Unveiling Peritoneum Membrane for a Robust Triboelectric Nanogenerator

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Supporting Information

ABSTRACT: Triboelectric nanogenerators (TENGs) are smart alternative energy harvesters to convert mechanical energy into electrical energy to power small and portable electronic devices. A key challenge in fabricating an efficient TENG lies in the choice of an active material in addition to the mechanical stability and robust output performance of the device. This report suggests, for the first time, the use of a peritoneum membrane as a triboelectrically positive material for designing TENGs. The peritoneum covers the abdominal wall and diaphragm of mammals except for the kidneys and the adrenal glands and consists of a structure of a well-defined network of elastic fibers. Our peritoneum-based TENG (p-TENG) can generate an open-circuit output voltage of ~550 V, output current density of ~100 mA m⁻², and instantaneous output power density of 9.4 Wm⁻². This work demonstrates the p-TENG as a portable power source, a self-powered pedometer, and a speedometer, which conveys its futuristic applications for health care purposes. Our p-TENG is highly stable, delivering a constant output voltage of ~550 V over a period of 90 days. The introduction of a biowaste peritoneum membrane as a triboelectrically positive component in the TENG has great potential as a portable alternative energy source owing to its abundance, stability, low cost, and ease of fabrication.

INTRODUCTION

The search for a clean alternative energy source with reduced carbon emission is crucial for sustainable development of human civilization. Hence, it is essential to develop novel renewable, environment-friendly, and cost-effective technologies.¹⁻⁶ Rapid development of the electronics industry has generated a variety of essential portable electronic gadgets, which are powered by conventional battery sources. However, conventional batteries have limited energy storage capacities and limited lifetimes and add considerable additional weights to the electronic gadgets. Alternatively, mechanical energy sources are abundant in nature and easily accessible in the ambient environment. Human motion is one of such easily accessible mechanical energy sources to generate power. In this regard, nanogenerators based on piezoelectricity and triboelectricity have appeared recently as an alternative green power source for harvesting mechanical energy, converting it into electrical energy that could power small and portable electronic devices.⁷⁻¹⁰ A variety of triboelectric nanogenerators (TENGs) relying on human motion-driven mechanical energy has been developed to date.¹¹⁻¹⁸ The working principle of TENGs relies on the periodic contact electrification effect between two active materials with different charge affinities.¹⁹,²⁰ Hence, a key challenge in fabricating an efficient TENG lies in the choice of an active material in addition to the mechanical stability and robust output performance of the device. In this regard, several works have been reported to find new triboelectric-positive and triboelectric-negative materials.²¹,²² In this work, we are introducing the peritoneum membrane as a triboelectric-positive material for the first time. The peritoneum covers the abdominal wall and diaphragm of mammals except for the kidneys and the adrenal glands.²³ The peritoneum consists of a single layer of mesothelial cells covering a basement membrane. The basement membrane is a well-defined network of elastic fibers containing glycosylated proteins, mast cells, macrophages, and lymphocytes.²⁴ The introduction of the eco-friendly peritoneum membrane as a triboelectrically positive component with high output performance has great potential for realizing the robust alternative energy source for powering portable electronic gadgets. It helps to expand the field toward a biocompatible and low-cost green energy harvester. Herein, we report, for the first time, the use of the peritoneum membrane as a triboelectric-positive material to design an ambient stable TENG (p-TENG) in combination with polydimethylsiloxane (PDMS). The p-TENG with an area of 4 × 4 cm² can deliver a high open-circuit output voltage of 550 V with an output current of 160 μA, defining a power density of 9.4 Wm⁻². Our p-TENG can be used as a direct power source to power more than 100 commercial blue LEDs. We demonstrate the capacitor...
charging ability using the p-TENG, which is further used as portable storage devices for powering commercial LED strips. Additionally, we demonstrate the use of the p-TENG as an electrical energy harvester from mechanical energy of human walking. We show that the p-TENG can be used as a step counter of human walking and as a self-powered pedometer for health care applications. Our p-TENG generates a constant open-circuit output voltage of 550 V over a period of 90 days, suggesting the robust mechanical stability.

## RESULTS AND DISCUSSIONS

The peritoneum membrane preparation method is presented in Figure 1a. First, the peritoneum membrane of a goat was collected from a slaughterhouse and immersed in lime water for 24 h.

![Figure 1. (a) Schematic representation of the peritoneum membrane preparation method. (b) Photograph of the peritoneum membrane. (c) SEM image of the peritoneum membrane showing the network of elastic fibers. (d) Schematic of an arc-shaped p-TENG device. (e) Photograph of the p-TENG device.](image)

The membrane was then cleaned with fresh water several times and kept in sunlight for 48 h in a stretched condition. Finally, a flat peritoneum membrane is obtained upon drying. The thickness of the membrane was measured to be 0.3 mm using digital Vernier calipers. Figure 1b shows a photograph of an as-prepared dried peritoneum membrane. We have examined the surface morphology of the as-prepared peritoneum film using scanning electron microscopy (SEM) (Figure 1c). The SEM image reveals that the membrane consists of a network of fibers with a highly rough surface morphology. Such a rough morphology of the peritoneum film is useful for triboelectrification since it provides improved friction with a counteractive material film in the TENG. The PDMS film and peritoneum membrane were stacked separately with polyethylene terephthalate (PET) substrates using conductive adhesive carbon tape. Finally, the PET substrate with PDMS and PET substrate with peritoneum membrane were attached together with scotch tape in such a manner that the PDMS and peritoneum membrane remain in a face-to-face configuration (Figure 1d). Using this process of fabrication, p-TENGs with different active areas of 2 × 2, 3 × 3, and 4 × 4 cm² were prepared. There exists reports on the design of TENGs based on the vertical contact separation between the triboelectrically active materials.34−38 We have designed a prototype arc-shaped device structure, where the working mechanism is based on the vertical contact and separation mode between PDMS and the peritoneum membrane under externally applied force. A top-view photograph of the fabricated p-TENG is presented in Figure 1e. We have used PDMS as a negative triboelectric material and the biological peritoneum membrane as a positive triboelectric material in the p-TENG. The effective friction takes place between the peritoneum membrane and PDMS to produce a large number of triboelectric charges during friction upon application of external mechanical forces. To probe the triboelectric-positive nature of the peritoneum membrane, we have carried out a control experiment using a steel plate and an oscilloscope. The steel plate was rubbed with the peritoneum membrane a few times and connected to the oscilloscope probe. A negative voltage pulse in the oscilloscope was obtained (Figure S1a in the Supporting Information), suggesting that the steel plate acquired negative charges after the friction with the peritoneum membrane. Since steel is located in the middle of the triboelectric series, the control experiment univocally suggests that the peritoneum membrane is a triboelectrically positive material.39,40 The position of peritoneum membrane is presented in Figure S1b in the Supporting Information. The elemental analysis suggests that the peritoneum membrane consists mainly of four elements, which are carbon, oxygen, nitrogen, and calcium (Figure S2 in the Supporting Information). These elements are responsible for the positive nature of the peritoneum membrane in the triboelectric series. A high dielectric constant (Figure S3 in the Supporting Information) at a low frequency (5 Hz) with a microstructured network fiber reveals that the peritoneum membrane is a good candidate in the field of TENGs.

The working principle of the p-TENG is described in Figure S4 in the Supporting Information. Upon application of an external force on top of the p-TENG using the palm of a hand, friction is produced between the peritoneum membrane and the PDMS film, generating charges. As a result, the peritoneum membrane surface becomes positively charged, and the PDMS film surface becomes negatively charged. Therefore, charge pairs formed at the interface of the peritoneum membrane and the PDMS film when both are in contact. These positive and negative charges are static charges on the surfaces of both of the films. Since the charges of opposite kinds are confined on the surfaces and coincide at the interface of the two films, there is practically no electro-potential difference between the electrodes when the two films are in contact (Figure S4a in the Supporting Information). Upon withdrawal of the force, two films are separated from each other due to the restoring force of PET substrates. Therefore, an electro-potential difference is created as the positive and negative charge surfaces are separated from each other. To reduce the electro-potential difference, electrons flow from the electrode attached to the PDMS film to the electrode attached to the peritoneum membrane through the oscilloscope (Figure S4b in the Supporting Information). This generates a negative pulse on the oscilloscope. This charge flow in the external circuit stops when the distance between the two film surfaces is maximum, and the potential difference between the peritoneum and PDMS films is fully balanced by the induced charges on the...
The current of the p-TENG was calculated by measuring the restoring force of PET substrates. This results in a larger magnitude of applied external force, which is higher than the peritoneum membrane and PDMS restoring force of PET substrates. The approaching time of the external force applied on the device and the open-circuit output voltage of the p-TENG reaches 550 V when the gap between the two triboelectric-active materials in the device. For this purpose, we prepared the p-TENG with the same effective area of 16 cm²; however, the gap between the two electrodes was varied to 0.5, 1, and 1.5 cm. The p-TENG with a gap of 0.5, 1, and 1.5 cm showed output voltages of 430, 485, and 510 V, respectively (Figure S8 in the Supporting Information). A close observation reveals that the positive voltage amplitudes are 310, 295, and 270 V for 1.5, 1, and 0.5 cm spacer distances, respectively. Hence, the positive voltage amplitudes do not change largely compared to the 320 V for a 2 cm spacer distance. However, the negative voltage amplitudes are significantly lower compared to the 225 V for a 2 cm spacer distance. The instantaneous output power reaches a maximum value of 15 mW for a 5 MΩ resistance, corresponding to a power density of 9.4 W m⁻² (Figure 2d). This indicates that our p-TENG is the most efficient for this output load. We have also taken an open-circuit voltage of the p-TENG with the peritoneum membrane dried in different conditions. The measurement shows that slow drying or faster drying of the peritoneum membrane does not have any effects on output voltage (Supporting Information, Figure S6). The output performance of the p-TENG relies on the magnitude of the applied forces. Due to the absence of a force measurement setup, we could not measure the applied force by hand. However, we have carried out a force-dependent output response experiment by dropping iron blocks of different masses from a fixed height on the p-TENG and calculating the force. The result is presented in the Supporting Information (Figure S7).

We have also measured the spacer-dependent open-circuit output voltages by varying the gap between the two triboelectric-active materials in the device. For this purpose, we prepared the p-TENG with the same effective area of 4 × 4 cm²; however, the gap between the two electrodes was varied to 0.5, 1, and 1.5 cm. The p-TENG with a gap of 0.5, 1, and 1.5 cm showed output voltages of 430, 485, and 510 V, respectively (Figure S8 in the Supporting Information). A close observation reveals that the positive voltage amplitudes are 310, 295, and 270 V for 1.5, 1, and 0.5 cm spacer distances, respectively. Hence, the positive voltage amplitudes do not change largely compared to the 320 V for a 2 cm spacer distance. However, the negative voltage amplitudes are significantly lower compared to the 225 V for a 2 cm spacer distance. The negative voltage amplitudes for three different spacer distances are 310, 295, and 270 V for 1.5, 1, and 0.5 cm spacer distances, respectively. Hence, the positive voltage amplitudes do not change largely compared to the 320 V for a 2 cm spacer distance. However, the negative voltage amplitudes are significantly lower compared to the 225 V for a 2 cm spacer distance. The negative voltage amplitudes for three different spacer distances are −200, −190, and −160 V for 1.5, 1, and 0.5 cm spacer distances, respectively. We attribute the change in the negative voltage amplitudes to the change in the restoring force of the PET substrates. The positive peak arises due to the external force applied by the palm of a hand, while the negative peak arises due to the restoring force of the PET.
substrate, which reduces with decreasing spacer distance for the arc-shaped nature of the p-TENG.

Figure 3 represents a comparative study of the open-circuit output voltages for the p-TENG with different active areas of 2 \times 2, 3 \times 3, and 4 \times 4 \text{ cm}^2. The open-circuit output voltages were measured to be 360, 460, and 550 V, respectively (Figure 3a).

A linear increase in the output voltage is observed with an increase in the device size of the p-TENG (Figure 3b). Output currents measured through a 100 k\Omega resistor for three devices with a different active area (Figure 3c). The output current also shows a linear relationship with the device area (Figure 3d). Corresponding power outputs are calculated to be 5.7, 12, and 15 mW for 2 \times 2, 3 \times 3, and 4 \times 4 \text{ cm}^2 devices, respectively (Figure S9 in the Supporting Information).

To show the realistic applications of the p-TENG, we have checked the stability of the device for a number of operational cycles. Our p-TENG resulted in an open-circuit output voltage of \sim 550 V over 6000 cycles (Figure 4a). However, 6000 cycles is an apparent number considering our data acquisition procedure. We applied the external force manually by striking with the hand due to the lack of availability of an automatic force generator instrument. Since our oscilloscope can save data of 10 s time frame at a time, we saved each 10 s data before repeating the next striking cycle. Additionally, striking the p-TENG with the hand often results in an unequal voltage amplitude. In order to acquire equal voltage amplitude within the 10 s time frame, we had to strike the device for a few additional minutes. We have shown 120 sets of such 10 s data cycles with a 5 Hz frequency, implying 6000 cycles of equal voltage amplitude (Figure 4a). Realistically, we had to strike the p-TENG almost over 80,000 cycles for 3 days by hand to acquire the displayed 6000 cycles of equal voltage amplitude. Again, we have carried out additional experiments for stability test for 15,000 cycles using a low-powered linear motor (electrical sewing machine), where the applied vertical force on the device is very low. The plot shows that it is highly stable over a large number of cycles (Supporting Information, Figure S10).

We have also tested the mechanical durability of our p-TENG over a time span of 90 days by applying 1500 cycles of periodic force at a regular interval of 30 days. We obtained a constant output performance with an open-circuit output voltage of 550 V, suggesting the mechanical robustness of the p-TENG with negligible degradation over 3 months (Figure 4b). The mechanical stability of the peritoneum membrane was tested using the tensile testing system. The stress versus strain curve indicates that the peritoneum membrane has very high mechanical stiffness (Figure 4c). The peritoneum membrane exhibits an ultimate tensile strength (UTS) value of 14 MPa, an elongation at break (EB) value of 14.75%, and a Young modulus of 0.94 MPa (Figure 4c). The mechanical strength measurements justify the high stability of the p-TENG over a prolonged operational cycle over a long period of time. To demonstrate that the p-TENG is capable of charging a battery or a supercapacitor to store the electrical energy for future applications, we used the p-TENG to charge commercial capacitors with capacitance values of 1, 2.2, 3.2, and 10 \mu F. The p-TENG was connected to the capacitor by a bridge rectifier, and the output voltage across the capacitor was measured simultaneously upon application of an external periodic force of 3 Hz. The transient response is presented in Figure 4d. The voltage reaches a maximum value of 31 V for a capacitance of 1 \mu F, 13.5 V for 2.2 \mu F, 7.9 V for 3.2 \mu F, and 1.9 V for 10 \mu F over a capacitance charging time of 120 s. Furthermore, we demonstrate the use of stored voltage in the
capacitor as a portable power source. We used a 1 μF charged capacitor as a power source to power a commercially available white LED strip (power rating: 12 V, 12 W) (Figure 4e). Additionally, for direct application as a power source, we have powered ~100 commercial blue LEDs (single LED power rating: 3.2 V, 25 mW) with the p-TENG (Figure 4f, Video S1 in the Supporting Information). The output performance of our p-TENG is compared with other triboelectric-positive materials in Table S1 of the Supporting Information. The comparison suggests that our device is more efficient and robust.

Earlier reports demonstrated the use of the TENG for electrical energy harvesting from human walking.\textsuperscript{41−53} We show that our device is useful to extract electrical energy from human motion and suitable for the application as a pedometer/speedometer. We attached the p-TENG to a shoe using double-sided tape (Figure 5a). The p-TENG generates electrical energy during walking, which is demonstrated by powering LEDs (Figure 5b). Moreover, we can use the p-TENG as a pedometer of human walking (Figure 5c) since the p-TENG is able to register every step of human motion (Video S1 in the Supporting Information). Two types of peaks are observed during voltage pulses by walking: one is for pressing the device by the heel, and the other is for releasing the device by the heel (Figure 5d,e). The number of peaks represents the number of steps during human walking, suggesting that the p-TENG can be used as a self-powered speedometer. A speedometer can record the number of steps, distance travelled, and speed of walking/running. The distance traveled (s) can be calculated by using the equation \( s = n \times t \) where \( n \) is the number of steps and \( t \) is each step length. The number of steps thus can be calculated from the number of voltage peaks generated from the device while walking. In the case of normal walking, the length of each step of an adult is approximately 0.6 m, and the length extends to nearly 1.2 m for running. Hence, the average walking/running speed (\( v \)) can be calculated using the equation \( v = t/\ell \) where \( t \) is the time taken by each step, which is calculated to be 0.6 m/s for normal human walking.

\section*{CONCLUSIONS}

In summary, we report the fabrication of a new stable, low-cost, lightweight, and environment-friendly p-TENG using peritoneum membrane and PDMS combinations for harvesting ambient mechanical energy. The development of an abundant bio-friendly peritoneum membrane for designing the p-TENG for mechanical energy harvesting is novel. Electrical output characteristics of the p-TENG reveal a high open-circuit output voltage of ~550 V with a short circuit current of ~160 \( \mu \)A, generating an output power of ~15 mW with a high-power density of 9.4 Wm\(^{-2}\). We demonstrated the application of the p-TENG as a direct power source by powering 100 commercial blue LEDs and a white LED strip. On the other hand, the p-TENG can charge capacitors as storage devices, which can be used further as portable storage devices for powering LED strips. The p-TENG can be fitted with shoes, treadmills, or doormats to convert mechanical energy into electrical energy during human motion activity. We also demonstrated the usefulness of the p-TENG as a step counter during human walking and as a self-powered speedometer for possible health care applications. Moreover, the p-TENG is highly stable and can deliver a constant output performance for a large number of operational cycles. The wide range of applications, simple design, cost-effectiveness, and stability of the p-TENG demonstrates the potential to meet the requirement of low-power portable electronic gadgets as a green energy source.

\section*{EXPERIMENTAL SECTION}

\textbf{PDMS Film Preparation.} PDMS solution was prepared by mixing a silicone elastomer and a curing agent (Sylgard 184, Dow Corning Co.) at a quantity ratio of 10:1 (w/w). The solution was stirred for 1 h at room temperature for homogeneous mixing of the elastomer and the curing agent. The mixture was then kept in a vacuum for about half an hour to remove the air bubbles that appeared due to mechanical agitation during stirring. The solution then was drop-cast on a glass plate and spread with a glass slide. It was then placed horizontally for 15 min to attain its uniform thickness before placing it on top of a hot plate for about half an hour at 110 °C for thermal curing. The prepared film was measured to be 0.2 mm with digital Vernier calipers.

\textbf{Peritoneum Membrane Film Preparation.} The peritoneum membrane of a goat was collected from a slaughterhouse. It was immersed in lime water for 24 h. The membrane was then cleaned with fresh water and kept in sunlight for 48 h in a stretched condition to prepare a flat peritoneum membrane. The thickness of the film was measured to be 0.3 mm.
**p-TENG Fabrication.** PDMS and the peritoneum film were stacked individually with the PET substrate using conductive adhesive carbon tape. Our peritoneum membrane and PDMS-based p-TENG was fabricated in an arc-like structured pattern using two rectangular PET substrates as top and bottom substrates (0.5 mm thickness). The carbon conductive adhesive tape with a thickness of 0.16 mm was attached to both of the concave surfaces of the PET substrate as the electrode. Carbon tape is flexible and has good mechanical strength. Hence, it can withstand forces externally applied on the p-TENG. Finally, the PET substrate with PDMS and the peritoneum film were attached together face to face with Scotch tape. In this process, three p-TENGs were prepared with three different active areas of 2 × 2, 3 × 3, and 4 × 4 cm².

**Characterization.** SEM measurements were carried out using a ZEISS Sigma FE-SEM to examine the morphology and surface feature of the peritoneum membrane. The image was captured at an operating voltage of 15 kV. The electrical output performance of the p-TENG was characterized by applying periodic forces manually with the palm of a hand. The top electrode was pressed by periodic tapping. The open-circuit output voltage was measured using a digital oscilloscope (Yokogawa DL 1620). The corresponding output current was measured by taking the voltage across a 100 kΩ resistor. The measured output performance of the p-TENG was digitized using a ZEISS Sigma FE-SEM to examine the morphology and surface feature of the peritoneum membrane. The peritoneum membrane was quick-dried, force-dependent dielectric constant, working principle, transferred charge elemental analysis of the peritoneum membrane, position of the peritoneum in the triboelectric series, electrical properties, and energy harvesting.

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