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Master's Degree Thesis

A study of core-shell structured cylindrical TENG for wearable energy harvesting

Graduate School of Chosun University
Department of IT Fusion Technology
Dogyun Kim

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웨어러블 에너지 하베스팅을 위한 코어-쉘 구조를 갖는 원통형 마찰전기 하베스터에 대한 연구

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Chosun University in partial fulfillment of the
requirements for the Master's degree

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This is to certify that the Master's Thesis of Dogyun Kim

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Acronyms

TENG	Triboelectric Nanogenerator
CCTENG	Core-shell Structured Cylindrical Triboelectric Nanogenerator
FTENG	Fiber based Triboelectric Nanogenerator
CTENG	Cylindrical structured Triboelectric Nanogenerator
AC	Alternating Current
LEDs	Light Emitting Diodes

요 약

웨어러블 에너지 하베스팅을 위한 코어-쉘 구조를 갖는 원통형 마찰전기 하베스터에 대한 연구

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웨어러블 디바이스의 수요 증가에 따라 신체로부터 지속적인 전력 생성이 가능한 에너지 하베스팅 기술이 주목 받고 있다. 그러나 기존 파이버 기반의 마찰전기 하베스터는 대전 물질과 전극이 파이버의 겉면에 위치하여 섬유 및 대면적 제작 시 합선과 같은 문제점이 발생된다. 또한 한정된 마찰면적으로 인하여 제한적인 하베스팅 동작이 강요되었다. 본 연구에서는 다양한 변형 및 신체의 움직임을 통해 전력생성이 가능하며 내구성 및 복원력이 뛰어난 코어-쉘(Core-shell) 구조를 갖는 원통형 마찰전기 하베스터(Core-shell structured cylindrical triboelectric nanogenerator)를 제안한다. CCTENG는 신축성 있는 원통형의 실리콘 튜브를 이용하여 마찰대전 물질들을 내부에 위치시킴으로써 추가적인 스페이서(spacer) 제작 없이 충분한 에어 갭 형성이 가능하고 외력으로 인한 마찰대전 물질들의 손상 보호한다. 또한 마찰물질들은 전도성의 실리콘 고무와 나선형 구조의 전도성 실을 이용하여 원통형 실리콘 튜브의 제한적인 내부 공간에 의한 마찰 효율 저하를 방지하였다. 제안된 CCTENG 세 가닥을 이용하여 Triple CCTENG를 제작하였고 수직 힘을 인가하여 169 V 및 18.9 uA의 전력을 생성하였다. 마찰대전 물질들은 내부에 위치하여 단락 현상을 방지할 수 있었고 신축성 있는 물질들로 인해 다양한 변형으로부터 에너지 생성이 가

능하다. 결과적으로 신체에 부착 시 임의의 행동에 의한 신체 데이터 수집 및 에너지 하베스팅이 가능하여 웨어러블 하베스팅 시스템으로써 응용 될 수 있다.

Abstract

A study of core-shell structured cylindrical TENG for wearable energy harvesting

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Energy-harvesting technologies continuously generate power from human movement through wearable devices, and have attracted increasing attention and demand. However, in traditional fiber-based triboelectric nanogenerators, the triboelectric material and electrodes are placed outside the fiber, with consequent issues such as short-circuiting. In addition, limited harvesting capability is inevitable due to the small frictional surfaces. In this study, we propose a new core-shell structured cylindrical triboelectric nanogenerator (CCTENG) with a core-shell structure that can generate power through various deformations and body movements, and that has high durability and resilience. In the CCTENG, the frictional charged materials are located inside a flexible cylindrical silicone tube, where sufficient air gaps can be formed without additional spacers, thereby protecting the frictional charged materials from external influence. Deterioration of the friction efficiency of the friction materials is also prevented by limiting the internal space of the cylindrical silicon tubes. These tubes are composed of conductive silicone rubber and a conductive fiber with a helical structure. A triple-structured CCTENG was fabricated using three strands of the CCTENG, and vertical forces were applied to generate a maximum voltage of 169 V and current of 18.9 μA. The friction materials were located inside the tube to prevent short-circuiting, and the flexible characteristics of the CCTENG were exploited to generate energy from various deformations. The proposed CCTENG can be used in wearable energy harvesting systems, where it collects physical data and harvests energy from arbitrary motion when attached to the body.

I. Introduction

Environmental pollution and energy depletion are major global issues arising from the excessive use of fossil fuels and limited resources. To overcome these issues, green energy studies have been conducted, in which previously untapped resources are exploited. Energy harvesting technology using eco-friendly energy sources are being widely studied as an infinite energy source. Energy harvesting can solve the issues related to existing fossil fuels based on the generation of electrical energy from the energy that would otherwise be lost to the surrounding environment.

Modern devices are becoming smaller with the development of science and technology. Recently, various wearable devices have been developed, such as smart watches and fitness bands. Therefore, small-scale devices have garnered increasing interest for power generation. However, battery capacity is directly proportionate to the device size. Thus, frequent charging or replacement can be troublesome.

To solve these issues, energy harvesting technology has gained prominence. A variety of energy sources are currently used for energy harvesting technologies: thermoelectrics [1,2], piezoelectrics [3,4], electromagnetics [5,6], and triboelectrics [7－10]. However, the energy harvesting technologies required for wearable devices [11－13] must be based on processes that promote time and environmental conservation.

Figure 1. Typical wearable energy harvesting technologies.

As shown in Fig. 1, typical wearable energy harvesting technologies include piezoelectrics that harness mechanical energy, triboelectrics using friction, and electrostatic coupling and thermoelectrics using waste heat. Triboelectric nanogenerators (TENGs) using friction have relatively few restrictions in terms of the environment, and can easily harvest energy from everyday life, making them suitable for wearable devices.

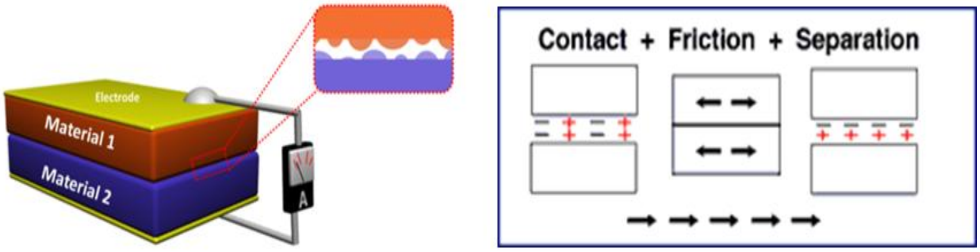

Figure 2. Working principle of TENG.

The working principle behind electricity generation using TENGs involves frictional charges and electrostatic coupling, which occur during the continuous contact and non-contact processes of materials with different electrical characteristics, as demonstrated in Fig. 2. Various TENG structures are being developed [14–17] to suit a variety of needs and applications. In particular, flexible fiber-based and cylindrical structured TENGs have the advantage of being easily implemented in wearable devices or on the human body [18−20]. However, in previously reported TENGs, it was difficult to harvest sufficient mechanical energy from human movement due to the small friction area between the surfaces.

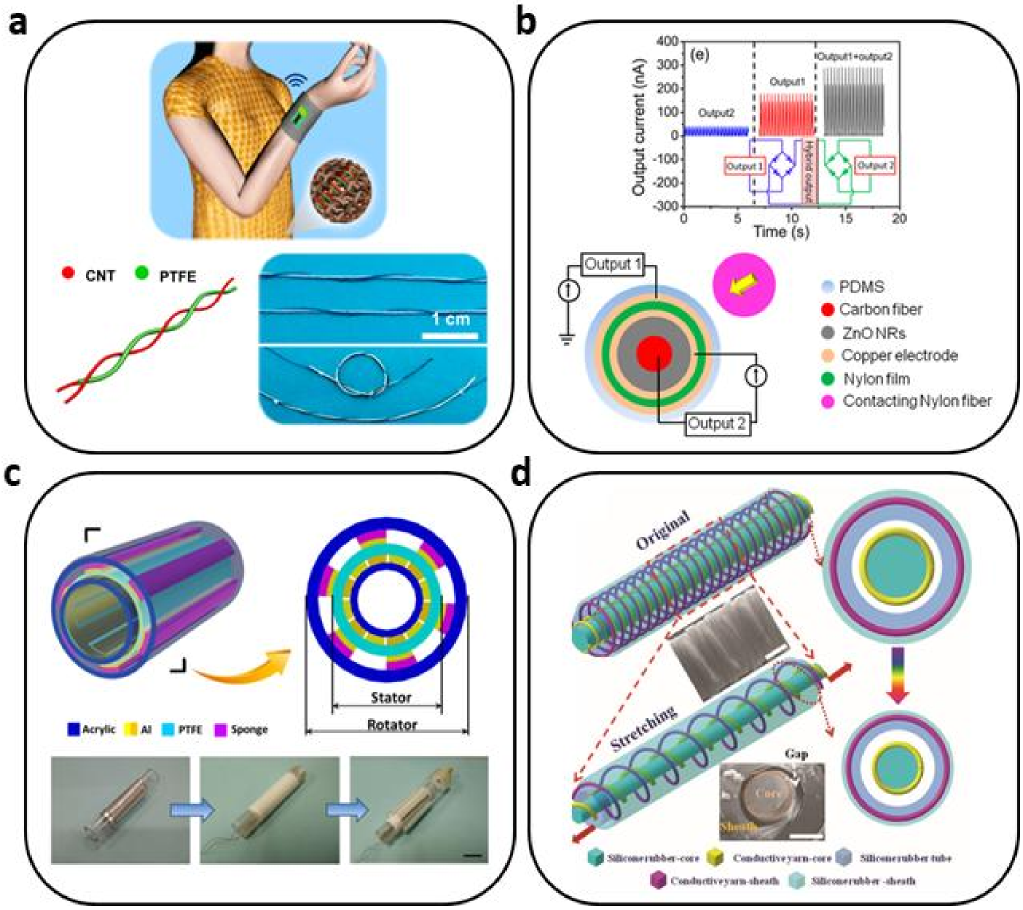

Figure 3. Previous TENGs with various structures. (a−b) Fiber-based TENGs and (c−d) cylindrical structured TENGs.

Additionally, previously reported fiber-based TENGs (FTENGs) can generate energy from the surrounding environment and human activity.

However, in the structure of FTENGs, the triboelectric material and electrodes are located on the outside of the fiber, leading to problems such as short-circuiting [21] (Fig. 3a), and it is difficult to achieve bending and elastic properties when a carbon material is used [22] (Fig. 3b). Previously reported cylindrical-based TENGs (CTENGs) can generate energy from natural energy and various tensile strains. However, they operate in only mechanical rotation [23] (Fig. 3c) and have low energy harvesting efficiency [24] (Fig. 3d).

In this study, we propose a new type of core-shell helical-structured cylindrical TENG (CCTENG). The core of the CCTENG comprises a helical-structure thread with urethane and a conductive fiber. The shell comprises a conductive textile coating inside the wall of a cylindrical silicone tube and rubber. The conductive fiber [25] is manufactured using Au-coated Cu fiber and polyester fiber. The Au-coated Cu fiber has high conductivity and low resistance. The CCTENG generates electrical energy from external forces by friction between charged materials inside the tube, and has little environmental restrictions because the charged materials are located inside the tube. Unlike conventional TENGs that generate electrical energy from basic deformations, CCTENGs can generate electrical energy from compression and rubbing to generate a maximum voltage of 169 V and current of 18.9 μA. The CCTENG uses a conductive fiber with better performance than the fiber-based TENGs of previous studies [24] and has a higher internal friction area. Thus, the flexible characteristics of the CCTENG can be exploited to generate energy from various deformations and human movement, and can be applied to a variety of wearable energy-harvesting systems.

II. Experimental details

A. Structure of CCTENG

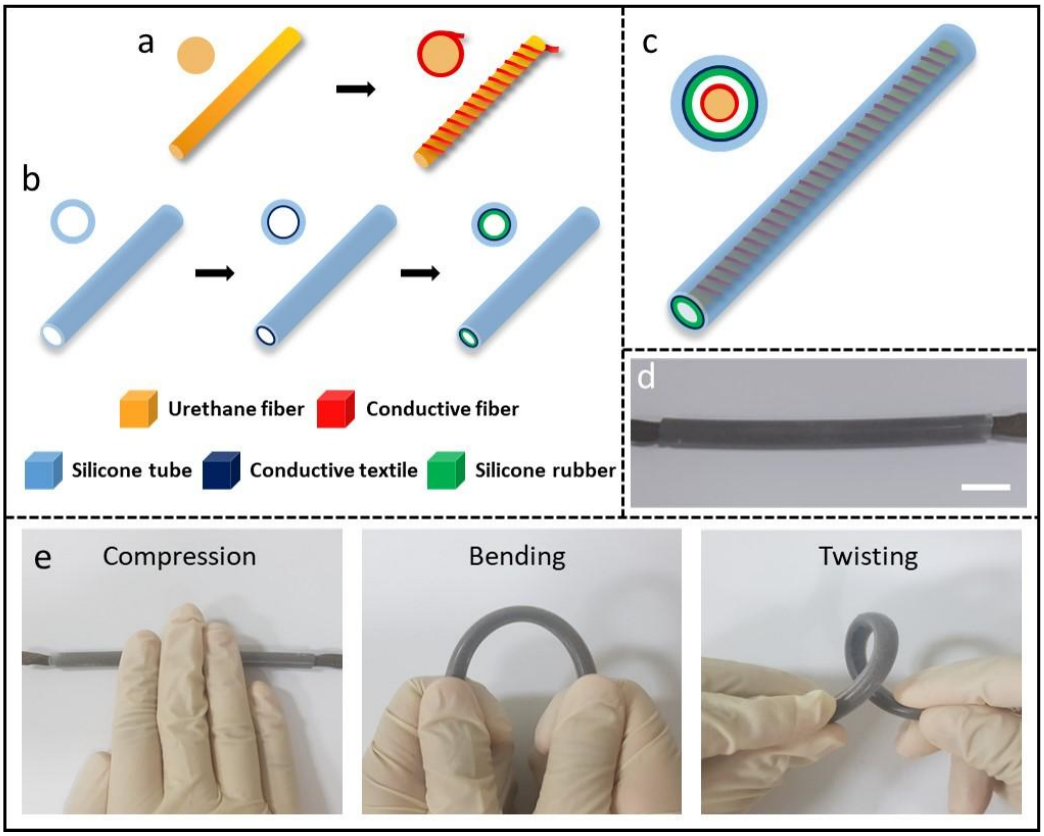

Figure 4. Representations of (a), (b) the fabrication process, and (c) the fabricated CCTENG. (d) Photograph of the CCTENG (scale bar: 1 cm), and (e) the different states under compression, bending, and twisting.

The schematic of the fabrication process and structure of the CCTENG. Fig. 4a shows the fabrication process for the helical-structure thread responsible for the core, fabricated by convolving the conductive fiber at a certain angle around the urethane fiber as the main axis. The conductive fiber is manufactured using a copper fiber coated with silver and polyester fiber. The conductivity and resistance of the copper fiber are 6.8×10^7 s/m and 0.037 Ω/cm (Table. 1), which are high values and positive characteristics for the triboelectric series (Fig. 5), suiting it for use as a positive friction material and an electrode.

Fig. 4b shows the fabrication process for the CCTENG's shell structure. The shell structure is constructed by inserting a conductive textile inside the silicone tube and injecting silicone rubber. The injected rubber is created by mixing an elastomer and a curing agent in a 1:1 ratio. It coats the conductive textile and then hardens. Silicone rubber is a negative friction material. The silicone tube is nonconductive and protects the internal frictionally charged materials from the outside; as well, it maintains the cylindrical structure by the resilience of the rubber material.

Finally, as shown in Figs. 4c and 4d, a helical-structure thread is placed inside the tube. The materials used in fabrication have flexible properties that allow various deformations, such as compression, bending, and twisting (see Fig. 4e).

	CTENG (Versatile core-sheath yarn)	CCTENG	Triple CCTENG
Resistance of conductive fiber	< 100 Ω/cm	0.037 Ω/cm	0.037 Ω/cm
Conductivity of conductive fiber	-	6.8×10^7 s/m	6.8×10^7 s/m
Maximum voltage in compression force	23 V	84 V	169 V
Maximum current in compression force	0.24 μA	5.8 μA	18.9 μA

Table 1. Comparison of Features of CTENG(Versatile Core-Sheath Yarn), CCTENG and Triple CCTENG.

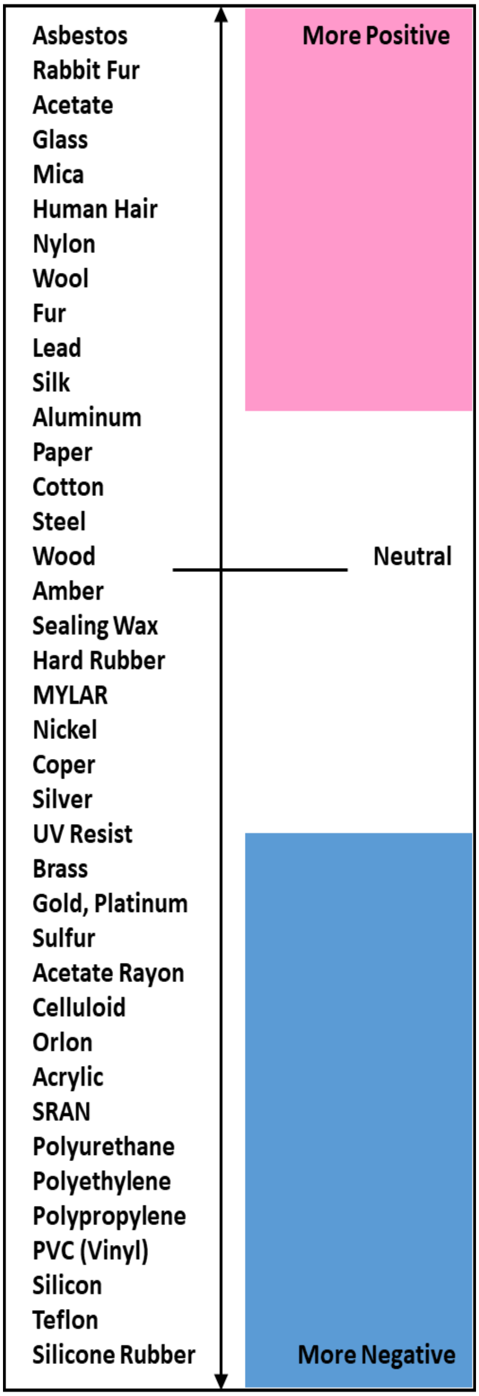

Figure 5. Triboelectric series.

B. Helical-structure of conductive fiber

In the helical-structure thread, the conductive fiber is present in a convolved state. Thus, it has very narrow spacing that allows for abrasion of the conductive fibers from various external forces. To guarantee a wide friction area, an electrical power comparison experiment was conducted on the basis of the convolving angle (Fig. 6).

Each conductive fiber was convolved at 150°, 135°, 120°, and 105° using a commercial linear mechanical motor on a 5 cm urethane fiber. As the angle decreased, the number of turns and the convolving length increased (Fig. 6a). We compared the electrical output of the helical-structure thread wound at various angles by providing the same vertical forces to the CCTENG (Figs. 6b, c). A smaller gap between the convolved conductive fibers corresponded with greater elasticity (+5%) from the convolving angle (150°, 135°, 120°, and 105°) in table 2.

However, the output performance increased by forming sufficient friction areas. We also considered the threshold convolving angle for the durability of the CCTENG, because decreasing the convolving angle increases the surface damage probability of the conductive fiber in the various experimental operations. Fig. 6d shows the potential for surface damage of the conductive fiber in a bent state at 105°, 100°, and 95°. It is possible to verify that 103 V is measured, lower than the initial measured voltage of 165 V at the 95° convolved angle test of Fig. 6e. As a result, to reduce this probability, the optimal angle of 105° was chosen and used for TENG production.

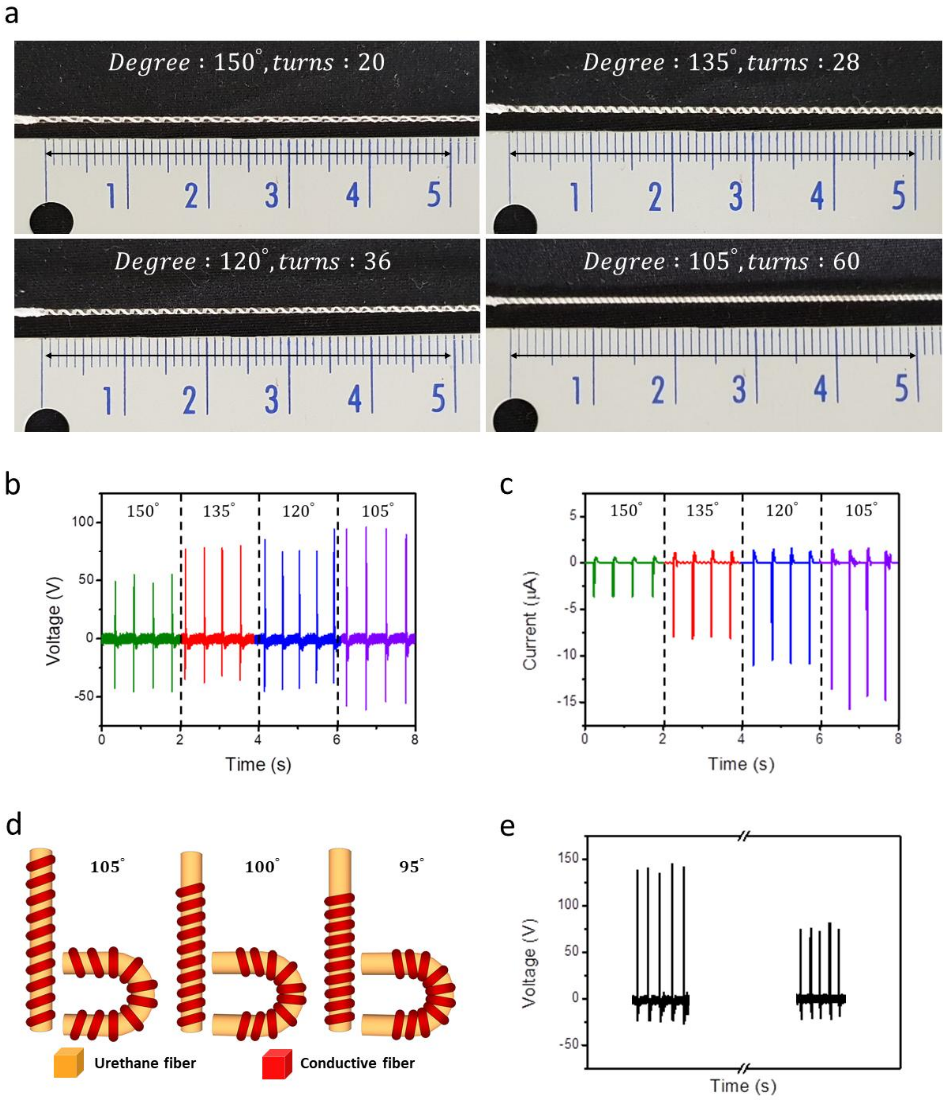

Figure 6. (a) Convolving a conductive fiber around an urethane fiber for maximum effect at 150°, 135°, 120°, and 105°. The output (b) voltage and (c) current under the compression state by convolving angle. (d) Damage to the surface of the helical-structure thread according to the convolving angle. (e) The CCTENG bending test (convolved at 95°).

Winding angle (°)	105	120	135	150
Number of turns	60	36	28	20
Original length (mm)	50	50	50	50
Maximum tensile length (mm)	70	66.5	63.2	60
Output voltage (V)	157	135	118	105
Output current (μA)	17.7	12.8	9.7	4.4

Table 2. Helical-structure thread characteristics according to convolving angle.

C. Experimental Setup

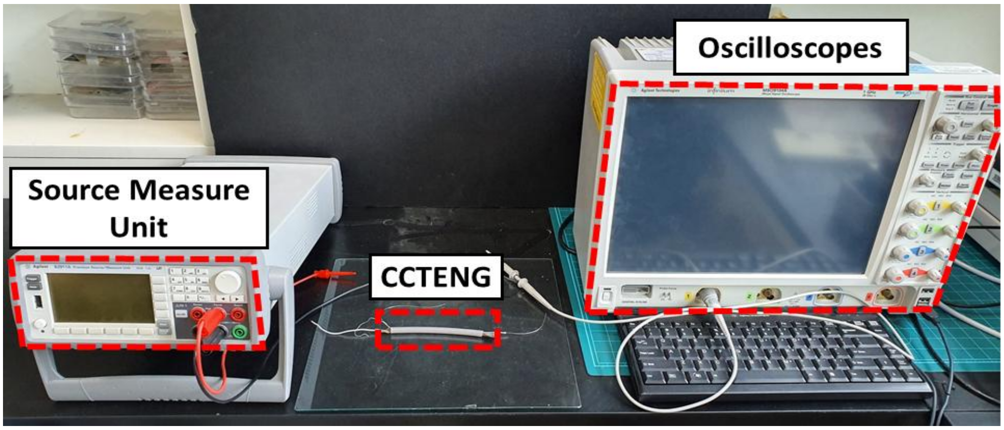

Figure 7-1. Experimental setup of output current and voltage of CCTENG.

Fig. 7-1 is an experimental setup picture of CCTENG. Voltage data was collected using Agilent Technologies′ Oscilloscopes and current data was collected using Agilent Technologies' Source Measure Unit for precise measurements. These data were graphed using the Origin software (version 8.6).

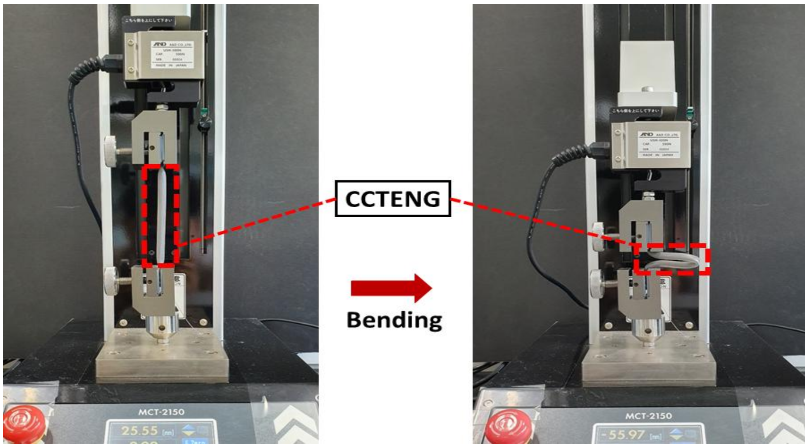

Figure 7-2. Experimental setup of bending test for durability.

Fig. 7-2 showed bending test experimental setup using the Tensile Compression Tester. The bending test was conducted to verify the durability of CCTENG (10 cm) using AND′s Tensile Compression Tester (MCT-2150).

III. Results and discussion

Figure 8 provides a schematic illustrating of the working principle of the CCTENG power generation using the triboelectric effect. Triboelectric harvesting generates energy by the frictional charge and electrostatic coupling that occurs during the continuous contact and separation of materials with different electrical characteristics.

The CCTENG generates electrical output by the continuous contact of the silicone rubber-coated conductive textile and the helical-structure thread inside the silicone tube. Per the triboelectric series, the silicone rubber exhibits a negative characteristic with high electron affinity, and the

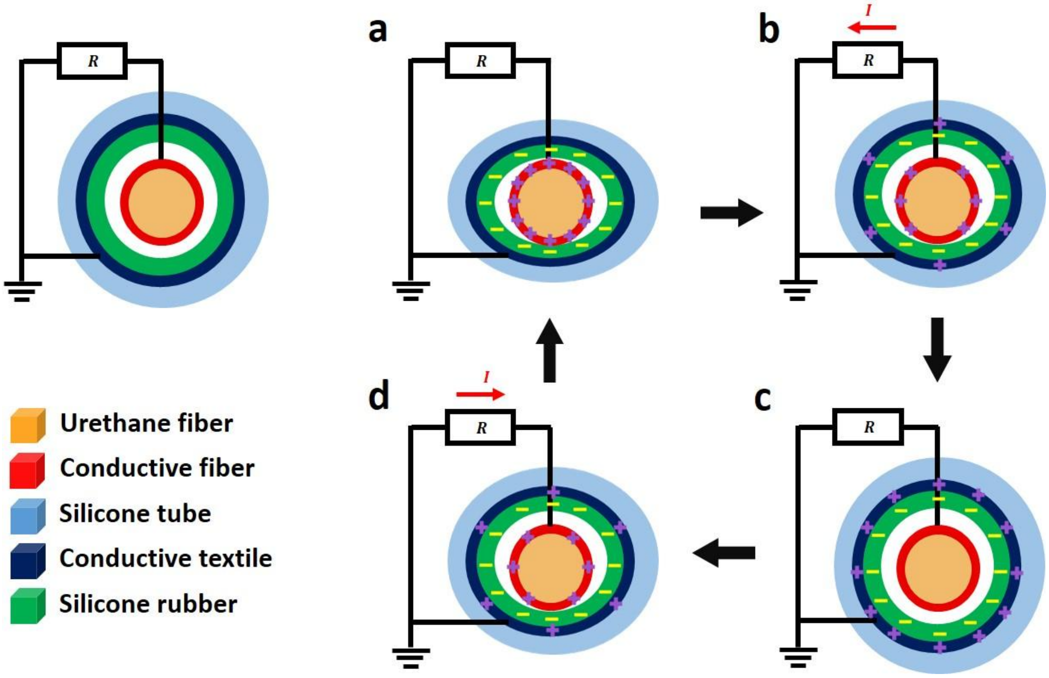

Figure 8. Representation of the CCTENG working mechanism (a), (d) compression state and (b), (c) releasing state.

conductive fiber of the helical-structure thread exhibits a positive characteristic. As shown in Fig. 8a, when an external force is applied, the silicone rubber is negatively charged, and the helical-structure thread is positively charged. As shown in Fig. 8b, when the two substances are separated, the electrons move from the electrodes to balance the frictional potential. As shown in Fig. 8c, when the two substances are maximally separated, the frictional charge is in equilibrium and electrical power generation is not observed. Finally, as shown in Fig. 8d, when the two substances come into contact again, the electrostatic equilibrium collapses, reducing the amount of charge induced from the electrodes. Thus, the CCTENG generates an alternating current (AC) by the continuous contact and separation of the silicone rubber and the helical-structure thread.

In daily life, friction is just as frequent as compression and bending. In this paper, the CCTENG was fabricated to enable triple-energy harvesting. Fig. 9-1 shows the structure and output performance of the triple CCTENG. Fig. 9-1a shows the three-strand CCTENG structure. The proposed triple CCTENG can generate energy in the rubbing state as well as by compression through its curved structure (Fig. 9-1b). When vertical force is applied to a single CCTENG, mechanical energy is evenly transmitted to the internal friction-charged material. However, if a horizontal force is applied, owing to the cylindrical shape, mechanical energy is not transmitted to the internally friction-charged materials. To compensate for this disadvantage, three-strand CCTENGs were used to create a continuously curved braided structure that allows energy to be transmitted from horizontal forces (Fig. 9-1c). The triple CCTENG has multiple curves (blue-dotted lines). Thus, there are multiple harvesting points (red bar, Fig. 9-1d). Therefore, the CCTENG can also collect mechanical energy from the rubbing state on the central axis (green dotted line). Fig. 9-2 shows Photograph and various deformations of the triple CCTENG.

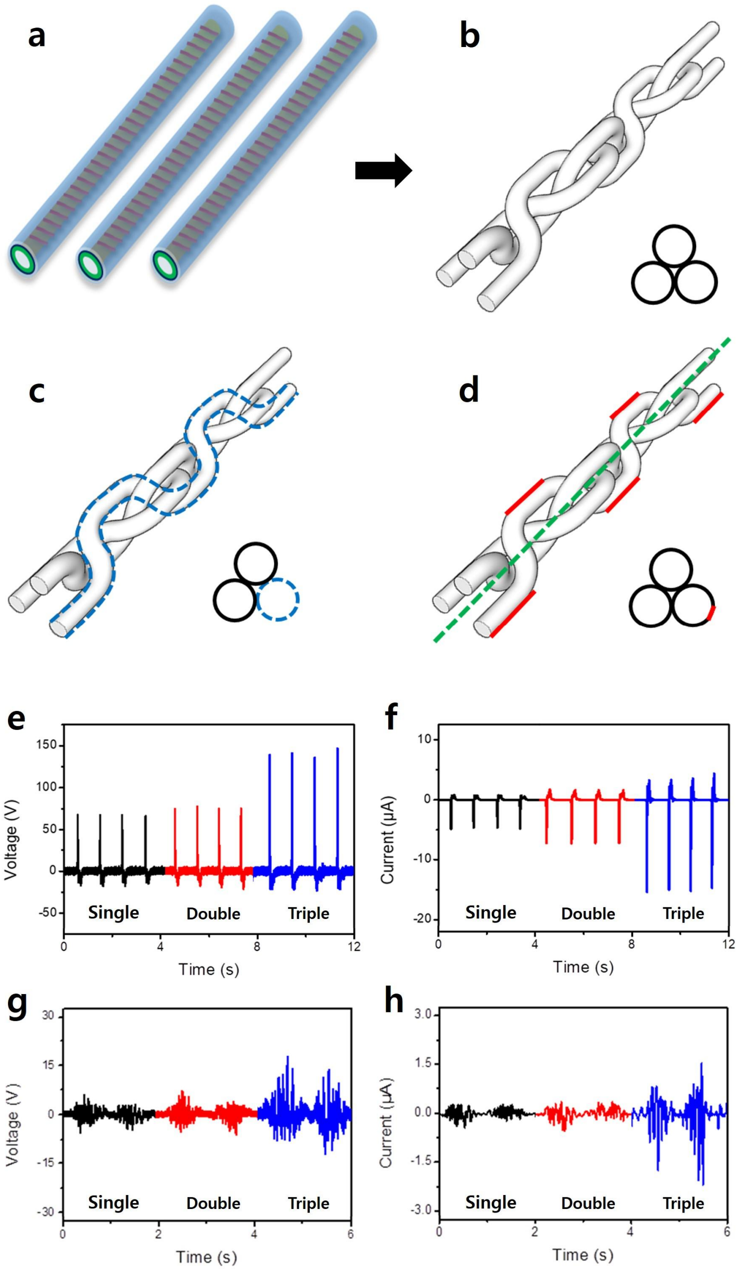

Figure 9-1. Schematic representation and output performance of the triple CCTENG: (a) - (d) Manufacturing process and description of the triple CCTENG. Output performance under (e), (f) compression and (g), (h) rubbing state.

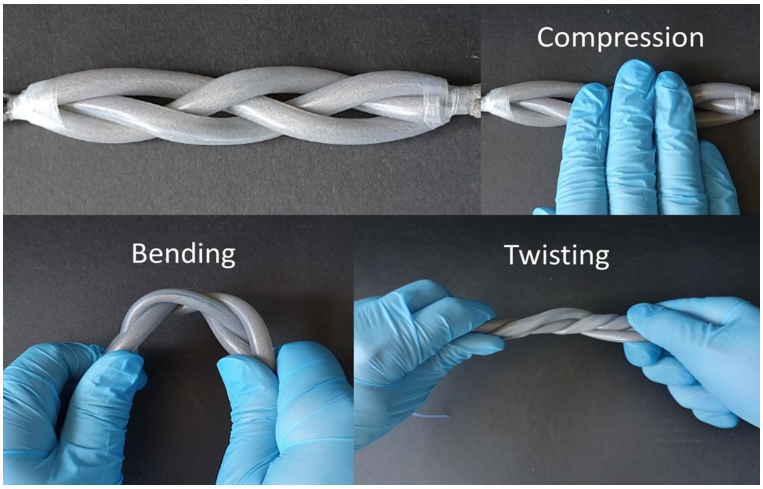

Figure. 9-2 Photograph of the triple CCTENG and the different states under compression, bending, and twisting.

As shown in Figs. 9-1e and f, the CCTENG was fabricated per the number of strands, and the electrical output performance by repeated compression was compared. The CCTENG was fabricated in single, double, and triple structures, and the same external forces were applied using a pushing test by a nonconductive material. With a vertical force of 1 kgf, single, double, and triple CCTENGs respectively provided open-circuit voltages of 84 V, 95 V, and 169 V (Fig. 9-1e) with 5.8 µA, 9.4 µA, and 18.9 µA short-circuit currents (Fig. 9-1f). Additionally, the contact nonconductive material on the triple CCTENG and sliding in one direction, enabling mechanical energy harvesting from the rubbing state, generated an output performance of 7 V, 12.4 V, and 25 V open-circuit voltages (Fig. 9-1g) with 0.85 µA, 0.97 µA and 3.70 µA short-circuit currents (Fig. 9-1h). As the number of strands increased, the friction area expanded to increase efficiency, allowing the triple CCTENG to provide continuous electrical energy from at least four valleys in the rubbing state.

Figure. 9-3 Quadruple and quintuple structured CCTENGs.

Additionally, as shown in Fig. 9-3, a quadruple-structured CCTENG was fabricated using four strands of the CCTENG and a quintuple-structured CCTENG was fabricated using five strands of the CCTENG. The CCTENG is flexible; hence, it can be fabricated in various structures. However, excessive bending of the structure disturbs the formation of the air gap. The quadruple- and quintuple-structured CCTENGs have a bent structure. Therefore, the energy harvesting efficiency of the quadruple- and quintuple-CCTENGs is lower due to ineffective formation of the air gap.

Figures 9-4 (a)—(d) show the output voltage and current of the quadruple-structured CCTENG, and a comparison of the electrical output under repeated compression. The quadruple-structured CCTENG provided an open-circuit voltage of 48 V (Fig. 9-4a) and short-circuit current of 6.7 μA (Fig. 9-4b). The quintuple-structured CCTENG provided an open-circuit voltage of 39 V (Fig. 9-4c) with a short-circuit current of 4.4 μA (Fig. 9-4d). The energy harvesting efficiency of the latter is lower due to the extreme bending angle and inefficient formation of the air gap, which interferes with the contact and non-contact process between the conductive fiber and the silicone rubber. Figures 9-4 (e)—(h) show the output voltage and current of the quintuple-structured CCTENG, and a comparison of the electrical output of the device subjected to repeated rubbing. The quadruple-structured CCTENG generated an output performance of 9.6 V (Fig. 9-4e) and 1.1 µA (Fig. 9-4f), and the quintuple-structured CCTENG generated an output performance of 7.2 V (Fig. 9-4f) and 0.68 µA (Fig. 9-4h)..

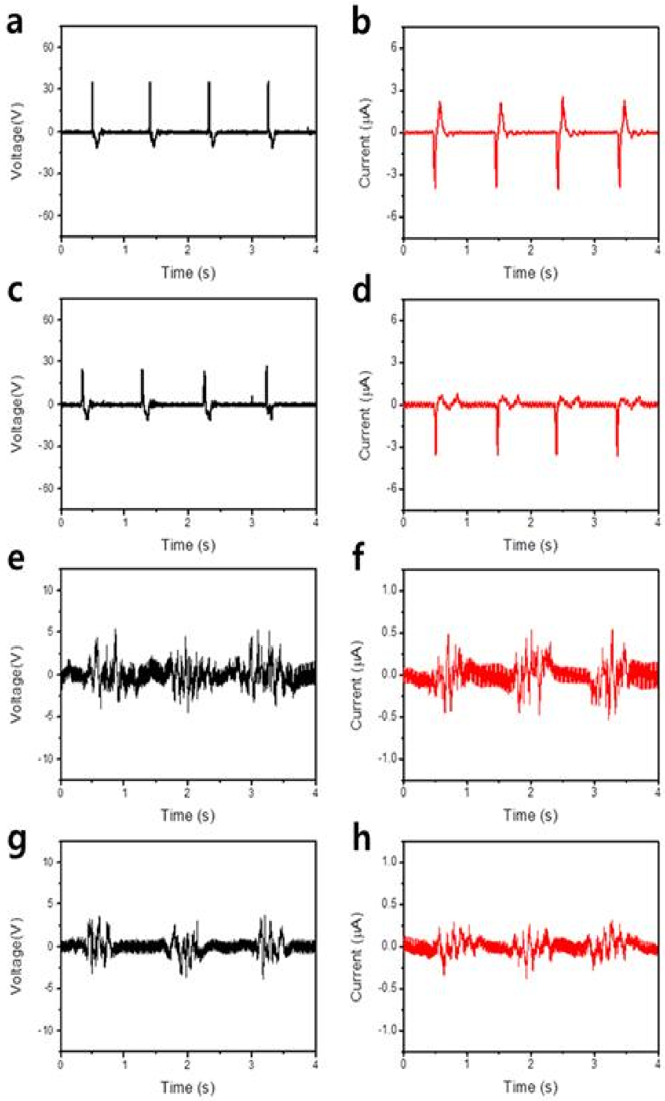

Figure. 9-4 Output performances under (a)-(d) compression and (e)-(h) rubbing state of quadruple and quintuple CCTENGs.

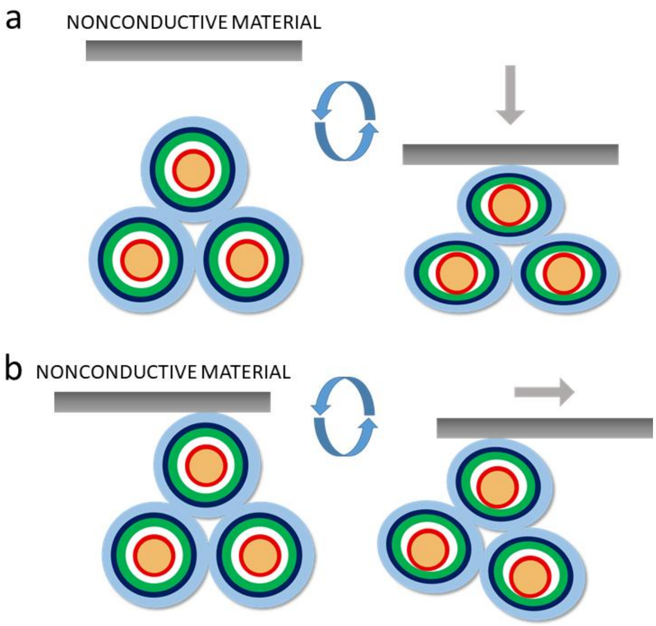

Figure 10. Experimental operation under (a) compression and (b) rubbing state.

Fig. 10a shows the compression operation of the triple CCTENG. It was applied with a vertical force using a nonconductive material. Fig. 10b shows the rubbing state of the triple CCTENG. It was applied with a horizontal force using a nonconductive material.

Figure 11 shows the energy generation and device-driven experiment with a human wearing the triple CCTENG to determine the potential for a portable wearable power source. In Figs. 11a–c, the triple CCTENG was attached to the bottom of a shoe to produce energy from the vertical forces applied by body movement. The vertical force is capable of more efficient energy collection because of simultaneous compression and rubbing. Output performance of 38 V, 70 V, and 145 V open-circuit voltages and 3.8 μA, 7.8 μA, and 14.9 μA short-circuit currents were respectively produced from walking, running, and jumping movements.

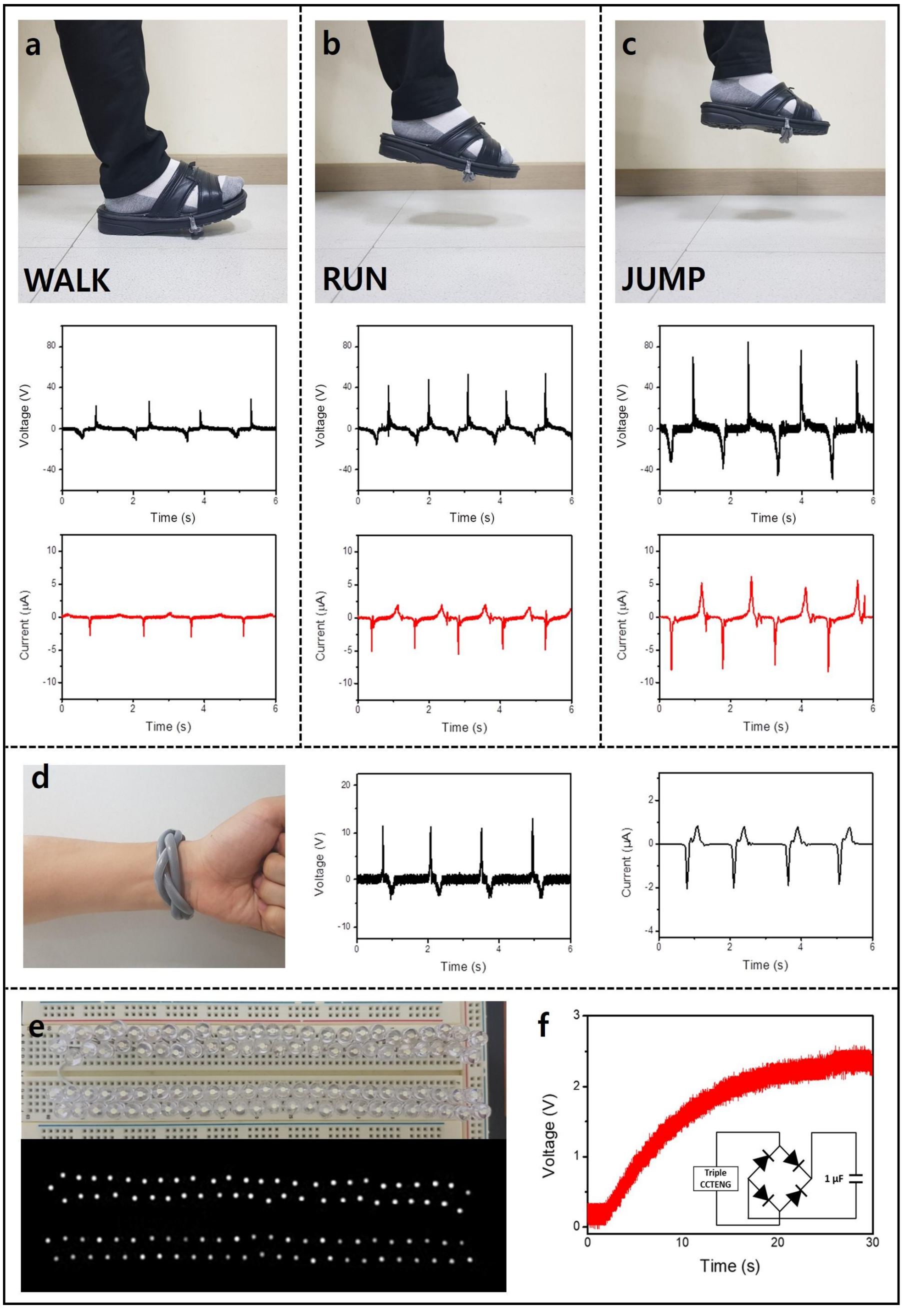

Figure 11. (a) - (c) CCTENG on the bottom of a shoe and (d) in bracelet form. (e), (f) Powering of LEDs and charging a capacitor at the compression state by CCTENG.

In Fig. 11d, the triple CCTENG was fabricated in bracelet form to produce energy by arm movements. The bracelet had high sensitivity, generating 17 V and 2.8 μA of energy in everyday life movements, such as writing or tapping. The CCTENG is free from broken lines and short circuits, because it uses nonconductive cylindrical tubes and collects energy by friction between the internal silicone rubber and the conductive fiber. It powered 100 LEDs and charged a capacitor of 1 μF to demonstrate the possibility of commercial use (Figs. 11e, f). Mechanical energy from human movement can thus be harvested for wearable energy harvesting and can be used as a promising power source for wearable devices.

IV. Conclusions

In this study, we propose a CCTENG with a structure that generates an electric output from various human body movements. Because the CCTENG is flexible, it can generate energy from various deformations, such as compression, bending, and twisting. It can also generate energy from rubbing the triple structure, because the helical-structure of the thread inside the CCTENG is fabricated by convolving a productive fiber at an optimal angle around a urethane core. This structure prevents abrasion of the friction material and maximizes the friction area among the internal parts. Additionally, the core-shell structure provides sufficient contact and separation space by featuring an internal air gap for friction between the internal structure fiber and the silicone rubber-coated conductive textile. Because positive friction materials and negative friction materials are present in the nonconductive silicone tubes, the devices are highly durable, which is an advantage. Moreover, continuously generated mechanical energy from the human body was steadily harvested without broken lines or short circuits. The triple CCTENG provided a reliable power supply to portable wearable devices by charging a 1 μF capacitor and by driving 100 LEDs. The triple CCTENG generated a maximum voltage of 169 V and a current of 18.9 μA in the compressed state; thus, the possibility of using the device as a portable energy source was confirmed. Finally, the device exhibits high durability and various energy generation states, and can potentially be applied to wearable energy harvesting systems or smart fabrics in the near future.

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