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# 3D spacer fabric based multifunctional triboelectric nanogenerator with great feasibility for mechanized large-scale production

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ABSTRACT

Harvesting energy from environment (e.g. human motions), is a cost-effective strategy to power the personal electronics. Triboelectric nanogenerators (TENGs) have been proven to be an effective device that can scavenge the biomechanical energy from human motions. However, the compatibility for wearing and mechanized production, two critical criterions for practical applications, of the TENGs remain as challenges. Here, we demonstrated an elegantly designed 3D knitted spacer fabric based TENG by utilizing the vertical contact electrification between two polymers with different tribo-polarities. The open circuit voltage of the one single TENG pixel of as-fabricated TENG reaches more than 3 V, while the short circuit current reaches around 0.3 μA. The output power reaches 16 μW, whereas it can be delicately tuned by controlling the number of TENG pixels involved. As a power source, the as-fabricated TENG can continuously lit up the LEDs. In addition, the as-fabricated TENG shows outstanding ability to effectively monitor the human motions. Furthermore, the ability of in situ sensing the pressure of a foot during the human walking was successfully realized. Our study reports a novel large-scale-fabrication method of TENGs compatible with mechanized production, which shows outstanding output performance as well as the excellent smart sensing abilities.



## 1. Introduction

A prominent technological trend in contemporary society is the rapid growth of miniature electronic devices applied in our daily lives. Accompanying with this trend, advances in wearable energy sources have attracted a lot of attention [1,2]. Meanwhile, the requirement of frequently charging during long-term use of conventional energy storage devices holds back their prospects [3–6]. Therefore, nanogenerators that can harvest the mechanical energy, especially from human motions (e.g. walking and stretching) are of great significance. Among different types of nanogenerators, triboelectric nanogenerators (TENGs) based on the conjunction of triboelectrification and electrostatic induction have been proven to be able to harvest the mechanical energy from human motions and convert it into electricity at a high efficiency and output power density [7–12]. Furthermore, TENGs can be easily incorporated into fabrics because the triboelectrification ubiquitously exists for most common materials used for fabrics, such as nylon, polyester and Teflon [7,9,13,14]. This indicates the intense potential of fabricating wearable TENGs. In addition to the ability of transferring the mechanical energy from human motions to electricity, the multi-functionalities of TENGs are another key pursuit [15–24]. Therefore, the achievement of self-powered sensors based on wearable TENGs with high-resolution and high sensitivity is highly attractive for a wide range of applications in motion monitoring and human health caring [2,25–29].

Generally, there are three modes of TENGs: sliding mode [7,16,27,30], rotation mode [16,31–34], and vertical contact mode [8,14,35–38]. Compared to the former two, the vertical contact mode based TENGs are more promising in wearable TENGs since the vertical movements account for the main part of human activities. The proper resilience, therefore, is the key challenge to fabricate wearable TENGs. Two common tactics to impart the resilience to fabrics are (1) adding springs or other elastic additives between two separate layers [9,10,12,29,39], and (2) designing an arch structure [35,37,40]. Although these strategies are effective, the compatibility with fabrics is very poor, letting alone the feasibility to mechanized production.

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Mechanization produced 3D spacer fabrics, which are delicately designed with excellent resilience, are very promising for inherently wearable TENGs. There are three layers in a 3D spacer fabric: the upper and down layer that are similar with the conventional fabrics, and a specially designed spacer layer that can provide proper resilience for the whole fabric. Meanwhile, the tribo-polarity of upper and down layer can be conveniently tuned by choosing the materials or coating with textile auxiliaries. Taking these advantages, 3D spacer fabric based TENGs show a great feasibility to mechanized production.

Herein, we report the vertical contact mode based TENG utilizing the 3D spacer fabric produced with the machine used in textile industry. The graphene ink is selected to coat the upper surface of the nylon layer in order to collect the charges generated by the triboelectrification. The key issue to establish a TENG is to choose a material with the opposite tribo-polarity compared to the nylon according to the triboelectric series. Based on the serious consideration of the nylon compatibility and the wearing compatibility, we choose polytetrafluoroethene (PTFE) textile auxiliaries to coat the other outer layer of the 3D spacer fabric. Furthermore, the 3D spacer fabric is pixelated by small TENG pixel arrays for the convenience of the realization of multi-functionalities in one device. The open circuit voltage of one single TENG pixel in the as-fabricated 3D spacer fabric based TENG reaches more than $3\ \mathrm{V\,cm^{-2}}$, while the short circuit current reaches around $0.3\ \mu\mathrm{A\,cm^{-2}}$. Moreover, the output of the whole fabric based TENG can be delicately tuned by controlling the number of TENG pixels. The output power can reach a maximum value of 16μW at an external resistance of about 0.6 MΩ with a single TENG pixel. The whole 3D spacer fabric based TENG can easily power the light-emitting diodes (LEDs), showing the excellent ability in transferring mechanical energy to electricity. In addition to the basic performance as the power source, the 3D spacer fabric based TENG also serves as the self-powered monitoring system to track and identify the human motions. Taking a step further, it can in situ sense the pressure of the foot during human walking with high sensitivity as well. Our demonstration successfully shows a novel design for a TENG with the ultimate wearable compatibility and feasibility to industrialization, as well as the self-powered tracking and sensing ability for human motions.

## 2. Materials and methods

### 2.1. Fabrication of the 3D spacer fabric

3D spacer fabrics used in this study were designed based on a 3D weft-knitted fabric structure, which consists of three layers: two outer fabric layers and a spacer yarn layer. They were knitted on a STOLL computerized flat knitting machine, wherein the front needle bed and back needle bed are positioned horizontally while the carriage, which contains the cam systems, moves back and forth across the needle bed to make the fabric. To knit a 3D spacer fabric, three sets of yarns are required. The fabric fabrication process includes three steps. The first step is to knit the front layer of the fabric on the front needle bed using the first set of yarn. The second step is to knit the back layer of the fabric on the back needle bed using the second set of yarn. The third step is to knit the spacer layer on both the front needle bed and back needle bed using the third set of yarn in order to link the front layer and back layer together. In order to fabricate the 3D fabric with hollow spaces, the spacer layer is alternately knitted with a defined sequence. It should be noted that in order to keep the space between two outer fabric layers, monofilament must be used to knit the spacer layer due to its high stiffness, and multifilament is normally used to knit two outer fabric layers to get a soft handle. In this study, double 30/70D spandex/nylon multifilament was used to knit the outer layers and double 0.15 mm polyester monofilament was used to knit the spacer layer.

### 2.2. Fabrication of the 3D fabric spacer based TENG

The as-fabricated 3D spacer fabric was used as the base of the TENGs. As nylon fibers have intrinsic positive tribo-polarity, the down layer of the 3D fabric was coated with the commercially available polytetrafluoroethene (PTFE) coatings, which show the negative tribo-polarity. In order to realize the multi-functionalities of the 3D spacer fabric based TENG, the 3D spacer fabric was pixelated before coating by the home-made screen as shown in Fig. S1. The area of a single TENG pixel is restricted to 1 $\mathrm{cm^2}$. (The detailed pixelating process is shown in Fig. S2 in Supporting Information.) For collecting the charges generated on the upper nylon layer, the graphene ink was used to coat the upper surface of the upper nylon layer. To avoid the totally rinsing of upper nylon layer, the lower surface of the upper nylon layer is previously coated with the tape as shown in Fig. S3 (Supporting Information).

### 2.3. Characterization and measurements

The morphologies were investigated by an environmental scanning electron microscope (FEI/Philips XL30). A home-made pushing tester was used to apply programmed forces to the 3D spacer fabric based TENG. A low-noise voltage preamplifier (model no. SR560, Stanford Research Systems, Inc.) and a low-noise current amplifier (model no. SR570, Stanford Research Systems, Inc.) were used to detect the output signals generated from the 3D spacer fabric based TENG.

## 3. Results and discussions

### 3.1. Design and fabrication of TENG based on the 3D spacer fabric

Fig. 1a shows the design of the 3D fabric based on a 3D spacer weft-knitted structure, which contains three layers: two outer fabric layers and a spacer yarn layer. The spacer yarn layer, which is made of polyester monofilament (inset in Fig. 1a), can offer the good resilience for the whole fabric. In addition, to make the 3D fabric easy for the fabrication of the TENG, the materials used for the upper and down layers were delicately selected. Taking the tribo-polarity, suitability for knitting and wearing compatibility into account, nylon multifilament, a common material used in clothes with very high tendency to lose electrons, is used as the material for the upper and down layers. The fabrication process is schematically described in Fig. 1b–e. The 3D spacer fabric is knitted on a STOLL computerized flat knitting machine as shown in Fig. S1 (Supporting Information). In such a type of machine, the front needle bed and back needle bed are positioned horizontally while the carriage which contains the cam systems moves back and forth across the needle bed to make the fabric. Three sets of yarns are required to knit the 3D fabric as shown in Fig. 1b. In particular, the first step is to knit the front layer of the fabric on the front needle bed using the first set of yarn (Fig. 1c). The second step is to knit the back layer of the fabric on the back needle bed using the second set of yarn (Fig. 1d). And the third step is to knit the spacer layer on both the front needle bed and back needle bed using the third set of yarn in order to link the front layer and back layer together. In order to fabricate 3D fabrics with hollow spaces, the spacer layer is alternately knitted with a defined sequence as shown in Fig. 1e. It should be noted that in order to keep the space between two outer fabric layers, monofilament must be used to knit the spacer layer due to its high stiffness, and multifilament is normally used to knit the two outer fabric layers to get a soft