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Textile-type triboelectric nanogenerator using Teflon wrapping wires as wearable power source

Seonghyeon Kim, Woosung Cho, Dong-Joon Won and Joonwon Kim*

Abstract

Wearable electronic devices such as mobile communication devices, portable computers, and various sensors are the latest significant innovations in technology which use the Internet of Things (IoT) to track personal data. Wearable energy harvesters are required to supply electricity to such devices for the convenience of users. In this study, a textile-type triboelectric nanogenerator (T-TENG), produced using commercial electrode fibers, was fabricated to generate electrical energy using external mechanical stimulation. The commercial fiber was an electrode coated with Teflon on a copper wire with a diameter of ~ 320 µm. Using this commercial fiber, a T-TENG was easily fabricated by knitting and weaving. The performance of the T-TENG was analyzed to understand the effect of force and frequency. It was observed that the performance of the T-TENG did not degrade even under harsh conditions and treatment. The textile-type TENG possessed an energy harvesting capability with an output power density of ~ 0.36 W/m^2 and could operate electronic devices by charging a capacitor.

Keywords: Energy harvesting, Triboelectric, Nanogenerator, Textile-type, Teflon wrapping wire

Introduction

Wearable technologies, also called "*wearables*", such as mobile communication devices, portable computers, and wearable sensors using smart Internet of Things (IoT) technology have received considerable attention recently [1–4]. Wearable electronic devices require a flexible and wearable electricity supply source instead of the existing rigid solid-state electricity supply sources [5–7]. Therefore, research on power storage such as wearable supercapacitors and batteries are being conducted. However, even with power storage capability, external power is required for charging. Several studies have been conducted on wearable energy harvesters for supplying electricity from natural movements [8, 9] to make *wearables* more convenient for use. Among them, triboelectric nanogenerator (TENG) and piezoelectric nanogenerator (PENG), which produce electrical energy from external mechanical stimulation, are receiving considerable attention [10]. However, PENGs have limitations because of their complicated manufacturing process and relatively low output power. Many studies are being conducted on TENGs that are easy to manufacture and have a low frequency and high output voltage [11, 12].

Substantial research has been conducted to produce wearable TENGs from wearable textiles [13–15]. The textile-type TENGs (T-TENG) are largely divided, based on the manufacturing method [16, 17], into fabric and fiber. For fabric TENGs, the fabric itself is used as a tribo-material, or the fabric is directly coated with a functional material to be used as a functional fabric [18–21]. For example, the fabric is coated with carbon nanotubes, metal nanowires, and metals (i.e., Ag, nickel, etc.) to achieve conductivity; or the fabric is coated with nylon, polydimethylsiloxane, polyurethane, etc. to make a tribo-material. The fabric-type TENG manufactured in

*Correspondence: joonwon@postech.ac.kr

Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH), 77 Cheongam-ro, Nam-gu, Pohang, Gyeongbuk 37673, South Korea

this manner has a relatively high output power because it has a higher areal density than the fiber type, however it is limited because of its airtight properties and low durability [22, 23]. Accordingly, research is being conducted on a new T-TENG manufactured using a fiber composed of a core–shell structure [24–26]. A fiber is manufactured using a conductive material (carbon nanotube, liquid metal, etc.) as the core, and the tribo-material is coated with a shell around the core. The fiber can be sewed, knitted, or woven into a textile that is used for energy harvesting. However, it is difficult to use in the clothing industry because thick fibers are formed in the coating of the shell with a tribo-material, and the process of manufacturing the fibers is relatively complicated [27]. To overcome the limitations of the existing fiber-type TENG, the easy-to-use fiber must have a thin diameter for use in the clothing industry [28]. In addition, TENG made of these fibers must be flexible, bendable, and be capable of large-scale fabricating.

In this study, a T-TENG was fabricated to produce electrical energy using external mechanical stimulation using a commercial fiber. The commercial fiber was an electrode (copper wire with a diameter of ~ 320 μm) coated with Teflon. A large area T-TENG can be woven or knit using this fiber. The fabricated TENG is flexible and bendable; therefore, it is suitable for wearables; it is easy to connect the copper electrode inside the fiber to electronic devices. The T-TENG has an energy harvesting capability that not only has an output power density of ~ 0.36 W/m^2, but also can operate electronic devices by charging a capacitor. In addition, it has good harvesting ability without degradation, even after immersion in acidic and basic solutions, owing to the hydrophobicity of Teflon. We believe that new research on energy harvesting using commercial fibers will not only be applicable to the clothing industry, but will be a new step in easily usable TENG.

Materials and methods

Materials

Yellow and blue Teflon wrapping wires (SME) were purchased from commercial vendor. A latex glove (Microflex) was purchased from commercial vendor. Special-grade hydrochloric acid (HCl, 35–37%), and electronic-grade sodium hydroxide (NaOH, 99.9%) were purchased from a commercial vendor (SAMCHUN Chemicals).

Fabrication of the textile-type triboelectric nanogenerator

The purchased Teflon wrapping wire was used without any further treatment. T-TENGs are fabricated using knitting or home weaving machines. In the case of weaving, a general yarn was used for the wrap, and Teflon wrapping wire was used for the weft. For knitting, the pattern density is controlled by adjusting the loop length of T-TENG. In this study, a knitted T-TENG was used for performance evaluation. The knitted T-TENG was fabricated with a middle pattern density and an area of 25 cm^2 was fabricated for characterizing of T-TENG. The latex was used as the opposite material of Teflon for T-TENG power generation.

Characterization

Scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM–EDS, SU6600, Hitachi) was used to characterize the surface morphology and properties. A solenoid motor (JF-1040) was used to provide mechanical stimulation for evaluating the performance of the T-TENG. The applied force was measured by using a load cell (BONGSHIN, DBBP-20). The output voltage and current signals of the textile-type TENG were measured using an electrometer (Keithley 2400). The data collection and preprocessing system used LabVIEW software and NI collection cards that allow real-time data collection. All tests were conducted by selecting an appropriate resistance to measure the output voltage within the measurement range of the equipment.

Results and discussion

A fiber made of commercially available wire wrapped by Teflon was used to fabricate the T-TENG used for energy harvesting. The fiber was a Teflon wrapped 160 μm copper wire with a diameter of 320 μm (Fig. 1a). Figure 1b, shows that the surface was generally flat, and fluorine and carbon were common. Traditional methods such as knitting can be used with these thin and flexible wires to fabricate T-TENG (Fig. 1c). As the T-TENGs can withstands bending, wrinkling, and torsion; they can easily be converted to wearable devices (Fig. 1d). The fabricated T-TENG was characterized using a pushing machine composed of a solenoid motor and load cell that measured its force (Fig. 1e). The working principle of the fabricated T-TENG is the coupling of the triboelectrification and electrostatic induction effects. As shown in Fig. 1f, when the two materials come into contact some electrical charge is transferred from one material to the other. One material becomes negatively charged as it gains electrons; the other material loses electrons, and becomes positively charged. When the charged materials are separated, current flows in the circuit. When the two materials come close again current flows in the circuit in the opposite direction. We used Teflon, which can easily absorb electrons as one material; we used Latex as the other material because it can be positively charged as it easily loses electrons. The performance of the T-TENG was evaluated using these materials.

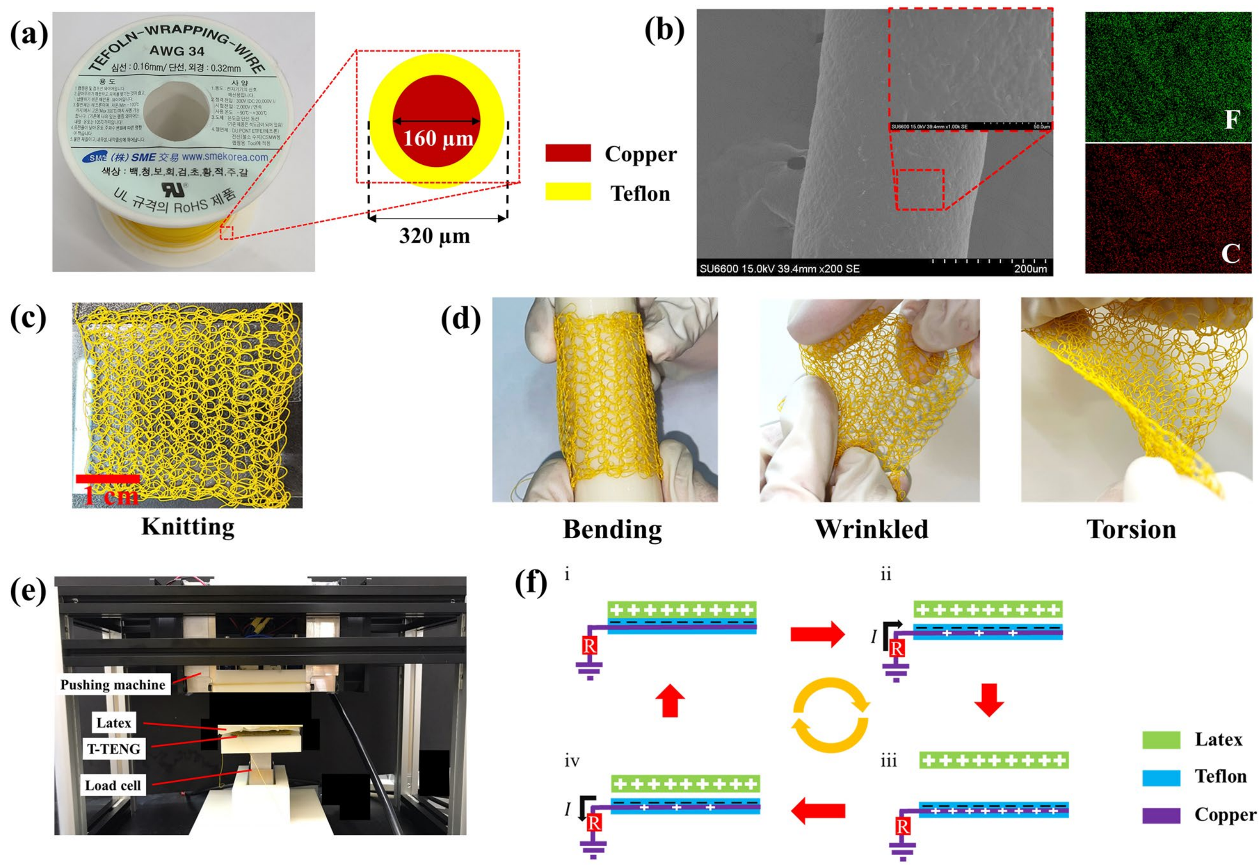

Fig. 1 **a** Photograph and **b** SEM image and EDS analysis of commercial Teflon wrapping wire. **c** T-TENG produced by knitting methods. **d** Photograph of fabricated T-TENG with flexible properties. **e** Experimental setup to characterize T-TENG. **f** Mechanism of T-TENG

Many factors affect the output of the T-TENG; among them, we investigated the effect of frequency and force. The frequency and force were adjusted using a solenoid motor and LabVIEW, respectively. The resulting force was measured using a load cell under the T-TENG. First, the open-circuit voltage and closed-circuit current of the T-TENG at 1 Hz were measured according to the applied force (Fig. 2a, b). As the force increased from 5 to 40 N, the voltage output of the T-TENG increased from ~ 100 V to ~ 250 V. This increase in voltage is due to the higher force applied to the T-TENG, tighter contact between the two friction materials, and an increase in the contact area. The current output increased up to a force of 20 N and then stabilized. The output current was stabilized compared with output voltage depending on the force because the short-circuit current is proportional to the speed of contact-separation.

The output voltage and current of the T-TENG were measured while increasing the frequency from 1 to 4 Hz (Fig. 2c, d). It was established that the output voltage increased to 3 Hz and then stabilized; the output current increased as the frequency increased. The increase in the electrical output of the T-TENG with increasing frequency is attributed to the contribution of the charge transfer and charge density. The output voltage and current of the T-TENG were measured varying the resistance from 10^6 to 10^{10} Ω (Fig. 2e). As the external resistance increased, the output voltage of the T-TENG increased and the output current decreased. The power density of T-TENG was ~ 0.36 W/m^2 with an external load resistance of 10^9 Ω (Fig. 2f). The fabricated T-TENG has a higher maximum output voltage and maximum power density compared with the previous fiber type T-TENG (Table 1).

The durability of T-TENGs in harsh environments is important for their application in wearable devices. Therefore, the ability of the T-TENG to generate electricity was tested after immersing it in 1 M acid and 1 M base for 1 h, respectively. Owing to the water repellency and chemical resistance of Teflon, there was little change in the surface after immersion compared to that before immersion (Fig. 3a, b). In addition, there was little change in performance when a pushing machine (at 1 Hz and 15 N) was used with the T-TENG (Fig. 3c). The

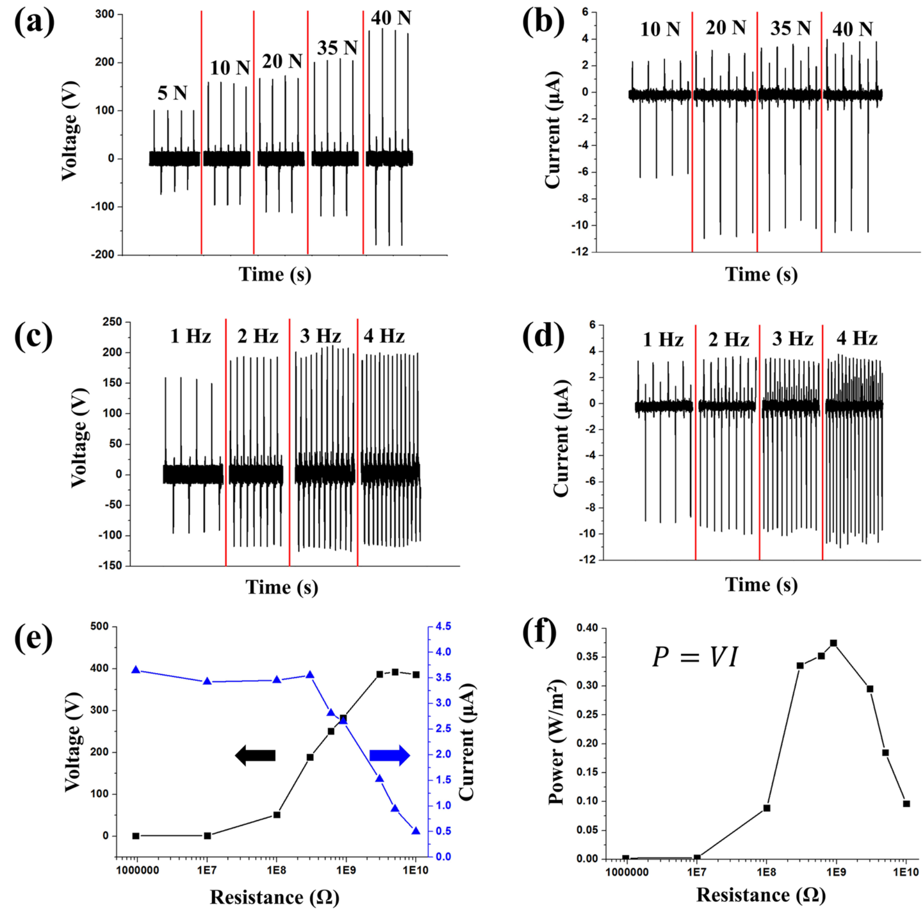

Fig. 2 Electrical output performance of the T-TENG using 500 MΩ. **a** Open-circuit voltage and **b** Short-circuit current of the T-TENG at varying pressure at frequency of 1 Hz. **c** Open-circuit voltage and **d** Short-circuit current of the T-TENG at varying frequency at pressure of 15 N. (**e**) Output voltage, current, and **f** Instantaneous power density of the T-TENG at varying external load resistances

Table 1 Comparison of the performance of different fiber type T-TENG

Reference	Triboelectric pair	Fabrication method of fiber	Thickness of fiber	Maximum output voltage	Maximum power density	Fabrication method of textile
This work	Latex–Teflon	Commercial product	~320 μm	400 V	0.36 W/m^2	Knitting and weaving
[29]	Polyester–Silicon rubber	Dip-coating	–	120 V	0.08 W/m^2	Knitting
[30]	Skin–Silicon	3D printing	~840 μm	–	0.03 W/m^2	–
[31]	Polyamide 6–polytetrafluoroethylene	Yarning	~500 μm	50 V	0.01 W/m^2	Knitting
[32]	Silk–polytetrafluoroethylene	Vacuuming	~600 μm	105 V	0.03 W/m^2	Knitting and weaving
[33]	Nylon–Silicon	Yarning and surface treatment	–	–	0.09 W/m^2	Knitting and weaving
[34]	Polyester–Parylene	Electroless plating and Chemical Vapor Deposition	–	50 V	0.39 W/m^2	Weaving
[35]	PET–Polyimide	Polymer-assisted meatal deposition and dip-coating	~350 μm	5 V	0.03 W/m^2	Weaving
[36]	Polyamide 6–Polyvinyl chloride	Yarning and roll-to-roll coating	~290 μm	29 V	0.02 W/m^2	Knitting
[37]	Nylon–Silicone Rubber	Dip-coating and spraying	~900 μm	4 V	0.001 W/m^2	–

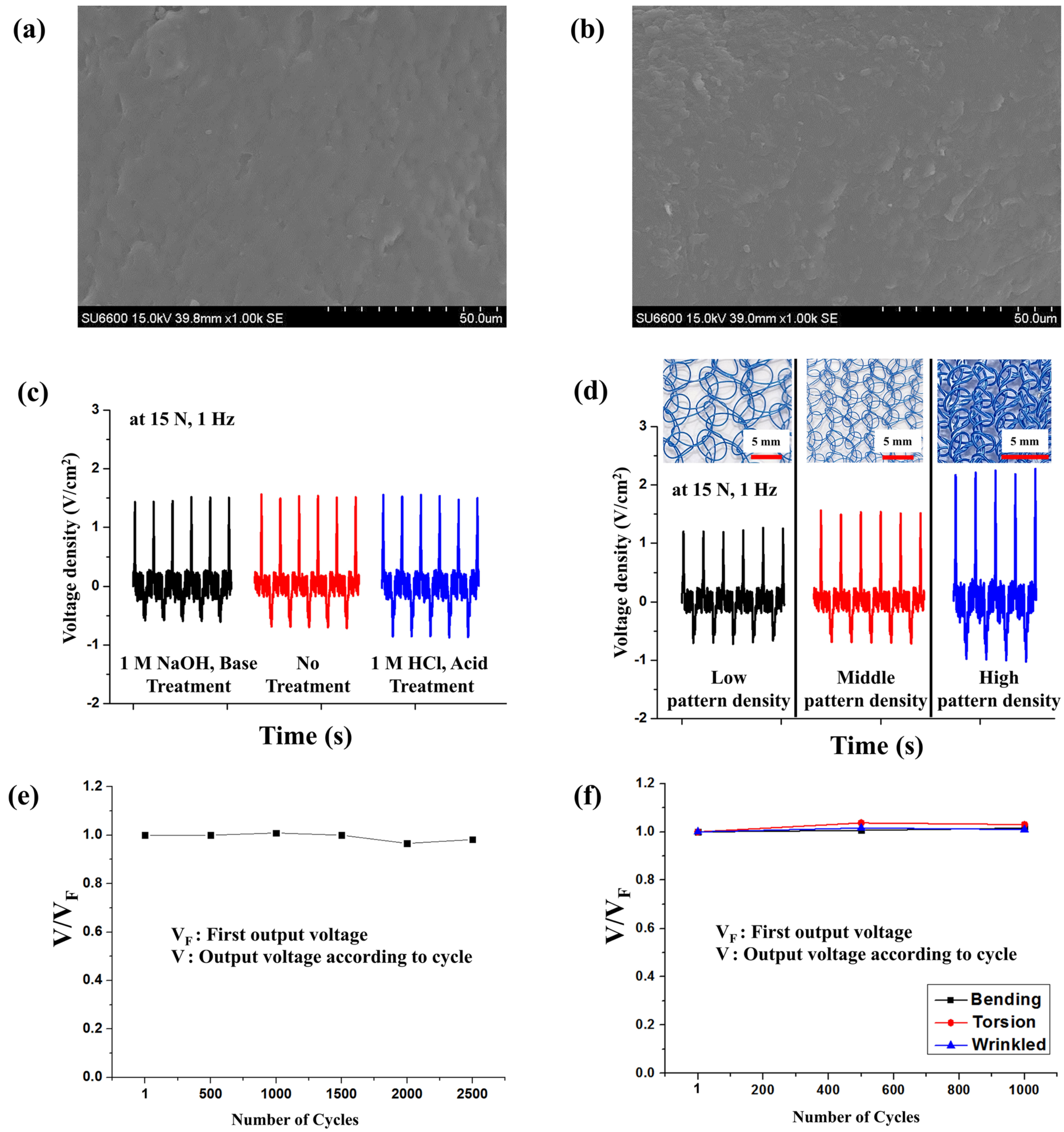

Fig. 3 SEM image of T-TENG after (**a**) Acid treatment and (**b**) Base treatment. **c** Output voltage density of T-TENG using 100 MΩ depending on treatment. **d** Output voltage density of T-TENG using 100 MΩ depending on pattern density. **e** Relative change of output voltage of T-TENG by repetition of contact-separation. **f** Relative change of output voltage of T-TENG according to durability test

pattern density varies by controlling the loop length of the T-TENG during knitting. The performance of the fabricated T-TENG varied depending on the pattern density, which was determined as low, middle, and high. The voltage produced increases from ~ 1 to ~ 2 V/cm^2 as the pattern density increases (Fig. 3d). This is because the area where the Teflon and latex meet in the same area increases.

For practical use, the durability of the manufactured T-TENG is important. Thus, the performance of T-TENG in repeated external stimuli was tested. The relative output voltage (V/V_F) did not change significantly when the contact-separation was cycled 2500 times using a pushing machine, which implies the output voltage of T-TENG was constant during the cycles (Fig. 3e). The performance of T-TENG were measured according to the cycle of bending, (Curvature: 0.35 cm^{-1}), wrinkling, and torsion (torsion angle: 15°). In the wrinkling test, T-TENG was attached to the palm of the hand. The clenching and opening of the fist was defined as one cycle. The performance degradation of the T-TENG was negligible in the cycles of bending, wrinkling, and torsion compared with the first output voltage (Fig. 3f).

Normally, the T-TENG generates an alternating current (AC); therefore, the output must be converted to DC to power an external electronic device. A commercial capacitor was charged by connecting a rectifier circuit to the T-TENG (Fig. 4a). The capacitor was charged over 2 V while repeatedly applying contact separation with a force of 15 N at 2 Hz using a pushing machine on the T-TENG (Fig. 4b). By connecting a 4.7 μF capacitor charged over 2 V with the T-TENG to the calculator, the calculator was able to perform simple additions and multiplications for ~ 8 s (Fig. 4c). The developed T-TENG can supply power to electronic devices by harvesting mechanical energy generated by normal human motion. We fabricated an insole in a shoe (Fig. 5a) with an integrated T-TENG (area: 30 cm^2). Based on the human motion of standing, walking, running, and falling, the contact separation between the socks and T-TENG is repeated to harvest energy. The output voltage varied depending on the human motion. The output voltage is higher when running than when walking (Fig. 5b). This is because the contact area between the socks and T-TENG increases during running. This indicates that the T-TENG fabricated by knitting can be used as a wearable energy source powered by human movement. In addition, there is little change in the output voltage in standing state. However, only negative output voltage occurs in the falling state (Fig. 5b). This makes it possible to distinguish a human motion state.

Conclusion

In this study, a T-TENG that can generate electric power via external mechanical stimulation was fabricated by knitting a commercial electrode as a fiber. The output voltage and current were measured according to the applied frequency and magnitude of the force, and the output power density was measured according to the resistance. The fabricated T-TENG had an output power

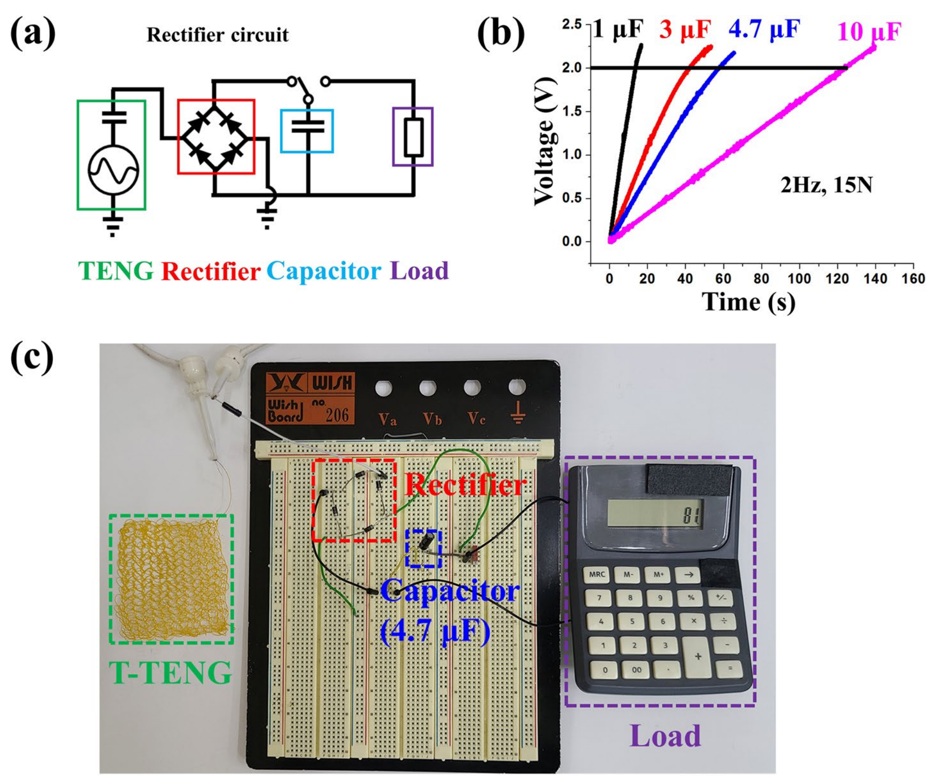

Fig. 4 **a** Circuit of charging capacitor using T-TENG under periodic mechanical stimulation. The voltage–time relationship at different load capacitances using (**b**) Pushing machine and (**c**) Photograph of a working calculator using a charged capacitor

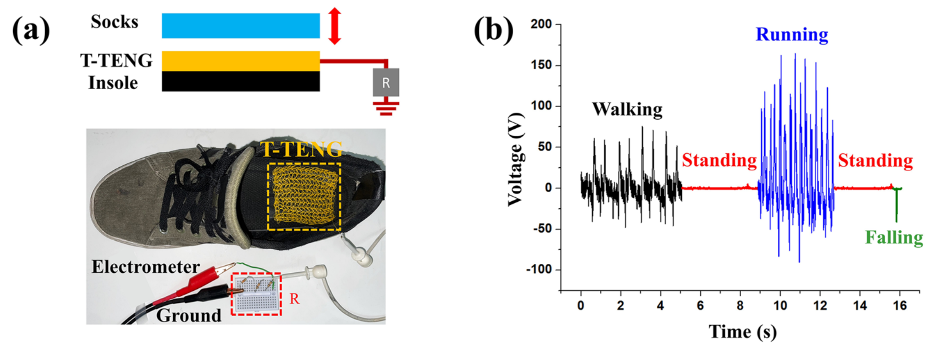

Fig. 5 **a** Photograph of a shoe with T-TENG integrated in the insole and a schematic diagram of the energy harvesting mechanism. **b** Output voltage of T-TENG measured when walking, standing, running and falling at 30 MΩ

density of ~ 0.36 W/m^2. We confirmed that it worked satisfactorily without degradation even in harsh external conditions. In addition, the T-TENG could charge a capacitor to drive electronic devices. We believe that, in the future, the fabricated T-TENGs could be used in wearable electronics with working environments such as bending and twisting.

Abbreviations
IoT: Internet of Things; TENG: Triboelectric nanogenerator; T-TENG: Textile-type triboelectric nanogenerator; PENG: Piezoelectric nanogenerator.

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Author contributions
KS performed the experiments, analyzed the data, and wrote the manuscript. CW supported the data analysis. WDJ carried out the device fabrication. KJ supervised the study and reviewed the manuscript. All authors have read and approved the final manuscript.

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Availability of data and materials
All data generated or analysed during this study are included in this published article.

Declarations

Competing interests
The authors declare that they have no competing interests.

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