Triaxial braided piezo fiber energy harvesters for self-powered wearable technologies

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Abstract
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Triaxial Braided Piezo Fibers Energy Harvesters for Self-Powered Wearable Technologies

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Today we associate wearable technologies with electronic devices and novel approaches for powering these devices are being enabled by the advent of new piezoelectric materials and novel fabrication strategies. Mechanical energy harvesters are needed for such diverse applications as self-powered wireless sensors, structural and human health monitoring systems, and cheaply harvesting energy from human movement. Herein, we demonstrate novel triaxial braided PVDF yarn harvesters that piezoelectricity convert tensile mechanical energy into electrical energy. Compressing or bending braided PVDF yarns generated maximum output voltage of 380 mV and power density of 29.62 µWcm⁻² which is ~1559% higher than previously reported for the piezoelectric textiles. It is found that developed triaxial energy generator exhibit significantly higher sensitivity by a factor 4 in compared with the PVDF energy generator. Unlike for other piezoelectric harvesters, the triaxial braided PVDF yarn produces tensile energy harvesting and enables extreme durability which is enabling cycles with up to 50% strain for thousands of cycles with no changes in its performance. The production processes is compatible with industrial, large-scale textile manufacturing that can be used for a variety of potential applications such as wearable electronic systems and energy harvesters charged from the everyday body movement.

Introduction

Smart garments are being developed to perform various ground-breaking social and protective functions. (1-5) Today’s wearable technologies are strap-on electronic devices like wrist bands and are extensively used for fitness and health monitoring. However, the fastest growth sector in the coming years is predicted to be smart garments where electronic functionality is seamlessly and invisibly integrated into the garment and without compromising aesthetic appeal and comfort. Strategies to achieve this objective do not yet exist and one of the challenges for manufacturing of smart fabrics is to develop textile based transmitters, sensors, interconnects and power sources. Recent developments in advanced materials are poised to create significant new opportunities for the development of smart textiles. (6-10) Materials researchers are attempting to produce fibers with desired electronic functionality without compromising strength, comfort and aesthetic appeal.

This recent research has identified that energy harvesting from ambient energy sources is an increasingly important method of providing power to distributed wearable electronics where physical connection to a power source is impractical. (11) The strategy is based on definable energy targets to be harnessed from body movements, such as human locomotion (12, 13) and human body functions. (14) Textile structure is highly attractive for unobtrusive energy harvesting from human activity in which piezoelectric polymers are the most suitable choice due to their low weight in combination with outstanding flexibility and tensile strength. (15) The best conventional mechanical energy harvesting methods typically rely on piezoelectric materials for the conversion of mechanical energy from ambient vibration sources to electrical energy. (11) Various flexible piezoelectric modules have been developed to capture energy from bending motions associated with heartbeat (16), respiration (17), muscle stretching (18) and eye blinking. (19) Self-powered stretchable elastic energy fibres have been developed that have the ability to use photoelectric energy to charge a battery. (20) Recently, flexible piezoelectric fibres have attracted significant attention due to their ability to be integrated into fabrics, or stitched into existing textiles. (15, 21) Poly (vinylidene fluoride), (PVDF) offers the highest piezoelectric coefficient, provided that one of the polar crystal phases can be accessed. (22) PVDF consists of four crystalline phases, α, β, γ, and δ. Among the three polar phases, the β-phase has the largest spontaneous polarization per unit cell. In order to achieve a high piezoelectric performance, a high content of the β phase in the PVDF material is required. (11)
β phase can be induced by a variety of means including fiber and fabric post-treatment process i.e. cold drawing and poling. The capabilities of PVDF to convert biomechanical energy to electrical power has been explored in a variety of architectures, including blocks in shoe soles, casted films and electro and melt spun fibers. (15-21) The most common problems associated with current flexible piezoelectric generators and architectures are tedious processing techniques, slow production speed, low output power and lack of comfort. (12) For instance, a novel composite material system and a method for constructing flexible, stretchable and wearable piezoelectric energy-generating fibers has been demonstrated using electrospun polyvinylidene fluoride-cotrifluoroethylene (PVDF-TrFE) as piezoelectric material, carbon nanotube (CNT) and silver coated nylon as outer and inner electrodes, respectively. (19) These flexible piezoelectric fibers can be stretched to a tensile strain of 5% and can generate over 50 μW/cm². Another study demonstrated a flexible nanogenerator manipulated from the polymer nanocomposite (PVDF-HFP/Co-ZnO) exhibits an output voltage as high as 2.8 V in 50 Hz. (23) A remarkable enhancement of the output voltage (∼32 V) of a nanogenerator based on a nonelectrically poled cerium(III) complex containing PVDF composite film is achieved by simple repeated human finger imparting. (24) In addition, all-fiber piezoelectric fabrics as power generators and energy harvesters have been developed based on 3D spacer technology. (12) Piezoelectric PVDF monofilaments acted as the spacer yarn material interconnected between silver coated polyamide multifilament yarn layers acting as the top and bottom electrodes. This textile structure provided an output power density in the range of 1.10–5.10 μW/cm² at applied impact pressures in the range of 0.02–0.10 MPa. More recently woven piezoelectrics fabric has been developed using core-sheath melt-spun PVDF/ carbon black/polyethylene and silver coated nylon which was able to produce a peak power output exceeding 1 μW/cm² at an impact pressure of 20 kPa. (15) Although these energy harvesting textiles based on piezoelectric PVDF fibers exhibited stable flexibility and energy harvesting performances, they still suffer from low piezoelectric performance (i.e. power output, durability, sensitivity) because the lower interfacial area between the piezoelectric fibers and outer electrode, in other words there is poor electrical connection between the piezoelectric fibers and electrodes. To solve these problems, the novel fabrication strategies are needed.

In this paper we explore a new type of energy harvesting devices developed by braiding melt-spun PVDF piezoelectric and conductive silver coated nylon yarns. The procedure developed for the fabrication is substantially different from conventional PVDF energy harvesting fabrication processes in which two rigid metallic electrodes and piezoelectric fibers are assembled together and then fabricated into the energy harvesting generator. In our case, a triaxial structure has been developed based on melt-spun PVDF fibers and silver coated nylon. The as-spun PVDF filaments were first braided around silver coated nylon yarn as a highly flexible inner electrodes and then the whole structure was braided a second time with silver coated nylon fibers as outer electrodes. The fabricated device exhibited improved mechanical (i.e. durability, flexibility, comfort) and piezoelectric properties (i.e. sensitivity, power output) as compared with PVDF fibers. In addition the fabricated triaxial braided piezoelectric energy harvesting textile exhibited an efficient and novel way to overcome the stability issues due to the poor fatigue resistance of the metallic electrodes. The triaxial braided piezofibers is strong, lightweight and exceptionally flexible that it is expected to be applicable to wearable devices where high performance is necessary.

Experimental

Material

The piezoelectric polymer used was poly(vinylidene fluoride) (PVDF) supplied in powder form by Solvay Soleris (Milan, Italy), under the commercial name Solef 6010. The melt flow index (MFI) of Solef 6010 is 2 g/10 min at a load of 2.16 kg (or 6 g/10 min at a load of 5 kg) at 230 °C. Silver plated polyamide yarn (235/36dtex 4 ply) was purchased from Shieldex USA. Silicone rubber (Dragon Skin 10 Platinum Silicone – very fast cure) was purchased from Smooth-ON, USA.

Melt spinning of PVDF fiber

Fiber spinning was carried out using a twin screw extruder (Barrel Scientific Ltd.) as schematically shown in Figure 1 and Movie S1 (Supporting Information). PVDF powder (30gr) was heated overnight at a temperature of 70 °C then fed into the extruder. A single hole spinneret with a diameter of 3 mm was used to produce PVDF monofilament. The volume of PVDF flowing through the spinneret was controlled to generate a uniform fiber diameter. The temperature profiles along the extruder ranged from 180 to 220°C over the nine sequential zones. The final diameter of the as-prepared PVDF fiber was ~170 μm. (See supporting information for more details.)

Poling process

The poling process was carried out to maximize the piezoelectric response of the PVDF fibers. For both a single PVDF filament and the triaxial braided PVDF structure the poling was carried out using two different methods of electrical contact (fiber axial and radial direction). A 10 mm section on each end of the PVDF filament was coated with silver paint to act as electrodes. Poling of a 20 mm length of filament between the electrodes was carried out using voltages of 9, 13, 17 or 20
kV applied for 10 minutes with the sample maintained at a temperature of 80 °C. (See supporting information for more details.) In addition, to evaluate the effect of poling process on the piezoelectric response, four different lengths of the as-prepared PVDF filaments were subjected to different applied voltages along their lengths. Table 1 shows the length and applied voltage for poling for each of the PVDF filaments. For each sample tested the applied voltage was increased until a spark was observed.

<table>
<thead>
<tr>
<th>PVDF filament length (mm)</th>
<th>Applied Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
</tr>
</tbody>
</table>

Piezoresponse Force Microscopy (PFM)

Polarization switching in as-prepared PVDF filament was performed using Piezoresponse Force Microscopy Switching Spectroscopy (SS-PFM) to evaluate the piezoelectric sensitivity. In this method, a direct current voltage (Vdc) was applied in a sequence of pulses, so that the phase and amplitude measurement could be done in the off-state of pulses. Both the electrostatic force and piezoelectric deformation contribute to the amplitude in on-state while the electrostatic force is eliminated in off-state. A significant difference in the off-state compared to the on-state measurements indicated the magnitude of the piezoelectric effect. SS-PFM measurements were carried out using an MFP-3D Atomic Force Microscopy (AFM) (Asylum Research, CA), wherein a small section of the as-spun PVDF fiber was attached to a glass slide using the silver paste. A Pt/Ir coated silicon tip (Type: EFM, Nanoworld) with a typical resonance frequency of 75 kHz and a force constant of 2.8 N m⁻¹ was used. Scans were performed at various positions along the length of each fiber to find surfaces suitable for PFM testing. The conductive tip and the silver paste were used as top and bottom electrodes to apply a DC voltage to the sample. The conductive tip was triggered with an AC voltage of 500 mV. During the experiments, the vertical piezoresponse was recorded and PFM amplitude-phase scans were performed with switching DC amplitude up to ±25 V.

The PFM applied voltage is to switch the local dipole underneath the AFM tip. The PFM applied electric field in this paper agrees with previous reports in the refs (25-27), which are also in order of kV/m. SS-PFM testing was carried out on PVDF filaments of different lengths (1, 4, 8, 16 cm). As-prepared PVDF fiber with 10 mm in length was mounted on a glass slide using the silver paste and 5 evenly spaced positions were defined along the fiber length with a marker (Figure 1S). During testing, the probe was pressed firmly onto the specified testing point on the sample with a static pressing force of about 40 nN. A large driving voltage of 10V was then applied in order to generate large amplitude responses.

Fabrication of Triaxial Braided PVDF fibers

A triaxial braided piezoelectric PVDF fiber was developed through a multi-step braiding process using a Trenz-Export braiding machine. The process of fabricating the triaxial braided structure is schematically illustrated in Figure 2a. A silver coated Nylon (235/36 dtex 4 ply thread) was used in the core as the inner electrode along the length of the fiber with 12 as-prepared PVDF filaments braided around the core to form the piezoelectric layer. Finally, the whole structure was braided a second time with 12 silver coated nylon fibers to serve as the outer electrode (Figure 2b). The developed triaxial piezoelectric energy generator device can be easily fabricated to unlimited lengths to meet specific energy and power needs. In addition, the triaxial braided structure provides more durability for the piezoelectric energy generator device due to novel packaging which could protect the PVDF fibers and silver coated nylon electrodes in the device.

Sample Excitation Method

The excitation of as-prepared piezoelectric PVDF samples was carried out using both impact and bending methods. A voltage difference was thereby induced between the inner and outer electrodes on either side due to a separation of charge.

1) Impact test setup

Impact type excitation of the braided PVDF piezoelectric sample was performed by the dropped weight method (Low velocity impact test) to generate an output voltage. The ball weight and size should be considered according to the sample size and its sensitivity. Among six different tested balls, a metallic ball.
(15 mm in diameter and 25g in weight) was dropped from a height of 10 and 20 cm through a guide pipe which directed the impact onto the surface of the braided PVDF device. The electrical response of the piezoelectric to the applied stress was recorded by connecting the inner and outer electrodes to an oscilloscope (Pico Scope4424). To protect samples from potential damage caused by repetitive impacts and also to excite and obtain voltage measurements from large active areas of samples, an aluminum sheet (thickness 5mm) was placed on samples during the impact tests and whole system (samples and aluminum sheet) were fixed with clamps to a rigid surface.

### ii) Bending test setup

The bending test has been carried out using a Shimadzu EZ mechanical tester to evaluate bending excitation performance as well as durability of the developed triaxial braided energy harvesting generator. The bending strain was set to 50% of sample length (20 mm) with a speed of 300 mm/min over 1000 bending cycles (Figure 3). Each of the two clamps of the tensile tester was also isolated by insulating tape to isolate the sample from any extraneous noise generated from the tester mechanism. The Picoscope clamps were also fixed with tape to the tensile tester clamps to help prevent any movement.

### PVDF Characterizations

Fourier Transform Infrared (FTIR) spectra of as-prepared PVDF filaments were carried out over a range of 400–4000 cm⁻¹ using a Shimadzu IR prestige-21 Spectrometer equipped with Pike Technologies MiracleA germanium crystal ATR attachment. The melting temperature (Tm) and melting enthalpy (ΔHm) of PVDF filaments were measured with a differential scanning calorimeter (DSC) (TA Instrument) at a heating rate of 20 °C/min. The fiber diameters were measured with a Leica M205A stereo microscope. The diameter measurement for each fiber was performed at 10 different points along the fiber lengths. The mechanical properties of the samples were measured using a Shimadzu tensile tester (EZ-S). The samples were mounted between two grips and were subjected to tensile test with a constant rate of 100 mm/min. Tensile strength and elongation at break of the sample were recorded by TRAPEZIUMX software. The Young’s modulus was calculated from the slope of the initial part of the curve, where the relationship between stress and strain was linear. The crystalline structures of samples were analyzed by XRD (GBC, MtriX SSD) using Cu Kα radiation (λ = 0.154 nm), with the generator working at 40 kV and 30 mA. Surface morphology of the as-prepared PVDF fibres were examined with the use of a JEOL 6490 Scanning Electron Microscope (SEM). Secondary Electron Imaging (SEI) was used at an accelerating voltage of 10 kV and a probe current setting of 30mV.
Results and Discussion

The melt-spun piezoelectric fiber and novel manufacturing process has been developed to create energy harvesting generator based on the piezoelectric textile. The piezoelectric textile was produced using low cost materials and manufactured with readily scalable textile manufacturing methods.

As-prepared PVDF fiber

The mechanical properties and morphology of the as-prepared melt-spun PVDF fiber have been investigated. The mechanical properties of the as-prepared stretched PVDF fibers (Figure 4 a) show that the ultimate tensile strength, elastic modulus and elongation at break were 110 MPa, 843 MPa and 58%, respectively, and significantly stiffer and stronger than the unstretched filament (Table S2). While the tensile strength and the elastic modulus of as-spun PVDF fiber is similar to previously reported PVDF fiber, the elongation at break of the as-prepared melt-spun PVDF fiber are almost double that of melt spun PVDF fiber reported by Leal and co-workers.(28) SEM micrographs of the as-spun PVDF fibers are shown in Figure 4b-c that show a smooth surface morphology (Figure 4b), with a circular cross-section and a dense internal structure (Fig. 4c). In addition the higher magnification images (inset) of the surface and cross-section of the PVDF fiber confirmed that there are no voids in the as-prepared PVDF fiber.(13)

PVDF Characterisations

The predominate crystalline phase of the as-prepared PVDF fiber and following different post-treatment processes (i.e. drawing, poling process) was investigated using FTIR, DSC, and X-ray diffraction. The FTIR results (Figure S5) indicated that drawing and poling processes could enhance β phase formation in the as-prepared stretched and poled PVDF fiber by more than 75% compared to PVDF powder (See Table S1 for more information). The X-ray diffraction patterns (Figure 4d) showed that the intensity ratio of β to α phase was increased from 1.21 to 1.58 in the as-prepared stretched and poled PVDF fiber compared to as-spun PVDF fiber. In addition, thermal analysis of PVDF fiber indicated that the formation of the β phase crystalline structure in the as-prepared PVDF fibers were to be found 67.5% and 71.2% for the as-spun PVDF fiber and stretched and poled PVDF fiber, respectively. (Figure 57)

Effect of poling voltage on piezoelectric response

Poling process that is a combination of extension, heating, and exposure to high voltage, is considered as an effective method to improve the power generation capability by re-orientation of the dipole moments. Mandal et al.,(29) Used IR analysis of dipole orientation during electrospinning. The results show that dipole orientation analysis can be done based on the asymmetric and symmetric stretching vibrational modes of CH2.

To evaluate the extent of penetration of the poling voltage along the fiber length and its effectiveness, PFM testing was carried out using the 10 mm PVDF fiber poled with 9kV. PFM amplitude responses as a function of distance along the fiber from the positive poling electrode are shown in Figure 5a (see Figure S1 for more information). As can be seen from Figure 5a, the piezoelectric response was sensitive to the distance from the electrode such that the maximum output amplitude for the poled PVDF filament occurred at the less than 1 mm distance from the positive poling electrode. Consequently, PFM characterization of the poled PVDF fibers of more than 40 mm in length were not carried out due to insufficient piezo responses. The results of PFM phase responses as a function fiber length for the sample with 10 mm length in vertical direction are shown in Figure 5b (and Figure S3). The amplitude versus Vdc loop was measured by applying a voltage of -25 V to +25 V to the tip with respect to the ground. As can be seen from Figure 5b, the amplitude versus Vdc curves are hysteretic and the shape of the loops strongly resemble the butterfly loop normally observed in piezoelectrics.(30) However the results of piezoresponse in horizontal direction was insignificant (see Figure S4 for more information). The phase of the PFM response signal is directly related to the direction of the electric polarization of the microscopic region of the PVDF fiber under the tip. Thus, the hysteretic switching of the response signal phase by 180° in response to a sweeping DC voltage is attributed to the switching of the direction of polarization of the PVDF dipoles along the direction of the electric field.
This implies that the hysteretic 180° phase switching observed in the PFM response is evidence of local piezoelectricity of the PVDF fiber. (30) The poled PVDF fiber with 10 mm length exhibits a nearly symmetrical butterfly-shaped amplitude curves (Figure S3). However, the PFM results for the poled PVDF fiber with 20 mm length in Figure 5c shown that the PFM exhibited an asymmetric butterfly amplitude curve. These results confirm that the poling process was most effective when fiber length is less than 10 mm. The mechanism behind the ferroelectric-like amplitude butterfly curves and phase hysteresis loops generated for poled PVDF fiber with 20 mm lengths are described in the supporting information and Figure S2. (14)

The piezoelectric performance of the PVDF fiber has been further analysed by investigating the deformation and changes to surface topography of the fiber through the PFM process. A variable voltage (0, 2.5, 5, 7.5, 10 V) was applied onto the fiber surface at a single test point. As can be seen from Figure 6 and Table 2, roughness of the PVDF fibre was significantly increased when an increasing voltage up to 10V was applied. This roughness change was switchable and could disappear when the voltage was removed. Table 2 shows roughness changes for the PVDF fiber and its vibration. This phenomenon can be explained by piezoelectric behaviour of the PVDF fiber and confirmed piezoelectric response of the as-prepared PVDF fiber.

<table>
<thead>
<tr>
<th>Applied Voltage (V)</th>
<th>Deformation (pm)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>2.5</td>
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<tr>
<td>5</td>
<td>34.298</td>
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<td>54.074</td>
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<td>10</td>
<td>72.372</td>
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**Table 2** Deformation (surface topography) of as-prepared PVDF filament as a function of applied voltage.

**Fabrication of Wearable Energy Harvesters**

A new strategy of triaxial architecture based on piezoelectric PVDF fiber, silver coated nylon and braiding technology has been developed to manufacture continuous lengths of the wearable energy harvesting generator. The fabricated triaxial braided PVDF structure here has a number of practical advantages including the ability for mass production, a practical architecture which is suitable for poling and charge collection for unlimited lengths energy harvesting devices while also being flexible and robust with the outer braid providing more protection from general physical damage.

As the PFM results indicate that high performance piezoelectric PVDF fiber requires short distances between poling electrodes, the design adopted here promotes poling along the fiber radial...
direction. The developed triaxial braided structure enables poling between the inner and outer electrodes where PVDF fiber is as an intermediate structure (Figure 7). The direction of the applied force and the direction of the produced dipoles are the same when the structure is compressed, hence making the active mode as $d_{33}$ (transverse mode). Fabrication of the triaxial braided PVDF fiber has been successfully developed using melt-extruded PVDF fiber and commercial silver coated nylon. These braided structures were exceptionally flexible and lengths of up to 100 m were prepared and only limited by the availability of PVDF fiber.

**Mechanical energy harvesting performance**

To characterize the mechanical energy harvesting performances of the developed textiles piezoelectric generators an impact test was carried out by dropping a ball from two different heights onto the surface of the braided devices that was fixed to a rigid structure. The dropped ball bounced a number of times before coming to rest and each impact generated a voltage peak with peak intensity diminishing with time. A 2 cm long braided energy harvesting sample produced an open-circuit voltage of $\sim 230 \text{ mV}$ (Figure 8a) and $\sim 380 \text{ mV}$ (Figure 8b) at an applied pressure of 0.017 MPa and 0.023 MPa, respectively. The pressure was the peak pressure measured using a pressure sensor (Flexiforce Pressure Sensor - 25lbs) located underneath the sample. As can be seen from Figure 8(a-b), from each drop event onto a sample surface, two peaks appear in the output voltage: the first corresponds to the applied force, resulting in a negative voltage output, while the second corresponds to the relaxation of the sample after the load has been removed, resulting in a positive voltage output. The intensity of the generated voltage peaks decreased over time as the applied energy from the bouncing weight dissipated as it came to rest. In addition, developed triaxial braided PVDF structure showed asymmetric output voltages and provides more negative voltage during impact test. This phenomenon could be explained by synergistic triaxial-architecture design which enhances the contact area between PVDF braid and electrodes during impact test that would be capable to transfer more negative charge after compressing. The voltage output of developed triaxial braided energy generator as function of applied impact pressure is shown in Figure 8c. The voltage output increase up to 465 mV with increasing applied impact pressure up to 0.09 MPa. It was observed that beyond a certain threshold of impact (0.09 MPa), the voltage output from the triaxial braided energy harvester was abruptly reduced to zero. In fact, the lower resilience of the triaxial braided structure was momentarily compressed and

![Fig. 7 photograph of the cross-section of the fabricated energy harvesting generator based on triaxial braided PVDF fibers; a) and b) silver coated nylon as outer and inner electrodes, respectively, c) braided piezoelectric PVDF fiber.](image)

![Fig. 8 The mechanical energy harvesting performance of developed triaxial braided piezoelectric fibers; a) and b) Output voltage for 2 cm fabricated device at applied impact pressure of pressure of 0.017 MPa and 0.023 MPa, respectively. Inset shows voltage output vs. time for the first peak, c) variation of current and peak power output as a function of applied impact pressure for developed triaxial piezo energy generator and d) the peak values of the power and voltage for the fabricated device (obtained at an impact pressure of 0.023 MPa).](image)
sheared to such an extent that the two opposite conducting ends shorted out each other and hence no output was observed. The power output of the developed triaxial energy harvesting textiles has been measured using a impact pressure of 0.023 MPa, which provided a reproducible response without causing any damage.

As can be seen from Figure 8d, the piezoelectric textile generator provided the maximum power output of 0.16 µW which is corresponding to voltage output of 380 mV at applied impact pressure of 0.023 MPa. This applied impact pressure is ~ 22% lower than previously reported for the 3-D spacer piezoelectric textiles.(21)

An in-house setup was constructed to apply a continuous pressure of 0.0145MPa on the sample and a bridge rectifier (4 diodes of 1N4004) placed in the circuit to feed a capacitor. The generated voltage after rectifier is 350 mV (Figure 9) that its power is 52.59 µW/cm³.

The power output from developed triaxial braided PVDF energy generator is much higher than those reported for energy generators based on PVDF films and fibers. The power density of developed piezoelectric textiles energy generator was found to be 29.62 µWcm⁻³ (5700 µW/kg) based on the volume and mass of the PVDF fibers. The value is ~1559% higher than previously reported for the piezoelectric textiles.(15) The power output of the developed triaxial braided piezoelectric energy harvester and pervious piezoelectric PVDF energy generators are compared in Table 3 and the date are illustrated in Figure 10. Ideally, wearable energy harvesting generators should be elastically stretchable and bendable to ensure a close fit, enhance wearer comfort, and increase the range of human motions accessible for energy recovery. In addition, the stability of the energy harvesting textiles is a critical issue for practical applications. Consequently, we performed a bending cycling test with a triaxial braided energy harvesting generator to evaluate the effect of bending on the voltage output and stability of developed device. The bending cycling test was carried out using a periodic bending strain test where the end-to-end distance was reduced to 50% at a deformation rate of 300 mm/min over 1000 cycles. As can be seen from Figure 11a, the output voltage was found to be 150 mV and power density of 4.62 µWcm⁻³ or 1090 µW/kg for up to 1000 bending cycles at a frequency of 0.6 Hz. These result indicated that the triaxial textile energy generator is extraordinarily flexible and stable for thousands of cycles with no change in its performance (Figure 11b). The bending deformation of the energy generator provided a lower voltage and power output ( ~150 mV and 4.62 µWcm⁻³) compared with the impact test.

![Fig.9 The rectified voltage from continues impact pressure of the developed triaxial piece braided structure using in-house setup.](image)

![Fig.10 Comparison of the power density for present triaxial braided energy harvesting generator and previous reported energy generators based on pure piezoelectric PVDF films and fibers. The maximum power density for the present triaxial braided energy harvester is comparable to or higher than that in previous studies, however, sensitivity (output voltage vs. the applied force) significantly exceeds them.(see Figure S8 in the supporting information) ![chart]

![Fig.11 Characteristics of the developed triaxial braided piezoelectric textile during bending cycling tests; a) the voltage output of the triaxial textiles energy generator with a maximum strain of 50% and at 0.25 Hz and b) the stability of performance generated from the triaxial braided piezoelectric textile in bending test during 1000 cycles to a maximum strain of 50% and at 0.6 Hz.](image)
(380 mV and 29.62 µW cm\(^{-3}\)) due to the greater stress exerted on the sample fibres during impact test. It is recognised that the low energy density of piezoelectric devices at low frequency and static load sources has limited their application. The lowest frequency reported for PVDF devices has been limited to between 1 and 10 Hz.\(^{(40)}\) Our results indicated that the developed triaxial braided energy generator overcomes this limitation with significant energy harvesting cycling at very low speed (0.25 Hz). This frequency is comparable to normal human walking, so that our textile energy harvester could be utilized for diverse applications such as self-powered wireless sensors and powering wearable electronic devices (i.e. electronic textiles). The sensitivity of the as-prepared triaxial piezoelectric textiles was evaluated using output voltage divided by the applied force (22) (see Figure S8 and Movie S2 in the supporting information). The results indicated that the triaxial piezo energy generator exhibited an almost 4-fold increase in value (1.6 V/N) compared to those previously reported.\(^{(41)}\) Furthermore, we have explored the scaling of the triaxial textile where multiple mechanical energy harvesters are assembled to meet specific energy and power needs for practical applications. As shown in Figure 12, a fabricated woven textile energy generator based on triaxial braided piezo fibers with five devices in parallel was assembled. This device provided a voltage output of ~380 mV and power output of 0.8 µW at an applied pressure of 0.023 MPa. The textiles energy generator can be integrated with soft and stretchable silicone material to provide protection from the environment including washing. Interestingly, the voltage output of the silicone coated triaxial braided energy generator was enhanced for more than 108% compared to device without coating. Such improvement may be due to better packaging of fibers within the silicone coated device which could improve efficiency of the charge collection as well as supporting the mechanical performance of the device. Also as a demonstration example, the developed triaxial braided textile energy generator can charge a commercial battery or capacitor from tensile and bending deformations. A wearable energy generator based on braided PVDF fibres was demonstrated in Movie S3 (see supporting information).
Table 3 Comparison of the power output of energy generator based on piezoelectric PVDF films and fibers

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Power</th>
<th>Power density</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td>ZnO+CNT Films</td>
<td>Casting</td>
<td>18.75 µW</td>
<td>-</td>
<td>(42)</td>
</tr>
<tr>
<td>alkaline niobate-based particles (KNLN)</td>
<td>Film</td>
<td>0.5mW</td>
<td>-</td>
<td>(41)</td>
</tr>
<tr>
<td>PVDF-HFP-TEA-BF4</td>
<td>Yarn</td>
<td>-</td>
<td>43 µWh/cm²</td>
<td>(43)</td>
</tr>
<tr>
<td>PVDF</td>
<td>Film</td>
<td>0.1 mW</td>
<td>-</td>
<td>(15)</td>
</tr>
<tr>
<td>PVDF</td>
<td>Yarn</td>
<td>-</td>
<td>-</td>
<td>(15)</td>
</tr>
<tr>
<td>PVDF-TrFE</td>
<td>Electrospun webs</td>
<td>-</td>
<td>5.9mW/cm³</td>
<td>(44)</td>
</tr>
<tr>
<td>PVDF</td>
<td>Monofilament</td>
<td>2.79 nW</td>
<td>-</td>
<td>(45)</td>
</tr>
<tr>
<td>PVDF</td>
<td>Nanofiber</td>
<td>-</td>
<td>-</td>
<td>(46)</td>
</tr>
<tr>
<td>PVDF</td>
<td>Film</td>
<td>-</td>
<td>65 nW/cm²</td>
<td>(32)</td>
</tr>
<tr>
<td>PVDF−NaNbO3 Film</td>
<td>Nanofilm</td>
<td>14.96 µW</td>
<td>16.2 µW/cm³</td>
<td>(31)</td>
</tr>
<tr>
<td>BaTiO3/P(VDF-TrFE)</td>
<td>Electrospun membrane</td>
<td>0.02 µW-25 µW</td>
<td>-</td>
<td>(47)</td>
</tr>
<tr>
<td>BaTiO3 Thin Film</td>
<td>-</td>
<td>7 mW/cm³</td>
<td>-</td>
<td>(48)</td>
</tr>
<tr>
<td>P(VDF-TrFE) and BaTiO 3 Membrane</td>
<td>Electrospun Fiber</td>
<td>-</td>
<td>16 µW/cm²</td>
<td>(49)</td>
</tr>
<tr>
<td>PVDF Meltspun</td>
<td>-</td>
<td>0.7 mW</td>
<td>-</td>
<td>(50)</td>
</tr>
<tr>
<td>PVDF+CBB Film</td>
<td>Meltspun</td>
<td>15 nW</td>
<td>-</td>
<td>(51)</td>
</tr>
<tr>
<td>PVDF+ZnO Film and nanowires</td>
<td>Film (hybrid device in plane shape)</td>
<td>-</td>
<td>16 µW/cm³</td>
<td>(33)</td>
</tr>
<tr>
<td>PVDF nanofiber</td>
<td>-</td>
<td>0.12 nW</td>
<td>-</td>
<td>(52)</td>
</tr>
<tr>
<td>PVDF+ZnO Film and nanowires</td>
<td>-</td>
<td>0.17 mW/cm²</td>
<td>-</td>
<td>(53)</td>
</tr>
<tr>
<td>PVDF+PZT Film</td>
<td>Film</td>
<td>1.3 mW</td>
<td>-</td>
<td>(54)</td>
</tr>
<tr>
<td>PVDF+BTZO Film</td>
<td>Film</td>
<td>15.8 mW</td>
<td>2.52nW/cm²</td>
<td>(55)</td>
</tr>
<tr>
<td>PVDF-Niobate-Based</td>
<td>Film</td>
<td>-</td>
<td>11.7 µW/cm²</td>
<td>(56)</td>
</tr>
<tr>
<td>PVDF + Activated Carbon Film</td>
<td>-</td>
<td>63.07 mW/cm²</td>
<td>-</td>
<td>(57)</td>
</tr>
<tr>
<td>PVDF+Graphitic Carbon Nitrid</td>
<td>Film</td>
<td>-</td>
<td>100 mW/cm²</td>
<td>(58)</td>
</tr>
<tr>
<td>PVDF+GO+AlO Nano composite film</td>
<td>Film</td>
<td>-</td>
<td>27.97 µW/cm³</td>
<td>(38)</td>
</tr>
<tr>
<td>PVDF Triaxial Braided Piezo Fibers</td>
<td>-</td>
<td>29.62 µW/cm³</td>
<td>-</td>
<td>This Work</td>
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</table>
Conclusions

In summary, a new strategy of synergistic triaxial-architecture design based on piezoelectric fiber, conducting fibers, and braiding technology is developed to manufacture a new class of wearable energy harvesting generator. A novel triaxial piezoelectric textiles energy harvester has been developed with a view to enhance both the piezoelectric performance and mechanical properties of the developed energy harvesting generator through a fabrication process. Triaxial braided energy generator has been fabricated using high-performance PVDF fiber as piezoelectric polymer, silver coated nylon as inner and outer electrodes though a melt-spinning and braiding process. We demonstrate novel triaxial braided textiles harvesters that piezoelectricity convert tensile mechanical energy into electrical energy. Compressing or bending braided PVDF yarns generated maximum output voltage of 380 mV and power density of 29.62 μWcm⁻³ which is ~1559% higher than previously reported for the piezoelectric textiles. It is found that developed triaxial energy generator exhibit significantly higher sensitivity by a factor 4 in compared with the PVDF energy generator. Unlike for other piezoelectric harvesters, the triaxial braided PVDF yarn produces tensile energy harvesting and enables extreme durability which is enabling cycles with up to 50% strain for thousands of cycles with no changes in its performance. Finally, the fabricated triaxial braided piezoelectric energy harvesting textile exhibited an efficient and novel way to overcome the stability issues due to the poor fatigue resistance of the metallic electrodes. The triaxial braided piezofibers is strong, lightweight and exceptionally flexible that it is expected to be applicable to wearable devices where high performance is necessary.

Conflicts of interest

There are no conflicts to declare.

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References