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Article

Developing a wearable, skin-based triboelectric nanogenerator

Armaan Srireddy[1], Satyamohan Srireddy[2]

[1] Westwood High School, Austin, Texas

[2] DecisionPath Consulting, Austin, Texas

SUMMARY

The widespread adoption of alternative energy sources is increasingly important as we try to create a more sustainable future. The wearable electronics field is growing at a rapid rate. In addition to smart devices like smartwatches and fitness trackers, biosensors are becoming progressively more popular to track critical health data. Summer temperatures in Texas regularly rise over 100°F, often coinciding with summer activities and camps. Left unchecked, this can lead to serious consequences, including heatstroke. A triboelectric nanogenerator (TENG) embedded in one's shirt can be used to sustainably power a temperature sensor to prevent heat emergencies. We hypothesized that the triboelectricity generated from the friction between one's skin and a negatively charged material placed on the inside of a shirt would produce enough voltage to power these biosensors. We tested numerous negatively charged materials and conductors to determine the optimal design of the generator. Our results revealed that silicone was the superior negatively charged material, producing nearly twice as much voltage as Teflon and five times more than cellophane. We tested the conductors and found that copper produced over 50% more voltage than aluminum. The wearable triboelectric nanogenerator (W-TENG) utilized silicone and copper, the superior negatively charged material and conductor, respectively. The W-TENG produced an average of 3.6 volts while running, enough to power the temperature sensor. Our project is novel due to its usage of skin as the positively charged material in a hybrid contact-separation/sliding mode TENG. The W-TENG created and tested in this experiment shows promise for tracking body temperature and preventing impending heat emergencies.

INTRODUCTION

One of the most pressing global challenges that we face is that of sustainability. To mitigate global warming and climate change, many are looking toward alternative energy sources to decrease fossil fuel-based carbon emissions. This is highlighted in the United Nation's seventh Sustainable Development Goal, which is to provide access to clean sources of energy throughout the world (1). Currently, major areas of exploration within energy include improving large-scale power sources, such as solar or wind plants, or increasing the efficiency of energy storage systems, like batteries and supercapacitors. However, an underexplored area of renewable energy that could have a large impact on improving our sustainability is energy scavenging, or the process of converting otherwise wasted energy into usable electricity (2). Each day, our natural body movement produces a lot of excess mechanical energy, which can be converted into electricity using power generators (3). This power can then be supplied to wearable devices, in order to limit – or even eliminate in the future – the need for batteries in these devices. This will also allow for a continuous power supply, as there will be constant generation occurring while the device is in use.

Wearable devices are experiencing exponential market growth and are rapidly becoming a staple in our society (4). More specifically, biosensors and other trackers to monitor critical health data are becoming increasingly important in a world ruled by data. In Texas, heat exhaustion is an especially prevalent problem. In fact, the Centers for Disease Control and Prevention (CDC) reported Texas to be one of three states that accounted for approximately one-third of national heat-related deaths (5). Temperature sensors can be used to measure our skin temperature and alert users prior to reaching the point of heat exhaustion (6). However, many situations where this is applicable – such as unsafe or high-temperature areas like construction sites, remote military operations, and isolated hiking areas – do not have easy access to power. Current biosensors are limited by their battery life. If one forgets to charge the battery or is in an extended-use situation without ready access to power, a biosensor will be rendered useless. A wearable generator that harnesses our body movement to generate electricity would bypass the need for an external battery and would almost always be able to function.

A wearable triboelectric generator (W-TENG) is a potential solution to powering such devices. Triboelectric generators (TENG) operate based on the triboelectric effect, meaning they generate electricity when two oppositely charged materials come into contact with each other (7). The triboelectric series shows the charge affinity of these materials, and the farther apart two materials are on the series, the higher the generation of the ensuing generator will be (**Figure 1**). Skin is ranked very high on the positive end of the triboelectric series (8). There are four different styles of TENGs: contact-separation, sliding, single electrode, and free-standing triboelectric layer mode (9). The design of the generator used depends on the application. For example, a contact-separation mode generator is suited for a shoe insert generator application, since the stepping motion will allow the generator to compress and decompress at a regular interval. To capitalize on the rubbing between our shirt and skin, we proposed a hybrid contact-separation, sliding mode TENG. (**Figure 2**). This design utilizes the natural consequence of

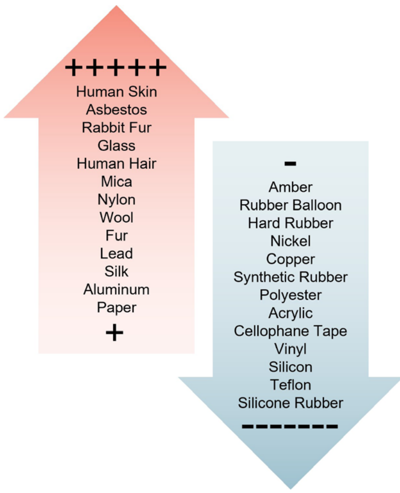

Figure 1. Triboelectric series of various materials. Ranking of materials by their tendency to gain/lose an electron (20). The red series indicates materials that have a more positive charge, whereas the blue section indicates materials with a more negative charge. The direction of the arrows, "+" and "-" represent a relative ranking of the materials' charge affinity.

the brushing movement that the shirt makes against skin.

In this study, we aimed to find the optimal combination of variables for a W-TENG that can be used to sustainably power a temperature sensor to prevent heat emergencies. There have been prior studies on W-TENGs, such as the one done by Somkuwar *et al.*, in which the authors created and tested a textile-based TENG, and Jiang *et al.*, in which the authors created a thin, flexible, and washable TENG (10, 11). These studies demonstrated successful creation of

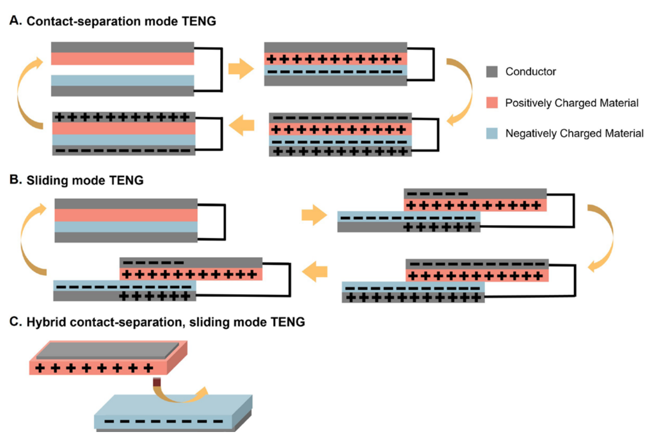

Figure 2. Types of TENGs based on different modes of operation. Each type of generator functions on the same principle: the two oppositely charged materials come into contact with each other and a transfer of electrons, facilitated by the conductor, occurs. For the contact-separation mode TENG (**A**), the two sides are tapped together in a vertical manner. For a sliding mode TENG (**B**), the two sides slide in a horizontal manner. The type of TENG used depends on its application. In this sense, the hybrid contact-separation (**C**), sliding mode TENG was born out of necessity due to the type of motion the shirt makes while brushing against skin (21). Red represents the positively charged material, blue the negatively charged material, and gray represents the conductor. The "+" and "-" symbols denote positive and negative charged states, respectively, of each side of the generator.

efficient, wearable generators, but these could be improved by eliminating the positively charged material from the design and replacing it with skin to reduce complexity and bulk. We proposed an alternative approach of using skin as a positively charged material with a hybrid contact-separation/sliding mode generator. We hypothesized that the triboelectricity generated from the friction between one's skin and a negatively charged material placed on the inside of a shirt would produce enough voltage, 3 volts, to power common wearable devices (12, 13). Furthermore, we hypothesized that surface area would have a proportional relationship with power generation, as a larger generator would result in an increased charge density. We hypothesized that the use of stronger conductors – such as silver or copper – in place of aluminum would improve the TENG's power generation, since a stronger conductor should facilitate more efficient electron movement.

RESULTS

Assessment of Charged Materials

The primary components of a TENG are the materials with which it is comprised. The positively charged material in the W-TENG was skin. Therefore, we conducted the first set of trials in order to determine the most effective negatively charged material. We tested cellophane, polytetrafluoroethylene (PTFE), and silicone rubber. We tapped the fabricated generators at a constant speed, and observed the voltage produced. These tests revealed that the generator which incorporated silicon produced 1.40 volts, which was significantly more than those that used cellophane and PTFE – 0.227 volts and 0.670 and volts respectively (adjusted $p < 0.01$, **Figure 3**).

Silver is known to be the most conductive material, followed by copper, gold, and aluminum (14). Due to the impracticability of using silver and gold, we focused on copper and aluminum. We conducted the second set of trials to determine whether a TENG that utilized copper as a conductor would generate more voltage than that of aluminum. We constructed identical

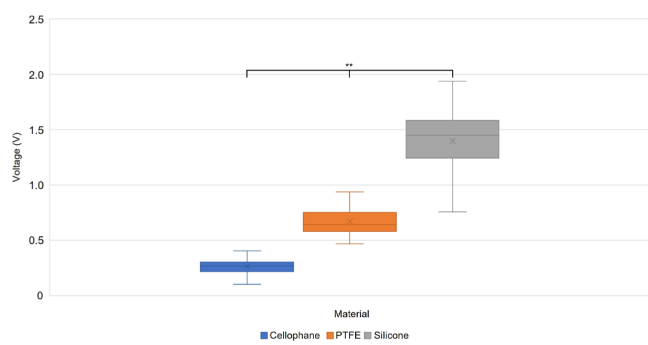

Figure 3. Voltage generation from cellophane, PTFE, and silicone as negatively charged materials in a TENG. Voltage generation across the different negatively charged materials (n = 20 per generator). The "X" denotes the mean values. Generators with differing negatively charged materials (cellophane, PTFE, and silicone) were fabricated using the same positively charged material (paper) and surface area (8 in^2). The generators were tested in identical conditions and tapped at a speed of 90 taps/minute. One-way ANOVA with a Tukey HSD correction for multiple comparisons, adjusted $p < 0.01$ for the mean voltage generation of the silicon-based generator being greater than that of cellophane and PTFE.

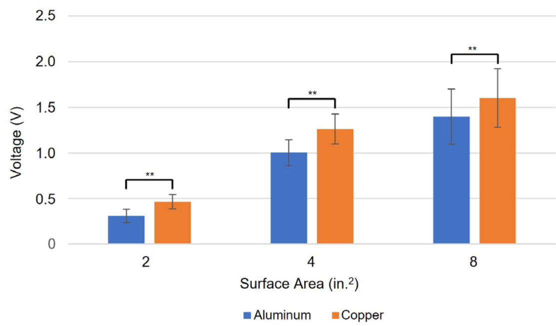

Figure 4. Mean voltage generation from copper and aluminum as conductive layers in a TENG. Mean voltage generation at differing surface areas from both conductors (n = 20 per generator). Error bars represent standard deviation. Generators of varying surface areas (2 in^2, 4 in^2, and 8 in^2) were fabricated using the same positively charged material and negatively charged material – paper and silicone, respectively. These three generators were replicated, using copper or aluminum as the conductive material. The generators were tested in identical conditions and tapped at a speed of 90 taps/minute. Paired t-test, $p = 0.01$.

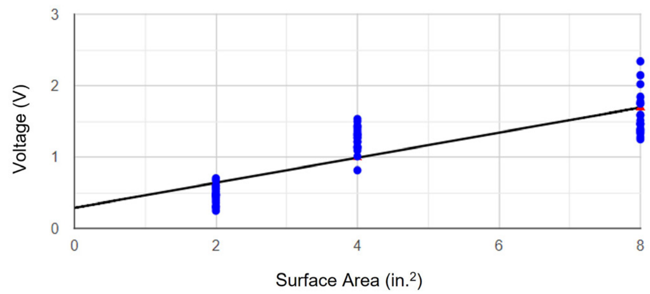

Figure 5. Mean voltage generation from TENGs with varying surface areas. Least squares regression line analysis showing the voltage generation at differing surface areas of a silicone and copper based triboelectric generator (n = 60). Generators of varying surface areas (2 in^2, 4 in^2, and 8 in^2) were fabricated using the same positively charged material, negatively charged material, and conductor – paper, silicone, and copper, respectively. The generators were tested in identical conditions and tapped at a speed of 90 taps/minute. Twenty independent voltage readings were recorded from each of these generators with a digital multimeter. t-test for regression slope, $p < 0.0001$. Regression line equation: $\hat{y} = -0.1622 + 0.2224x$, $r = .943$.

silicone TENGs which utilized different conductive surfaces and tapped them at a constant speed. When observing the voltage with a multimeter, we found the TENG that incorporated copper produced significantly more voltage than the TENG that incorporated aluminum ($p = 0.01$, **Figure 4**). The p-value represents a paired t-test that encompassed the differences in voltage generation for the two conductors across all three surface areas.

Generator Size and Shape

In addition to the material choice, the size of a generator can also affect a generator's production, as it will result in varying charge densities (15). To determine the exact impact that surface area had on power generation, we tested three different sizes (2 in^{2,} 4 in^2, and 8 in^2), and used the means of our readings to create a least squares linear regression ($p < 0.0001$, **Figure 5**). The regression line can be extended to estimate the voltage generation of the optimized W-TENG through extrapolation. The optimized W-TENG was 118 in^2. Thus, the regression line predicted a power generation of 21 volts for the W-TENG.

The primary challenge that we had to work through was developing a design that incorporated both contact materials' conductive surfaces on the same layer. In a TENG, electricity is generated from oppositely charged materials coming into contact with one another and transferring electrons. This electron transfer is facilitated by conductive surfaces placed on the non-contacting side of each triboelectric layer. In our application – which was a shirt-based generator – skin was the positively charged material. However, it is not feasible to attach a copper sheet or other conducting material to the skin every time the generator is used. Thus, we had to work around this by creating a design that allowed the conductive surface for the skin, and the silicone (the negatively charged material) to be present on the shirt. This led to the use of the "HH" shape for the silicone in the W-TENG (**Figure 6**). This allowed the copper to come into contact with the skin whenever the silicone does, whilst keeping it all as a singular unit.

W-TENG Voltage Generation

The final aspect of the experiment was to test the W-TENG whilst it was embedded in a shirt to determine whether it would produce enough voltage to power a low-power temperature sensor. We inserted the generator into the shirt (**Figure 6**). We conducted trials while walking and running in the same environment, using a digital multimeter to record its voltage production. We found the shirt-embedded generator produced a mean voltage of 2.6 ± 0.7 volts while walking and 3.7 ± 0.9 volts while running, the latter of which was enough to power the temperature sensor (**Figure 7**). However, these measurements were much lower than the theoretical W-TENG voltage generation of 21 volts estimated through extrapolation (**Figure 5**).

Our preliminary experiments revealed that of all the materials we tested, a combination of silicone rubber and copper yielded the highest power generation. Additionally, the surface area had a proportional relationship with power generation. Our secondary trials of the W-TENG showed that it generated an average of 2.6 volts while walking, and 3.6 volts while running, which was sufficient to power the temperature sensor used in our experiment. The W-TENG created and tested in our experiment shows potential for being used to power temperature sensors – and other low power biosensors – whilst one is engaged in running orrelated physical activity, especially in areas where power is not readily available.

DISCUSSION

Our data supported the hypothesis that triboelectricity can produce enough voltage to power small sensors and devices. We found silicone to be the superior negatively charged material compared to cellophane and PTFE (**Figure 3**). We determined copper to be a more efficient conductor over aluminum (**Figure 4**). We found surface area and power generation to have a proportional relationship (**Figure 5**). We tested the optimized W-TENG whilst walking and running and generated 2.6 ± 0.7 volts and 3.7 ± 0.9 volts, respectively (**Figure 7**). There were some discrepancies between the voltage generated from the W-TENG and the predicted

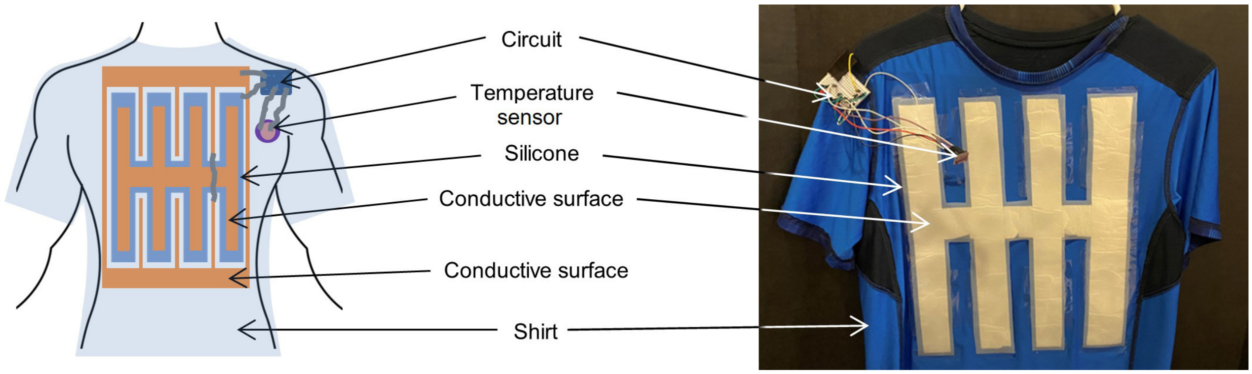

Figure 6. Diagram and image of the W-TENG. The diagram (left) and an image (right) of the W-TENG are laid out side-by-side to illustrate the different elements of the generator.

voltage, both from initial tests in our experiment and past research on the subject matter (16). The regression model created during the surface area tests predicted that the W-TENG would produce 21 volts (**Figure 5**). However, the true voltage generation of the W-TENG was found to be much less (**Figure 7**). This can be attributed to a few fundamental differences between the surface area and W-TENG tests: increased contact force and frequency. The contact-separation mode TENGs were tapped at a constant speed of 90 taps/minute, whereas the shirt brushing against the skin experienced a large variation in frequency and force. Some studies, such as the one done by Li *et al.* document much higher voltage output, most likely due to factors such as using nanotechnology to create microstructures on the surface of the generator to increase power generation (16). These are refinements we would like to implement in the future.

If this experiment were to be repeated, there are a few changes we would make while conducting the initial tests with the contact-separation mode TENGs. Firstly, although we controlled variables such as generator design, tapping frequency, and environmental conditions, there was not a way to control the contact force. Thus, creating a tapping apparatus to ensure a consistent contact force would likely

Figure 7. Mean voltage generation from the W-TENG while walking and running. Mean voltage generation of the wearable triboelectric generator while walking and running (n = 20). Error bars represent standard deviation. The wearable generator follows the design specified in Figure 5. The generator was tested while walking and running over a fixed distance within the same time interval. This was done by measuring the device's generation 20 times while walking over the course of 5 minutes to obtain 20 independent voltage measurements. t-interval, CL = 99%. Running is observed to produce voltage readings between 3.1 and 4.3 volts. The lower bound of the confidence interval is seen to surpass the 3 volts threshold.

reduce the variability of our results. Additionally, when measuring the voltage generation of the TENGs, the use of an oscilloscope would allow for a more in-depth analysis of the voltage waveform.

Past wearable TENGs utilized a positively and a negatively charged material, such as nylon and PTFE, and embedded the generator within the linen of a shirt (10). Our design is unique from past studies due to its incorporation and use of skin as the positively charged material, allowing for a less complex generator. Additionally, the hybrid mode of operation (sliding/contact-separation) contributes to its novelty.

There are additional variables that could affect the power generation of the W-TENG, namely environmental conditions – such as temperature, humidity, and pressure – and sweat. Past research has been conducted on the effects of these conditions on the generation of triboelectric generators. A study done by Lu *et al.* found the efficiency of a TENG to remain relatively constant throughout the 20ºC to 60ºC range (17). We tested the generators in our experiment at room temperature (22.2ºC), the optimized W-TENG at 26.7ºC. Summer temperatures typically do not rise above 60ºC. Therefore, the data we gathered in our experiment should be consistent with what the W-TENG would produce during peak summer temperatures. Another study done by Nguyen and Wang found humidity to have an inversely proportional relationship with the generated charge (18). As the relative humidity increased from 10% to 90%, they found that the generated charge decreased by ~25%. We tested the TENGs at a relative humidity of ~50%, and the optimized W-TENG at a relative humidity of ~75%. This increase in humidity could have also contributed to the discrepancy between the theoretical and actual W-TENG production. Although there has not been much research conducted on how sweat could affect the generation of a TENG, sweat-resistant W-TENGS have been developed (19).

We are looking to make various improvements to our generator to improve its power generation and feasibility. Converting the W-TENG to a single electrode or free-standing triboelectric layer mode might allow for a more streamlined device, which would make our generator more conducive for everyday application. In addition to this, including the option of choosing whether to transmit data wirelessly via Bluetooth or transceiver would be helpful. For individual applications, such as hiking in a remote area, a Bluetooth sensor might be more suitable, but in a group situation, for example, a soccer team, a transceiver might be more applicable. Using nanotechnology related techniques, such as lithography or wet etching to increase the surface area of the silicone by creating microstructures on its surface would likely provide a higher power output of the generator (14). The voltage generation of the W-TENG could potentially be doubled by adding an additional identical generator on the backside of the shirt. It would also be interesting to explore other generator placements, such as the legs, to determine if they provide more efficient power generation. By improving the power generation of the W-TENG, we will be able to expand its range of applications, as it would be able to surpass the 3 volts threshold while walking. It is also important to increase the robustness of the W-TENG by ensuring any drop in power generation caused by variability in skin will not affect the operation of the device. This can be done by improving its voltage generation so that any drops will still allow it to meet the 3 volts threshold.

The W-TENG developed in this study has a wide range of applications. Temperature tracking is important in many different situations. In addition to alerting users of heat exhaustion, it can also provide warning for hypothermia or frostbite. Additionally, it has uses in situations where power might not be readily available, such as at construction sites or remote areas utilized by hikers or military personnel. Since our generator has demonstrated the capability to power a temperature sensor, it is reasonable to assume that it is able to power other biosensors with similar power demands. Other sensors that could be used with our W-TENG in the future are bioimpedance sensors, heart rate trackers, accelerometers/gyroscopes, glucose sensors, and cortisol sensors. A bioimpedance sensor can be used to detect the hydration level of athletes, military personnel, and outdoor workers. A heart rate monitor has applications for athletes or individuals with heart diseases. Accelerometers and gyroscopes can be used together to help monitor seniors and individuals with motor or balance limitations. Sweat-based glucose sensors can be used to monitor blood sugar levels in those suffering from diabetes. Lastly, cortisol sensors can be used to monitor stress levels, which is an increasingly important metric to track due to the recent prominence of mental health issues. The W-TENG developed in our study shows promise as a future wearable generator, which can be used to sustainably power a host of low-power wearable technologies.

MATERIALS AND METHODS

Assessment of Charged Materials

The negatively charged materials tested were cellophane, PTFE, and silicone rubber. Other variables, such as the positively charged material, conductor, generator size, and generator shape were controlled by using the same design for all three negatively charged materials (**Figure 8**). Additionally, we tapped the generators at the same speed – 90 taps/minute – using a metronome. This meant that the two oppositely charged sides of the generator came into contact 90 times each minute. The tests were conducted in the same environment (study room at 22.2ºC). Twenty readings were recorded every 5 seconds during the tapping period. This was done using a Neotek digital multimeter. A Vassar Stats online calculator, in conjunction with Microsoft Excel, was used to conduct a one-way ANOVA with a Tukey HSD correction for multiple comparisons at a significance level of α = 0.05 with this data.

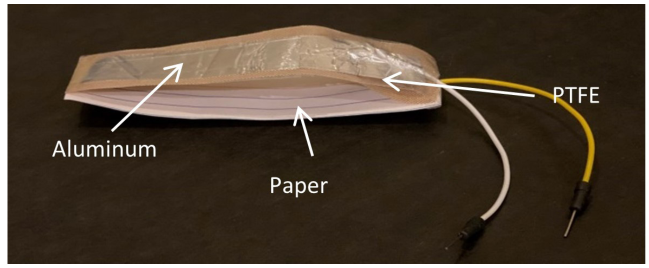

Figure 8. Aluminum, paper, and PTFE based TENG. This is a contact-separation mode TENG made to evaluate the effects of using different negatively charged materiasl in a TENG. In this generator, PTFE is the negatively charged material, paper is the positively charged material, and aluminum is the conductive surface.

The second set of trials focused on determining which conductive material would be most effective in the generator. Similar to the first experiment, other variables such as the positively and negatively charged material (paper and silicone, respectively) and generator shape were controlled across the copper and aluminum trials. The tests were conducted using generators of varying surface areas (2 in^2, 4 in^2, 8 in^2) and conductors (aluminum, copper). The generators were tapped at a constant speed of 90 taps/minute in a study room at 22.2ºC. Twenty readings were recorded every 5 seconds during the tapping period. This was done using a Neotek digital multimeter. A Texas Instruments graphing calculator, in conjunction with Microsoft Excel, was used to conduct a paired t-test at a significance level of α = 0.05 with this data.

Generator Size and Shape

Another set of trials were conducted in order to assess the exact effect of surface area on power generation. In order to do this, we fabricated TENGs using paper, silicone, and copper, as the positively charged material, negatively charged material, and conductor, respectively. These generators were created in three different sizes: 2 in^2, 4 in^2, and 8 in^2. The generators were tapped at a constant speed of 90 taps/minute in a study room at 72 ˚F. Twenty readings were recorded every 5 seconds during the tapping period. This was done using a Neotek digital multimeter. The means of each of these generators were used to create a least squares regression line to predict the power generation of the W-TENG. A Texas Instruments graphing calculator, in conjunction with Microsoft Excel, was used to construct a was used to conduct a t-test for regression slope at a significance level of α = 0.05 with this data.

W-TENG Voltage Generation

The next set of trials focused on the testing of the W-TENG, which was embedded in a shirt (**Figure 6**). These tests were conducted in the same environment (outside, constant temperature of 26.7ºC), and the shirt was worn by the same person. The generator was tested while walking and running over a fixed distance (marked on the pavement) within the same time interval to maintain consistency among trials. This was done by measuring the device's generation using a Neotek digital multimeter 20 times while walking over the course of 5 minutes in order to obtain 20 independent voltage measurements. This process was repeated while running.

A Texas Instruments graphing calculator, in conjunction with Microsoft Excel, was used to construct a t-interval at a confidence level of 99% with this data.

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