile strain, a stable structure, and high fabricating efficiency, but also has a high contacting-separating area between yarns during the stretching-releasing motion, which does not need to rely on external substrates or surfaces to acquire sliding or contact-separating triboelectricity. In this work, two styles of 3DWE-TENG are designed, including the electrode as the warp yarn and the weft yarn. Therefore, several 3DWE-TENGs are fabricated to investigate the influence of structures, raw materials, tensile strains, and warp yarn densities on the electrical output performances. This work not only provides a promising new direction and design mentality toward fabricating stretchable textile-based TENGs, but also promotes the development of self-powered wearable electronics.

2. Materials and Methods

In the 3DWE-TENG, the exterior and lining layers are both woven with the plain structure to improve the structure's stability. In the woven structure, due to the nature of interior mutual interlacing yarns, which usually run horizontally and vertically straight, there are many gaps between the yarns. The interspace between adjacent warp yarns and weft yarns endows the woven structure with good breathability. It is generally believed that the selection of appropriate materials with opposite polarities is crucial for electrical

outputs. Here, a commercially purchased 12tex/72F PET multifilament was chosen as the dielectric material of 3DWE-TENG due to its low cost, fluffy structure, and a strong tendency to lose electrons. The warp yarn density was 533 ends per 10 cm (5 ends per dent). Figure 1a presents the scanning electron microscopy (SEM) image. A two-ply polyamide (PA) yarn coated with Ag was used as the electrode, owing to its excellent conductivity and good softness. The yarn density was 280D. The surface morphology of PA conductive yarn with uniform silver coating on the surface was observed by SEM, which is presented in Figure 1b. In Figure 1b, it can be seen that the Ag coating is uniform on the surface of each fiber in the yarn. All fibers were twisted into the PA conductive yarn, which gave the yarn good breathability. Its tensile property is shown in Figure 1c. Due to its superelasticity and low cost, Polyurethane (PU) multifilament was chosen as a part of the warp yarns, which was the key point in achieving fabric stretchability. As already known, it is hard for most woven structures to achieve stretchability, owing to the nature of mutual interlacing yarns, which run horizontally and vertically straight. Therefore, a creative woven method was applied in the fabrication process of 3DWE-TENG. In the weaving machine, the PU elastic yarn, as part of the warp yarns, was stretched to 300%, and the other warp yarns without stretchability were kept straight on the machine. The fabric retracted after coming from the loom, owing to the perfect elastic resilience of PU, which resulted in a large warp yarn wave highness of non-elastic yarns, including the PET multifilament and PA conductive yarn. The suspended loops and the superelastic PU yarn in the fabric can be easily stretched in the warp direction, which gives the stitching in double weave fabrics much more elasticity than most woven fabrics. That is the reason why woven fabric achieves stretchability.

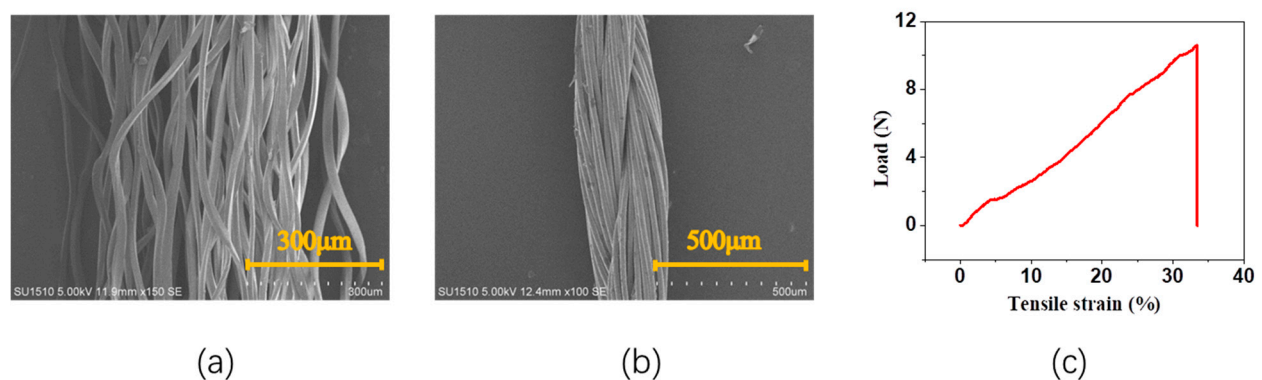


Figure 1. (a) Scanning electron microscopy (SEM) photograph of PET multifilament; (b) SEM of PA conductive yarn; (c) tensile property of the PAconductive yarn.

Due to the excellent flexibility of common textile materials (PA conductive yarn, PET multifilaments, and PU), good breathability and structure stability of the mature textile structure (woven structure), 3DWE-TENG achieves high flexibility, breathability, and good structure stability.

The 3DWE-TENG was fabricated using a weaving machine. The surface morphology of the PET multifilament and the silver-coated PA yarn was characterized by a field emission scanning electron microscope (SU-8010, Hitachi, Hitachi, Japan). The mechanical tensile test was conducted by a universal mechanical testing machine (Model, Instron 5567, Instron, Norwood, MA, USA). The electrical outputs (V_{OC} , I_{SC}) of TENG during stretching operations were implemented by a linear motor and an electrometer (Keithley 6514 System, Tektronix, Beaverton, OR, USA). The V_{OC} represents the open-circuit (OC) voltage and the I_{SC} represents the short-circuit (SC) current. The stitching double weave structure has two systems of independent warp and weft, forming the exterior and lining layers of the fabric on the same machine, respectively. These two layers are stitched by the third system of warp yarn, known as the extra warp stitching method. The warp and weft yarn on the exterior layer becomes the exterior warp and exterior weft yarn, respectively. The warp and weft yarn on the lining layer become the lining warp and the lining weft yarn, respectively.

3. Results and Discussion

The 3DWE-TENG in an unstretched state is presented in Figure 2a; the PA conductive yarn, PET multifilament, and PU were chosen as the warp yarns, PET multifilament was chosen as the weft yarn. Figure 2b presents the 3DWE-TENG in a stretched state. From the photographs of 3DWE-TENG in different states, PA conductive yarn and PET multifilament are in contact before the stretch and separate after the stretch, which generates electricity. According to the weave diagram of 3DWE-TENG (Figure 2c), one warp weave repeat unit is 10. In one weave repeat unit, the yarn arrangement is PU/PA/PET/PA/PET/PU/PET/PA/PET/PA. The weft yarn density during the weaving process has to be adjusted to a relatively low value; 83 yarns per 10 cm. Due to fabric retraction, the weft yarn density is 250 yarns per 10 cm after coming from the loom. With the low weft yarn density on the loom and large weft yarn density after coming from the loom, the distance between the adjacent weft yarn after the stretch is big enough.

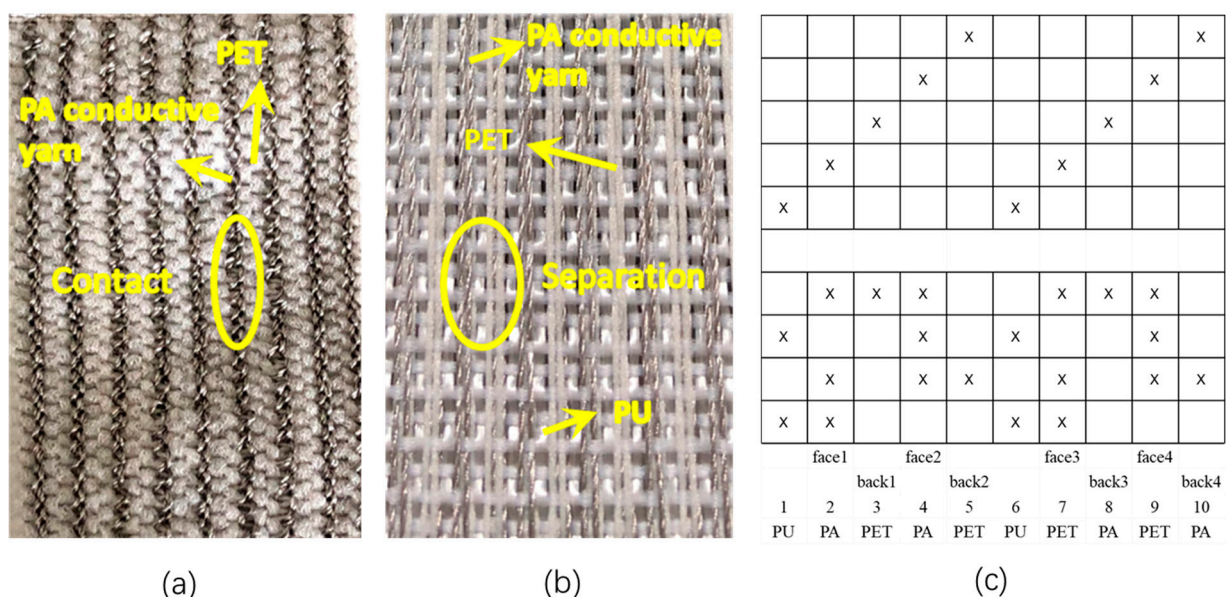


Figure 2. (a) Photographs of 3DWE-TENG before the stretch; (b) Photographs of 3DWE-TENG before and after stretch; (c) Stitching double weave diagram.

In the fabric in the original state without stretch, all warp yarns, except PU yarns, are fluffy with large warp yarn wave highness, due to the long yarn float on the loom. Once it is stretched, the PA conductive yarns and PET multifilaments are gradually straightened, which contributes to a decrease in yarn fineness. Furthermore, the yarn fineness of PU yarns decreases. Due to the change in the yarn fineness, the distance value between the PA conductive yarns and PET multifilaments increases, which explains the reason for electricity generation. Under the driving of external mechanical motions, the relative position of the PA conductive yarn and the PET multifilaments surface will periodically change in the 3DWE-TENG, which will lead to periodic variation in the induced potential difference between the electrode (PA conductive yarns) and the ground. In order to maintain the electrostatic equilibrium between the PA conductive yarns and the ground, the free electrons in the electrodes will be driven to flow back and forth to screen the induced potential difference. In this way, the applied mechanical energy is converted into electricity. As shown in Figure 3, the working mechanism of the 3DWE-TENG is briefly presented. To simplify the discussion, a PA conductive yarn and a PET multifilament of the lining and the exterior layer in one warp weave repeat unit were considered, since they are the basic units. All PA conductive yarns in the fabric were connected as the electrodes of the fabric. In the original stage, no electrical potential existed between the surface of the PA conductive yarn and the PET. According to contact electrification theory, the surfaces of the PA conductive

yarn and PET are charged with the same amount of opposite charges (Figure 3i). The PA conductive yarn proved to be negatively charged because of the silver's ability to attract more electrons than the PET. When they were stretched and separated from each other, the potential difference between the electrode and the ground prompted electrons to flow from the Ag through external loading to the ground (Figure 3ii), resulting in an electrical current. As the PET and the PA conductive yarn were moved quite far away, a new electrical equilibrium was achieved and the electrons stopped moving (Figure 3iii). As the external force was withdrawn, PET approached the PA conductive yarn; again, electrons inversely flowed from the ground to the electrode (PA conductive yarn) to achieve a charge balance (Figure 3iv). When the PET fully contacted the PA conductive yarn, charge neutralization occurred again. Through continuous contact–separation movements between the PET and the PA, conductive yarn generated continuous alternating current outputs from the 3DWE-TENG fabric through the external loading.

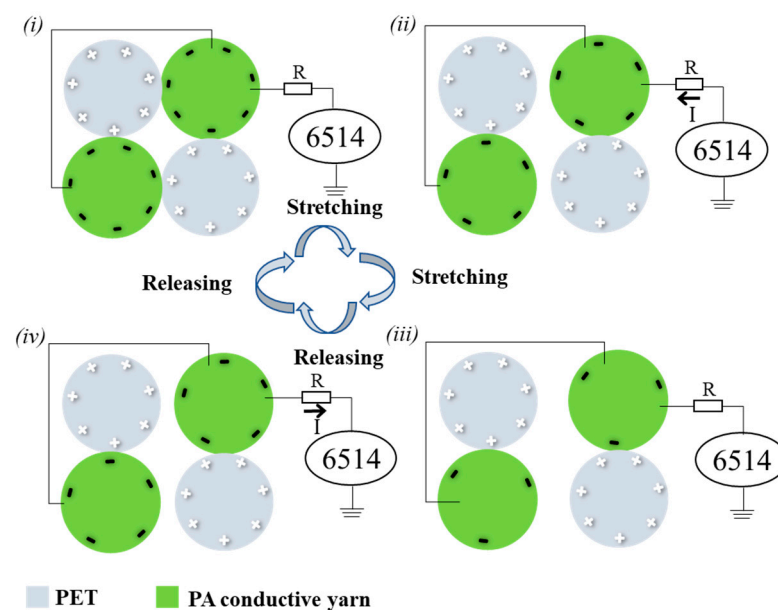


Figure 3. The working mechanism of the 3DWE-TENG with a stitching double weave, (i) In the original state without stretch; (ii) The 3DWE-TENG is gradually stretched; (iii) The 3DWE-TENG is stretched to the largest deformation; (iv) The 3DWE-TENG is recovering to the original state.

To optimize the electrical output performances of the 3DWE-TENGs, the influences of the structure parameters, including the PA conductive yarn fineness, the tensile strain, and the weft yarn density, were systematically investigated. To this end, the outputs of two 3DWE-TENGs which were fabricated by 280D and 140D, respectively, were tested at different tensile strains. The electrical output performances were measured using a linear motor to provide periodic stretching-releasing movements. The length chosen was 5 cm. For the accuracy of the test results, the other structural parameters of these two 3DWE-TENGs were kept the same, known as the control variable method. Under different tensile strains, ranging from 20% to 100%, the electrical output performances of two 3DWE-TENGs fabricated by 280D (Figure 4a,b) and 140D (Figure 4c,d) PA conductive yarn were presented, respectively. According to the results, as the tensile strain increases from 20% to 100%, the stretching-induced electrical output performances of both 3DWE-TENGs gradually increase, owing to the higher separation distance between the PA conductive yarn and the PA yarn. Electrical output performance comparisons between these two different 3DWE-TENGs are presented in Figure 4e,f; the outputs of 3DWE-TENGs fabricated by 280D PA conductive yarn are significantly higher than those of 140D PA conductive yarn. Due to the decrease in conductive yarn fineness, the effective contact area between PA conductive yarn and PET decreases, and the outputs are lower.

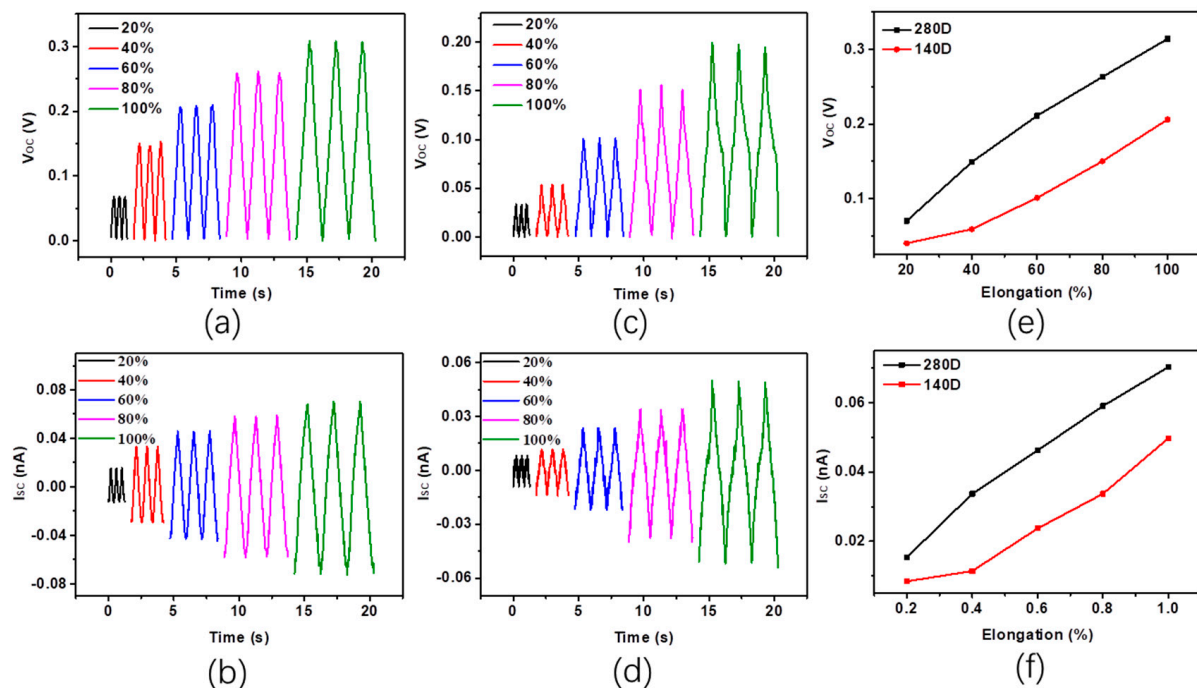


Figure 4. (a,b) Electrical output performances of the 3DWE-TENG fabricated with 280D PA conductive yarn; (c,d) Electrical output performances of the 3DWE-TENG fabricated with 140D PA conductive yarn; (e,f) Electrical output performance comparison between two 3DWE-TENGs fabricated with 280D and 140D PA conductive yarn.

In this unique woven structure, the warp yarn density during the weaving process is relatively lower than in the common weave structure. As a result of the lower weft yarn density and the large PU tensile strain, the 3DWE-TENG is qualified with excellent stretchability. Therefore, the weft yarn density may affect the outputs of 3DWE-TENG. To this end, the 3DWE-TENG with a warp yarn density of 417 ends/10 cm (three ends per dent) was fabricated and tested under different tensile strains, ranging from 20% to 100%. For the accuracy of the test results, the other structural parameters of these two 3DWE-TENGs were kept the same. The electrical output performances are presented in Figure 5a,b. Similar to the above results, as the tensile strain increases from 20% to 100%, the stretching-induced electrical output performances of 3DWE-TENG gradually increase, owing to the higher separation distance between the PA conductive yarn and the PA yarn. To further reveal the relationship between the warp yarn density and the electrical output performances, the outputs of 3DWE-TENGs with 533 ends/10 cm (five ends per dent) and 417 ends/10 cm (three ends per dent) were compared to find the difference. As illustrated in Figure 5c,d, the electrical output performances of 3DWE-TENG with a bigger warp yarn density are slightly higher than those with a smaller warp yarn density when the tensile strain is below 100%. However, the outputs of these two 3DWE-TENGs are nearly the same when the tensile strain is 100%. For all TENGs, the contact area and the separation distance simultaneously affect their electrical output performances. Compared with the 3DWE-TENG with a smaller warp yarn density, the 3DWE-TENG with a bigger warp yarn density has a large contact area and low contact-separate distance between the PA conductive yarn and the PET multifilaments. In our opinion, when the tensile strain is below 100%, the contact-separate area may be the main influence factor, which results in higher outputs of the 3DWE-TENG with a bigger warp yarn density. When the tensile strain is 100%, the contact-separate distance may be the main influential factor, which results in the higher outputs of the 3DWE-TENG with a smaller warp yarn density. According to the linear fitting results of the V_{OC} curve, the R^2 of the 3DWE-TENG with a larger warp yarn density and a smaller warp yarn density is 0.9877 and 0.9676, respectively. Furthermore, in common clothes, as

well as the requirement for cloth stretchability in general use, the tensile strain of cloth is below 100%. According to the output difference, linear fitting results comparison of the two 3DWE-TENGs, and the tensile strain requirement in wearable textiles, the 3DWE-TENG with a larger warp yarn density is more adaptable to be used as a stretchable sensor.

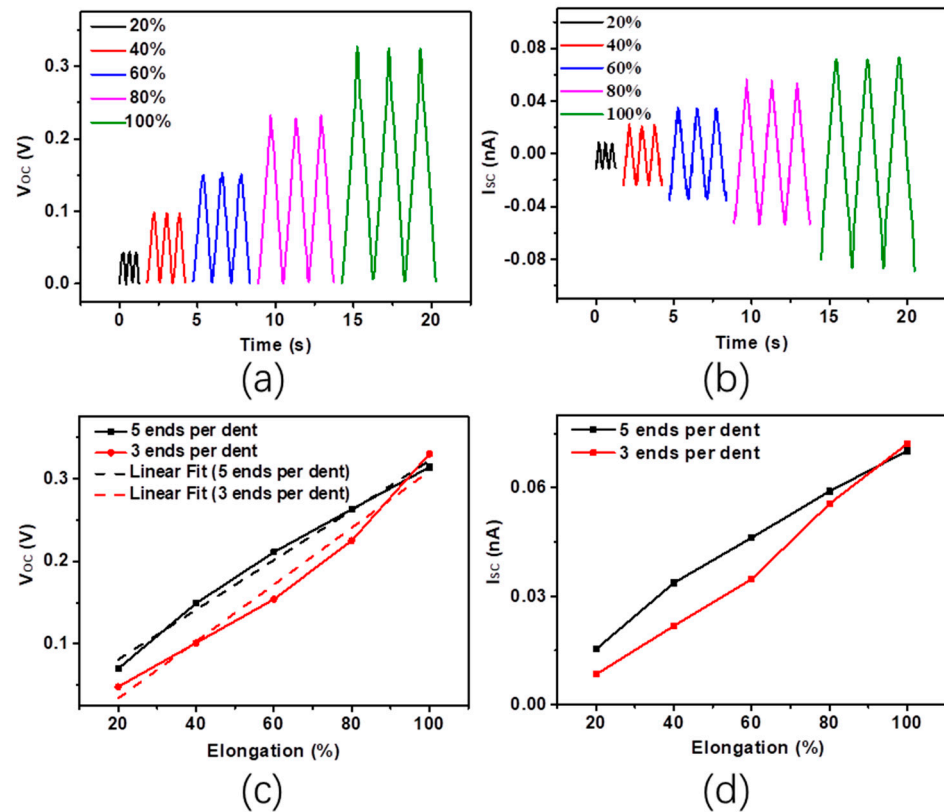


Figure 5. (a,b) The electrical output performances of the 3DWE-TENG with warp yarn density 417 ends/10 cm; (c,d) The electrical output performances comparison between two 3DWE-TENGs with different warp yarn densities, including five ends per dent and three ends per dent.

Based on the most common yarns applied and the unique woven structure, the 3DWE-TENG is not only qualified with advantages, including lightweight, low cost, high efficiency, flexibility, stretchability, and a wide choice of materials, but can also rapidly respond to external mechanical stimuli, which can be used for self-powered sensing and energy harvesting. However, practically, it still faces a challenge. In this stitching double weave structure, the PA conductive yarn is simultaneously used as the electrode and warp yarn. Therefore, the PA conductive yarns are exposed on the surface of the fabric, which decreases the fabric's comfortability and limits its application in wearable electronics. The potential solution is to choose the PA conductive yarn as the electrode and the weft yarn, which could be hidden between the lining layer and the exterior layer. The face and back sides of 3DWE-TENG are covered with loops of PET multifilaments, which improve wearability, protect the electrode, decrease air oxidation, and provide more opportunities for wearable device applications.

Here, by using the same fabricating method, a 3DWE-TENG with 280D PA conductive yarn as the weft yarn and the electrode, PET multifilaments, and PU yarns as the warp yarns were designed and fabricated. To clearly present the woven structure, two different colors of PET multifilaments were chosen as the lining warp yarns and exterior warp yarns, including red and white. Red PET multifilaments acted as the lining warp yarns and white PET multifilaments acted as the exterior warp yarns. As shown in Figure 6a–c, the photographs of the face view (Figure 6a), the back view (Figure 6b), and the side view (Figure 6c) of 3DWE-TENG are presented and show the good flexibility of 3DWE-TENG.

From the pictures, the PA conductive yarn is concealed in the middle of the fabric, which improves the fabric's wearability and comfort, and protects the service life. To investigate the influence of warp yarn density on the structure and the output, two 3DWE-TENGs with different warp yarn densities were fabricated. Photographs of them in a stretched state are presented in Figure 6d,e, which show the warp yarn density difference.

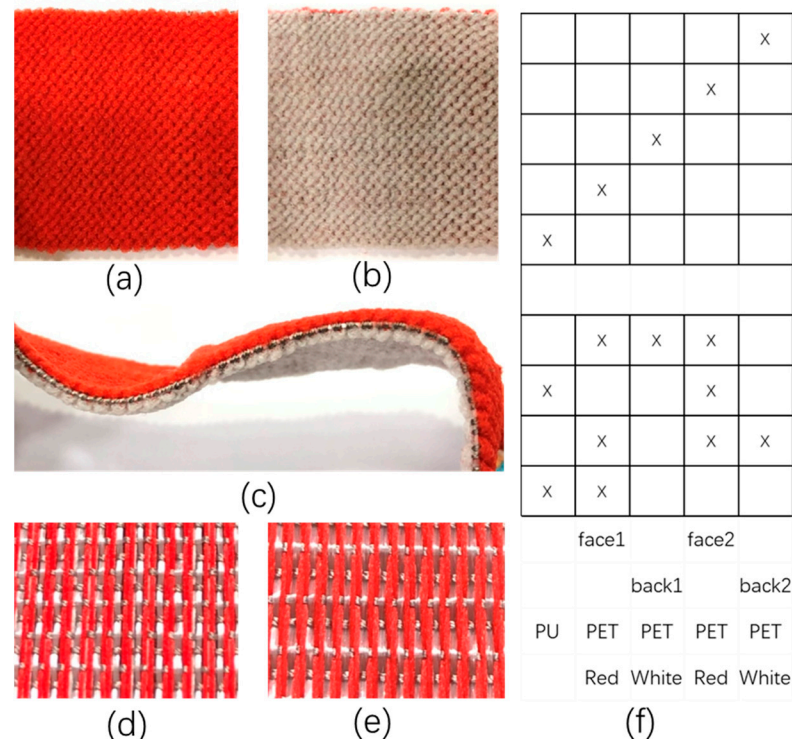


Figure 6. (a) The face view of the 3DWE-TENG with the electrode as the weft yarn; (b) The back view of the 3DWE-TENG with the electrode as the weft yarn; (c) The side view of the 3DWE-TENG with the electrode as the weft yarn; (d) 3DWE-TENGs with a warp yarn density of 417 ends/10cm in a stretch state; (e) 3DWE-TENGs with a warp yarn density of 533 ends/10 cm in a stretch state; (f) The stitching double weave diagram of the 3DWE-TENG with the electrode as the weft yarn.

Due to the stretched PU yarns on the loom, the fabric will retract after coming from the loom and achieve high elasticity, which results in the large warp yarn wave highness. As explained above, the stitching weave fabric is covered with suspended loops of warp yarns, including red PET multifilaments and white PET multifilaments. With a large warp yarn wave highness, these loops of the fabric do not come into contact with the weft yarns (the PA conductive yarn). While the fabric is stretched, the warp yarn wave highness of the PET multifilaments decreases, and the float increases. The PET multifilaments in the lining and exterior layers become gradually closer to the weft yarns and finally come into contact with the PA conductive yarn. During the stretching and releasing process, the PA conductive yarns in the middle layer come into contact with and separate from the PA conductive yarns on the lining layer and the exterior layer, which can generate electric energy. According to the weave diagram of 3DWE-TENG (Figure 6f), one warp weave repeat unit is five. In one weave repeat unit, the yarn arrangement is PU/Red PET/White PET/Red PET/White PET. The weft yarn density during the weaving process has to be adjusted to a relatively low value, 83 yarns per 10 cm. Due to the fabric retraction, the weft yarn density is 250 yarns per 10 cm after coming from the loom.

The working mechanism is presented in Figure 7a. To simplify the discussion, one weft yarn (PA conductive yarn) and one warp yarn (PET multifilament) in one warp weave repeat unit were considered, since they are the basic units. During the stretch-release process, the triboelectric layer (PET multifilament) contacts and separates from

the electrode (PA conductive yarn), which changes the local electrical field distribution of the electrode. Therefore, there are electron exchanges between the PA conductive yarn and the reference electrode (ground) to keep the potential balanced. In the original stage (Figure 7(ai)), no electrical potential exists between the surface of the PA conductive yarn and the PET multifilament. According to the polarity difference, the surfaces of the PA conductive yarn and PET are charged with opposite charges. The PA conductive yarn proves to be negatively charged because of the silver's ability to attract more electrons than the PET. When the fabric is stretched, two yarns get gradually closer, which affects the surrounding electric field of the PA conductive yarn and contributes to the change in its potential. The potential difference between the electrode and the ground prompts electrons to flow from the ground through external loading to the PA conductive yarn (Figure 7(aii)), resulting in an electrical current. As the tensile strain is big enough, the PET and the PA conductive yarn come into contact with each other, a new electrical equilibrium is achieved, and the electrons stop moving (Figure 7(aiii)). As the external force is withdrawn, the warp yarn wave highness of the PET multifilament increases, which results in the separation between the PA conductive yarn and the PET multifilament. Due to the change in the electric field, electrons inversely flow from the electrode (PA conductive yarn) to the ground to achieve a charge balance (Figure 7(aiv)). When the fabric returns to its original state, a new electrical equilibrium is achieved and the electrons stop moving (Figure 7(ai)). Continuous contact–separation movements between the PET and the PA conductive yarn generate continuous alternating current outputs from the 3DWE-TENG fabric through the external loading.

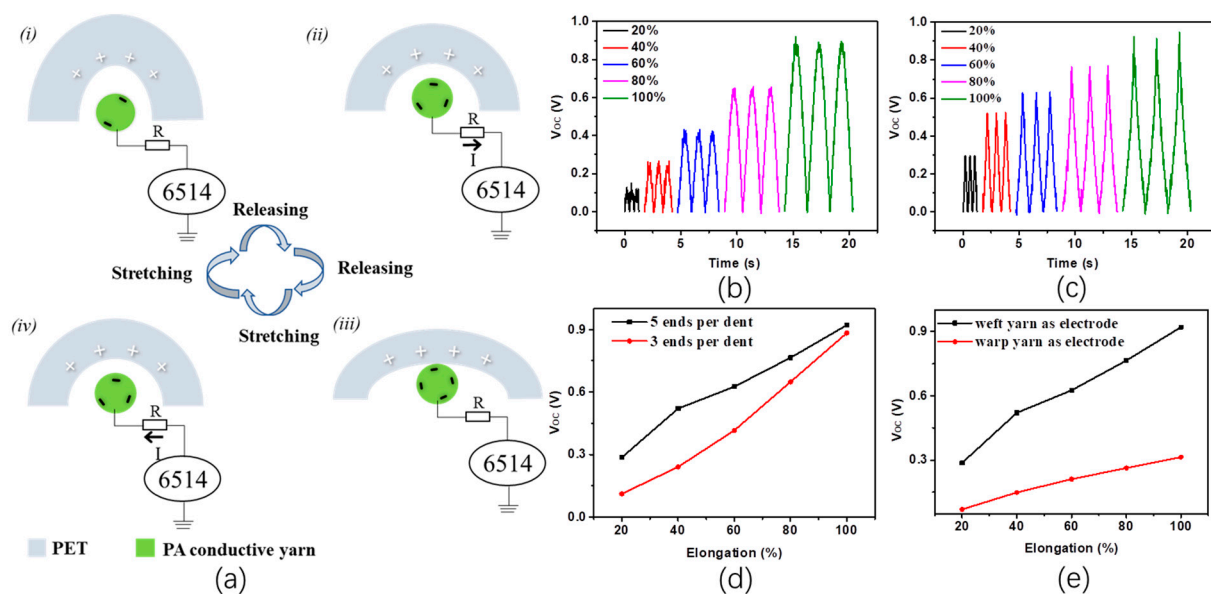


Figure 7. (a) The working mechanism of the 3DWE-TENG with the electrode as the weft yarn, (i) In the original state without stretch; (ii) The 3DWE-TENG is gradually stretched; (iii) The 3DWE-TENG is stretched to the largest deformation; (iv) The 3DWE-TENG is gradually recovering to the original state; (b) The V_{OC} of 3DWE-TENG with a warp yarn density of 417 ends/10 cm in a stretch state; (c) The V_{OC} of 3DWE-TENG with a warp yarn density of 533 ends/10 cm in a stretch state; (d) The V_{OC} comparison of two 3DWE-TENGs with different warp yarn densities, including five ends per dent and three ends per dent; (e) The V_{OC} comparison of two 3DWE-TENGs with the weft yarn and the warp yarn as the electrode, respectively.

To quantify the electrical output performances, the 3DWE-TENGs fabricated with different warp yarn densities, including five ends per dent and three ends per dent, were fabricated and tested. The results are presented in Figure 7b (three ends per dent) and Figure 7c (five ends per dent). The V_{OC} comparison between 3DWE-TENGs is presented in Figure 7d; the output of 3DWE-TENG with large warp yarn density is a little higher than

that of small warp yarn density, which is consistent with the outputs of 3DWE-TENGs (the warp yarn as the electrode).

As the two styles of 3DWE-TENG had the same structure parameters, including the warp yarn density, the weft yarn density, and raw materials, the outputs were compared to investigate the influence of the electrode, as presented in Figure 7e. From the comparison, it can be found that the 3DWE-TENG with PA conductive yarn as the electrode has higher output performances, owing to the working mechanism difference. The V_{OC} of 3DWE-TENG with the electrode (the PA conductive yarn) as the weft yarn and the warp yarn is 0.893 V and 0.312 V, respectively. The V_{OC} of the 3DWE-TENG with the electrode (the PA conductive yarn) as the weft yarn is 0.893 V, which is nearly three times larger than that with the electrode (the PA conductive yarn) as the warp yarn; about 0.312 V. Regarding the output difference, the 3DWE-TENG with the electrode (the PA conductive yarn) as the weft yarn uses less PA conductive yarn in the fabric. For the electrode as the weft yarn, the fabric with a 5 cm length and a 2.3 cm width needs to use at least 5.7 m PA conductive yarn. For the electrode as the warp yarn, the fabric needs to use 2.9 m PA conductive yarn at least, which is more cost effective. More importantly, with the PA conductive yarn concealed in the middle of the fabric, it decreases air oxidation and protects the dielectric coating from external friction damage. According to the experiment results, the stitching double weave 3DWE-TENG with PA conductive yarn as the electrode not only has higher electrical output performances, low cost, and perfect comfortability, but also protects the electrode and decreases the air oxidation.

The photograph comparison of the 3DWE-TENG (with warp yarn as the electrode) at 0% tensile strain and 300% tensile strain is presented in Figure 8a. The photograph comparison of the 3DWE-TENG (with weft yarn as the electrode) at 0% tensile strain and 300% tensile strain is presented in Figure 8b. This demonstrates the high elasticity of 3DWE-TWNG with a stitching double weave structure.

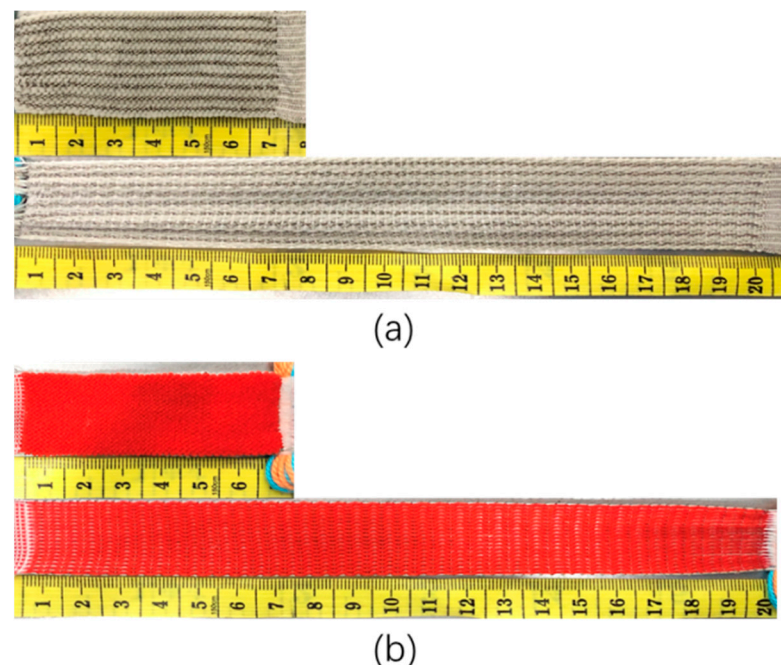


Figure 8. (a) Photograph comparison of the 3DWE-TENG (with warp yarn as the electrode) at 0% tensile strain and 300% tensile strain, (b) photograph comparison of the 3DWE-TENG (with weft yarn as the electrode) at 0% tensile strain and 300% tensile strain.

To demonstrate the ability of 3DWE-TENG for energy harvesting, a PTFE fabric was driven by the linear motor to periodically make contact with and separate from the 3DWE-TENG with a frequency of 0.5 Hz, a pressure of 1 kPa, and a contact area of 15 cm². The

V_{oc} , I_{sc} , and Q_{SC} are presented in Figure 9a–c. Through this contact-separation motion, the 3DWE-TENG can be used to light up 87 LEDs, which is presented in Figure 9d. Due to the high detection precision of the 3DWE-TENG, it is chosen to be used as a bend-stretch sensor, which is applied on the elbow of the human body to detect bend angles, as shown in Figure 9e. The output voltages of 3DWE-TENG as a bend-stretch sensor at different bend angles (including 15°, 45°, 90°, and 120°) were tested, and they are presented in Figure 9f. As a bend-stretch sensor, 3DWE-TENG can be used to detect human motion.

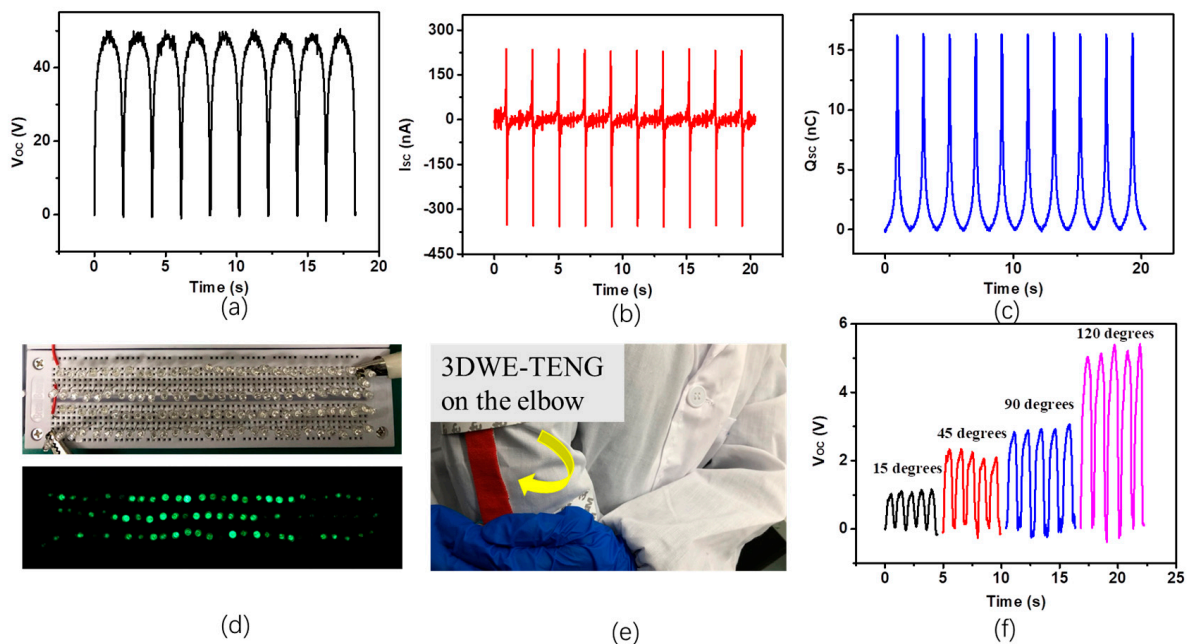


Figure 9. (a–c) The V_{oc} , I_{sc} , and Q_{SC} of the 3DWE–TENG when it comes into contact with and separates from the PTFE fabric, (d) the 3DWE–TENG can be used to light up 87 LEDs, (e) photograph of the 3DWE–TENG as a bend-stretch sensor, (f) output voltages of 3DWE–TENG as a bend-stretch sensor at different bend angles (including 15°, 45°, 90°, and 120°).

4. Conclusions

In summary, a mass-manufactured 3D stitching double weave fabric-based elastic triboelectric nanogenerator (3DWE-TENG) is developed. Based on the mature woven technology and creative method, 3DWE-TENG is qualified with high tensile strain, a stable structure, high fabricating efficiency, and perfect stretchable resilience. This 3DWE-TENG fabric is woven by PET multifilaments, PU elastic yarns, and PA conductive yarns. These three raw materials are easy to obtain, low in cost, and simplify the fabricating process. Due to its stable electrical output performances and rapid response to external tensile strain, it can be simultaneously used for energy harvesting and self-powered bend-stretch sensing through both the lining layer and the exterior layer. Yarn arrangements in the weft yarn and the warp yarn of the 3DWE-TENG were compared to find a better structure design. By taking advantage of this 3D stitching double weave structure, we improved the fabric comfortability by choosing the PA conductive yarn (the electrode) as weft yarns, which not only enhanced the electrical output performance, decreased the raw material cost, and improved fabric comfortability, but also protected the electrode and decreased the air oxidation. This work provides more opportunities for stretchable power sources and self-powered sensors with applications in wearable electronics. With these excellent performances, the designed, highly stretchable 3D woven self-powered fabric can be a practical alternative for modern popular wearable electronics.

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