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Embroidery Triboelectric Nanogenerator †

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Abstract: The "Embroidery Triboelectric Nanogenerator" (E-TENG) is a wearable device that extracts energy from human motion by making use of the triboelectric phenomena, in addition to conductive fabric along with embroidery threads. One of the greatest ways to transform ambient vibrational energy from the human body is to use a wearable triboelectric energy harvester. In this study, different E-TENGs were developed using conductive fabric as an electrode and two different triboelectric yarns, 100% Polyester (electron donor) and Nylon 6,6 (electron receiver). To investigate the electrical outputs and energy-collecting potential of the ETENG, different stitch length and line spacing of embroidery TENG were investigated by testing samples in a specially manufactured tapping and sliding devices. The optimized wearable embroidery energy harvester effectively captured 72 μJ (12 V) of human motion energy in a 1 μF capacitor in 120 s and 307.5 μJ (24.8 V) of energy in a 1 μF capacitor by 1.5 Hz sliding motion in 300 s from an ETFS3.1 sample. A maximum of 4.5 μJ (3 V) was collected in a 1 μF capacitor from ETFS2.3 using a tapping machine for 520 s at a 2 Hz tapping motion and a 50 mm separation distance. The effects of the stitch length and line spacing in the embroidered structure on the electrical output performance of the embroidery energy-harvesting TENG were investigated.

Keywords: E-TENG (embroidery triboelectric nanogenerator); wearable energy harvesting; triboelectric effect; human kinetics; conductive substrate

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1. Introduction

The Embroidery Triboelectric Nanogenerator is a great development in energy harvesting, providing a sustainable and environmentally friendly way to power the upcoming wearable technology while capturing the kinetic energy produced by human motion [1,2]. The field of wearable technology holds enormous potential for this novel energy harvesting approach. It makes it possible for continuous power generation without the need for frequent charging or battery replacement, which makes it perfect for smart wearables created for everyday use and for use in emergencies and monitoring one's health [3]. Adjusting the embroidery stitch length and line spacing allows the gadget's functionality to be maximized, enabling customized energy-collecting capabilities.

Due to the hunt for renewable resources and increased awareness of environmental protection over the past few decades, turning ambient energy into electricity has attracted much attention. Our environment may contain a variety of energies. Large-scale energy harvesting (macro energy harvesting) like solar, wind, hydro, and geothermal generators have been deployed for industrial and domestic electricity. These, however, are unable to provide practical wearable energy harvesting solutions. TENGs, or wearable triboelectric nanogenerators, can power not only a variety of wearables but also IoT devices [4,5].

Triboelectricity is a typical occurrence in everyday life. But in the past, it was thought to have a negative impact since it occasionally sparks electrostatically, which can lead to mishaps [6,7]. The development of the triboelectric nanogenerator reveals a previously untapped source of energy from human biomechanics [8,9].

2. Materials and Method5

TENG embroidery was made with Brother Embroidery PR670E. 100% polyester yarn was used in the embroidery machine to create the triboelectric layer and cotton bobbin for aid the embroidery process. To minimize shrinking during embroidery, the thin woven fabric was assembled underneath the conductive fabric. The embroidery frame's four magnetic clamps stretched materials evenly and smoothly for optimal results. Circular forms fill stitch embroidery TENG samples with different stitch lengths and line spacing factors were designed using Ink stitch, an Inkscape extension. Fill stitch connects underlay and overlay layers transversely.

The main elements of our design were the fill stitch pattern and two crucial independent variables: stitch length and line spacing. Three distinct stitch and line spacing were carefully chosen. They are known as ETFS1, ETFS2, and ETFS3, and have relative stitch lengths of 1.5 mm, 2 mm, and 3. There are three distinct line spacing levels: 0.65 mm, 0.90 mm, and 1.2 mm for each variation of stitch length. The table shows the sample design specifications. In the same way, the reference sample was made with the tribo- positive Nylon 6,6 yarn embroidered on the conductive substrate. The stitch length of the sample is 2 mm, and the line spacing is 0.65 mm. Line spacing was kept very low to fully cover the electrode to prevent system short circuits by contacting some of the main samples' electrodes with higher line spacing. The specifications about the embroidery samples can be found in Table 1, providing the details about the stitch length and spacing between lines.

Table 1. Specification for designing the polyester embroidery samples.

Sample Name	Stitch Length l (mm)	Spacing between Lines d (mm)
ETFS1.1	1.5	0.65
ETFS1.2	1.5	0.90
ETFS1.3	1.5	1.2
ETFS2.1	2	0.65
ETFS2.2	2	0.90
ETFS2.3	2	1.2
ETFS3.1	3	0.65
ETFS3.2	3	0.90
ETFS3.3	3	1.2

2.1. Tapping Test

Tapping test is resembled to contact separation mode of TENG. The tapping tests were run by the pneumatic foot driven by aid of controlled air pressure. The tapping test's tapping frequency remained fixed at 2 Hz throughout, with an applied force of 1 bar over an area of the main sample measuring around 201 cm2. Every test ran for 60 s, and each sample was tested three times.

2.2. Sliding Characterisation

A custom-designed machine as shown in Figure 1. performed the friction test through lateral sliding motion driven by a DC motor. The mechanical arm features a clamp for securing the primary sample, allowing for horizontal movement at varying frequencies up to 2 Hz. The machine frame and the sample mounting clamps are made from wood and the diameter is 10 cm. The wooden structure is suitable for electrostatic testing because wooden structure has minimal effect on test results.

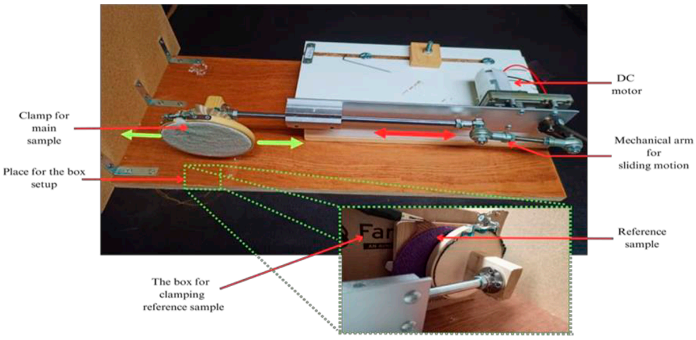


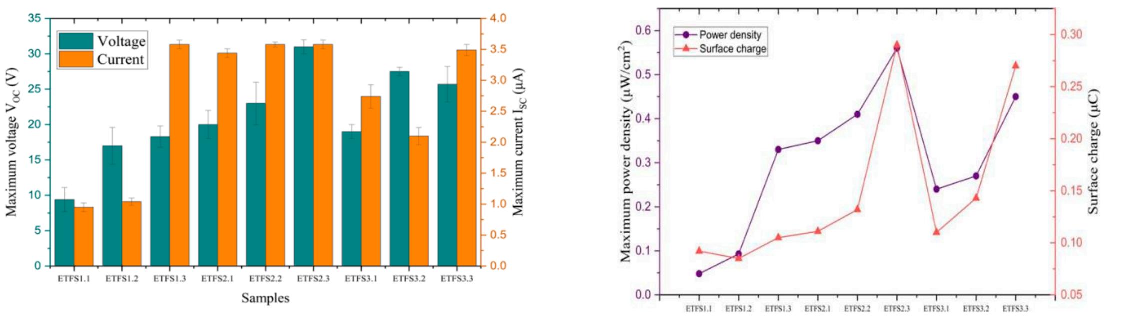
Figure 1. Sliding test machine setup for characterization of the embroidery TENG.

The samples were tested for current measurement both in tapping and sliding characterization machine for 60 s and for each sample three times. Open-circuit voltage, short-circuit current, and induced surface charge were measured by an electrometer and a current measuring circuit subsequently. The tapping tests were conducted at a 50 mm distance between two triboelectric layers and 1 bar pressure on the 201 cm^2 active area of the main sample (100% polyester). For sliding tests, the frequency was 1.5 Hz and a 10 cm^2 active area of the main sample. A full-wave rectifier circuit was made for both tapping and sliding characterization, used for storing charge in different capacitors. A critical component in harnessing the full potential of TENG technology lies in developing circuits capable of converting AC voltages into usable DC power sources. Since the Triboelectric Nanogenerator produces AC voltage, a compatible rectifier diode was used to transform AC voltage into DC voltage, and a capacitor was employed to store the DC voltage.

First, the TENG's output connection with the rectifier diode's input is made, and the rectifier diode's output is connected to the capacitor's positive terminal. The capacitor's negative terminal is connected to the negative leg of rectifier. Connecting the device through capacitors allows for fully harnessing storage energy. The parallel connection between the electronic device and the capacitor is crucial. In the first step, low capacitance capacitors (1 µF or 4.7 µF) were used for storing charge during tapping or sliding motion for all samples After that best performing sample was tested with 1 µF, 4.7 µF and 10 µF capacitor to select the best performer for use in the first stage of power storing for the embroidery energy harvester.

3. Result and Discussion

The following graph (Figure 2) shows the average maximum open-circuit voltage and average maximum short-circuit current for tapping test with 1 bar machine pressure, 201 cm^2 active sample area, 50 mm distance between two triboelectric layers measured by the electrometer. ETFS2.3 and ETFS3.2 are the best sample for generating higher voltage with minimal error bar in case of tapping test.



(**a**) (**b**)

Figure 2. Open circuit voltage, maximum power density and surface charge: (**a**) average maximum open circuit voltage and average maximum short circuits current; (**b**) maximum power density and surface charge generated in 60 s by tapping test in 2 Hz frequency.

From the above graph, power density and surface charge for tapping test increase from lower to higher line spacing for all three groups, namely ETFS1, ETFS2, and ETFS3. Sample ETFS2.3 and ETFS3.3 outperformed those with the same line spacing of 1.2 mm with stitch lengths of 2 mm and 3 mm, respectively. The overall performance of the ETFS 2.3 for open-circuit voltage, short-circuit current, induced surface charge, and power density is the average best performer.

Figure 3 shows that the best performers for voltage generation are ETFS2.2, ETFS3.1, and ETFS3.2. But ETFS3.1 is the most consistence performer because error bar is lower than compared to ETFS2.2 and ETFS3.2. All the best three have longer stitch length with lower line spacing. For the current generation, ETFS3.1 and ETFS3.2 are outperformed. However, ETFS3.1 is the best with lower error bar than ETFS3.2. This sample has longer stitch lengths and narrower line spacing, which enhance charge generation by increasing the available surface area. Figure 4 shows the result of energy harvesting with full wave rectifier bridge circuit in 4.7 μF capacitor on lateral sliding experiment. The *x*-axis shows the voltage (volt), and y-axis represents time duration.

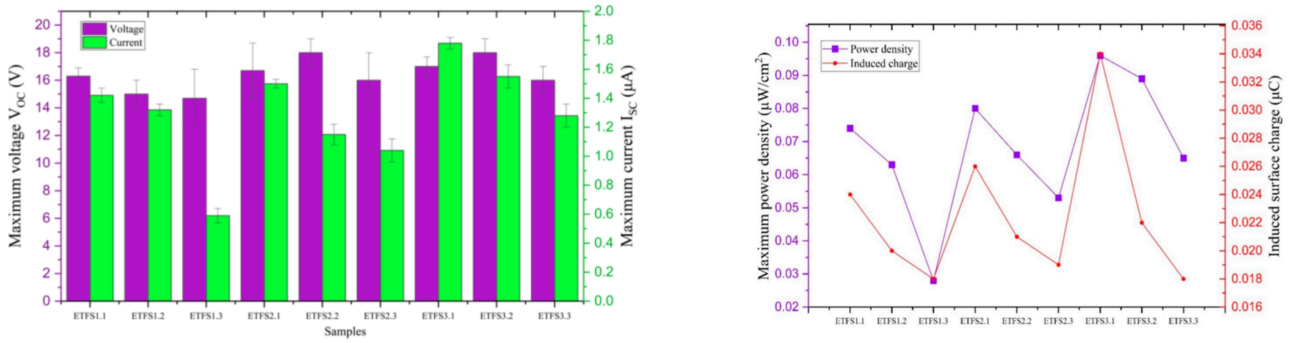


Figure 3. Sliding test results: (**a**) Average maximum open circuit voltage and average maximum short circuits current; (**b**) Average maximum power density and surface charge generated in 60 s.

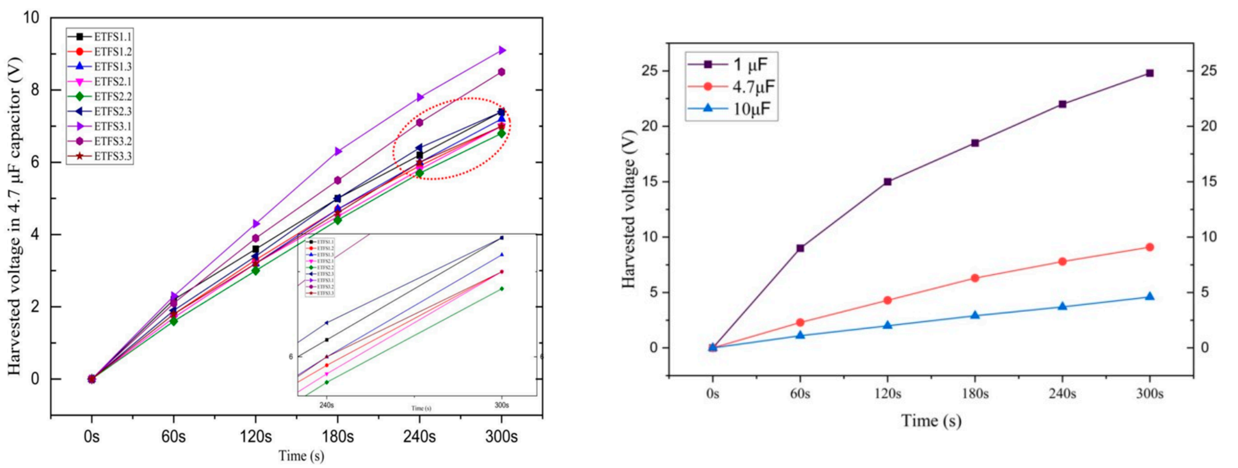


Figure 4. Harvested voltage sliding at 1.5 Hz frequency: (**a**) stored in 4.7 μF capacitor; (**b**) stored in 1 μF, 4.7 μF and 10 μF capacitors for the sample ETFS3.1.

Further investigation the same test was conducted with 4.7 μF and 10 μF capacitors for ETFS3.1. The result is shown in Figure 4. The 1 mif capacitor was able to Store 24.8 V in 300 s. Using the harvested energy, 20 small (3 mm) red LEDs and 11 green LEDs were illuminated, as shown in Figure 5.

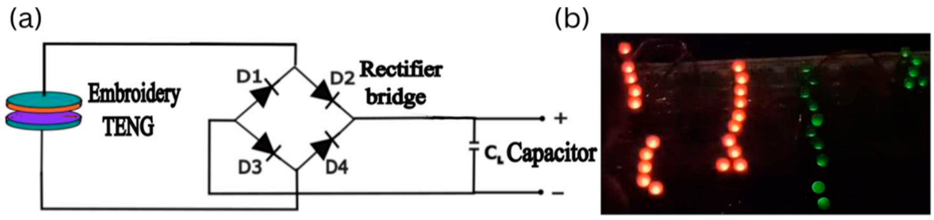


Figure 5. Harvested rectifier circuit for energy harvesting in capacitor, (**a**) Embroidery TENG with full bridge rectifier to store the harvested energy in capacitor (**b**) lighted red and green LEDs by harvested energy.

From this experiment, 1 µF capacitor is the best performing for storing harvested energy through the rectifier. From the analysis of all the results, it appears that the tapping test gives the highest maximum open-circuit voltage and short-circuit current during every contact and separation with a 50 mm distance between two triboelectric layers and 1 bar pressure on 201 cm^2 active sample area. However, the friction test shows a slightly lower instant maximum open-circuit voltage and short- circuit current than the tapping test in a 1.5 Hz frequency. In the tapping test, it was observed that the samples with higher line spacing and a lower amount of triboelectric yarn showed comparatively better performance. The best performing sample is ETFS2.3 which comprise 3 mm stitch length, 1.2 mm line spacing. However, in the case of friction, because of comparative longer stitch length during sliding stitches can generate better friction than lower stitch length. Moreover, samples with higher stitch with lower spacing have higher amounts of triboelectric yarn for storing a higher amount of charge.

4. Conclusions

In conclusion, the usage of the energy-harvesting embroidery TENG designed based on the triboelectric effect employing 100% Polyester and Nylon 6,6 triboelectric yarns has been examined in this study. The manufacture of the embroideries TENG and its optimization of the fabrication parameters, along with study of the impact of variations on the electrical output performance of the TENG, were investigated. Energy extraction from the embroidery TENG was successfully performed using both specialized tapping and sliding devices. The most energy was extracted from the ETFS3.1 sample that was 307.5 µJ (24.8 V) in a 1 µF capacitor over the course of 300 s using a 1.5 Hz sliding motion, and 72 µJ (12 V) over the course of 120 s using a human walking frictional simulation device. A maximum of 4.5 µJ (3 V) was collected in a one µF capacitor from ETFS2.3 using a tapping machine for 520 s at a 2 Hz tapping motion and a 50 mm separation distance. There was an increase in maximum voltage, maximum current, and power output due to the combinations of stitch length and line spacing used in the different experiments. In the case of the contact and separation modes, it was concluded that samples with intermediate stitch lengths and greater line spacing displayed a higher level of triboelectric charging. However, a different tendency was noticed for the sliding mode. The sample that has a longer stitch length and closer-spaced lines produces more electric power. Longer stitch length and closer-spaced lines in the embroidery of a triboelectric nanogenerator improve its performance by increasing the surface area, promoting more frequent and extensive friction, and enhancing the charge transfer.

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Conflicts of Interest: The authors declare no conflicts of interest.

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