Project 1: Optimizing 3D Structure for TENG Applications

THOMAS RYAN, Georgia Institute of Technology
FERESHTEH SHAHMIRI, Georgia Institute of Technology
ALAN ZHANG, Georgia Institute of Technology

Triboelectric nanogenerators (TENGs) can be used to harvest mechanical energy from human motions, sounds, and structure vibrations. This phenomenon has been applied to paper-based user interactions. Our project goal is to explore how to amplify the energy generation that can achieved with paper-based TENGs through an exploration of materials and structure. To achieve a better understanding of the technology, we implemented the findings from two existing papers in this subject area. Next, we explored multiple materials and interaction methods to determine which ones generated the most electricity. Finally, we played with structure by getting inspiration from origami structures to maximize the triboelectric effect between our chosen materials.

Additional Key Words and Phrases: Energy Harvesting, Paper Electronics, Tangible Computing, User Interfaces, Origami, Self-Powered Sensors, Triboelectric Nanogenerators

1 INTRODUCTION

This project explores the use of triboelectric nanogenerators to harvest electrical energy through simple gestures. TENGs create electricity through the triboelectric effect and electrostatic induction. The triboelectric effect describes how some materials can become electrically charged through contact and then separation with other materials. Material properties such as surface roughness, temperature, and others determine how much energy is created through this effect. Therefore, with certain materials the mechanical energy from human motions can be converted to electrical energy. Once converted, this energy can be stored and then used in a simple circuit. A project goal is to explore the materials and interaction methods that can be used to operate a TENG.

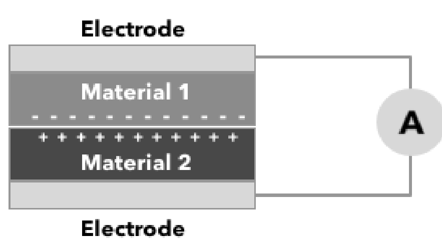


Fig. 1. Basic TENG Structure

1.1 Function

Simple TENGs are made up of thin, paper-like structures stacked together in a way to maximize contact during gestures like tapping, touching, and rubbing. Ultimately the energy harvested from these gestures can be used to actuate LEDs, buzzers, IR transmitters and other low-power devices. In order to operate these simple output devices, TENGs are augmented with energy harvesters to store up enough energy for use.

1.2 TENG Structure

Along with the materials and interaction method, the structure of the TENG impacts electricity generation. A couple of simple structures were explored in "Paper Generators", while Wang introduced the idea of exploring more complex structures via origami techniques. Origami structures allow for energy harvesting to occur from multiple TENGs with the same human motion and more force. In addition, this harvesting can be done without any changes to the layering of materials and fabrication of units. Finding effective energy generating origami structures is one of our project goals.

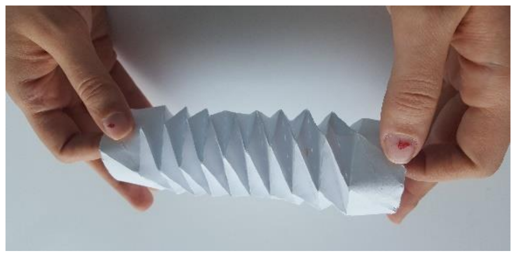


Fig. 2. Example Origami Structure that we tested

From our project, we found that the combination of dark PTFE and photo paper generates the most voltage when compared to other materials. In addition, we found that tapping generates the most energy through the triboelectric effect. Finally, during our form exploration we discovered the most effective layout of TENGs in an origami structure.

2 BACKGROUND

Our project relies heavily on taking advantage of the triboelectric effect in TENGs. We began our work by investing time into understanding the triboelectric nanogenerator. Put simply, a TENG is an energy harvesting device that takes mechanical energy and converts it into electrical energy. It operates via an interaction between two materials: one, an electron donor and the other, an electron acceptor. Contact between these two materials causes electrons to flow. Then, when the two materials are separated, they hold an electric charge. By connecting the two materials via electrodes on the outer edges, a current can be induced. Current flows through the circuit in order to balance the charges. The amount of current flow and the strength of the voltage drop is related to the amount of contact between the two materials. This is a relatively new type of nanogenerator and was first introduced by Prof. Zhong Lin Wang at Georgia Tech. A TENG has three basic operation modes: vertical contact-separation, in-plane sliding, and single-electrode. The choice in operation mode depends on the application. A common choice of materials to create TENGs includes PTFE (Material 1 in Figure 3), paper (Material 2), and aluminum foil (electrodes).

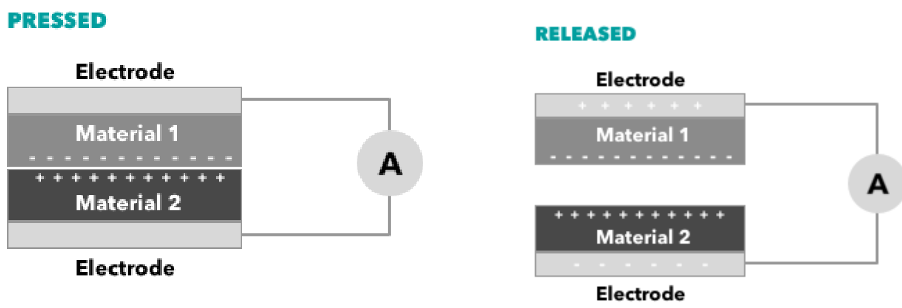


Fig. 3. TENG Operation

2.1 Existing Work

From our literature review, we found multiple papers on this topic. We focused on understanding the work of Disney Research and Prof. Wang. In “Paper Generators” by Disney Research, they present their work on developing, exploring, and evaluating interactive paper-based power generators. The principle of operation for these energy harvesters was explained in detail; this proved to be very useful in developing our understanding of this technology. With this background, they proceeded to design a series of “paper generators” (i.e. energy harvesting structures) and matched them with simple gestures. This part is the most useful contribution of the research paper. Then, these paper generators were used to create a handful of interactive self-powered applications, such as an interactive children’s book. The paper from Wang built on existing knowledge about the construction of simple TENGs and explored using origami to more efficiently harvest energy from human motions. According to their research, TENGs are useful for applications in green electronics and sensor networks because of their flexibility, low cost, light weight, and recyclability. They explore slinky and doodlebug-shaped TENGs by using origami techniques to fold printer paper. The paper does a great job of introducing the idea of incorporating origami techniques into the construction of TENGs.

2.2 Origami

Origami is the art of paper folding. It’s commonly associated with Japanese culture, but today refers to any paper folding practices. The process starts with a flat sheet of paper and ends with a paper structure made exclusively through folds. One of the primary materials used to create TENGs is paper. Using origami techniques, the paper part of the TENG can be folded into a complex structure and then overlaid with the second material (PTFE commonly) and the electrode material. The energy generation of TENGs can be amplified through studying origami structures that maximize contact between the paper and PTFE. In addition, each TENG module can be connected to the circuit either in parallel or in series depending on the application requirements. Finally, origami techniques result in structures that provide an unique affordance that works well with TENG technology - namely how these structures can be built in such a way that simple human motion transforms the structure. Some styles of origami structures have two states to transform between - one is a closed state where different parts of the structure have a lot of contact while the other is an open state without contact. These two states map well to the Pressed and Released states in Figure 3. Also, in general the transformation just requires a simple human motion

3 TECHNOLOGIES AND IDEAS EXPLORED

To design appropriate self-powered applications, three key questions must be studied and answered.

1. What is the triboelectric effect and what causes such effect on the atomic level?
2. How do interaction techniques, materials and physical forms impact maximizing the amount of harvested energy?
3. How do you measure TENG electrical outputs, including open circuit voltage and short circuit current?

Since question one was answered in previous section, in this section we mainly focus on the second and third questions. Four sets of materials have been tested and we focused on two common methods of interaction - tapping and sliding. To measure electrical output, we have developed a simple circuit that by using triboelectric effect can theoretically power LEDs. We have also evaluated similar case studies.

3.1 Material Testing

The main materials used in this study are paper, copper, aluminum foil and Polytetrafluoroethylene (PTFE). In fact, periodical contact and separation of paper and PTFE cause triboelectric charged surfaces. Paper works as a positive and PTFE as a negative charged surface. Copper and aluminum foil are conductive and won't be impacted by the electrical field. During the motions of contact and separation, potential differences are created which will contribute to the flow of electrons between the back conductive electrodes. This ultimately generates electrical output. Table 1 illustrates our experiment in material testing and our findings in terms of the average peak voltage for four different combinations of paper and PTFE. Dark PTFE was found to generate a higher voltage with very quick tests, hence it was omitted from testing with the other types of paper.

Table 1. The experimental finding of average peak voltage for four combination of paper and PTFE. Interaction method is tapping and all options have the equal size 5 * 5 cms.

Material testing (all tests are 2 dimensional sheets with equal size 5cm * 5cm)	Copper Photo Paper Dark PTFE Copper	Copper Photo Paper Light PTFE Copper	Copper Regular Paper Dark PTFE Copper	Copper Transparent Sticky Paper Dark PTFE Copper
Avg. Peak Voltage	10.00V	4.50V	5.50V	8.00V

3.2 Interaction Methods

There are various kinds of human motions and gestures that cause the triboelectric effect among materials with opposite triboelectric polarities. In this study, we have focused on tapping and sliding [1]. In literature, tapping is called vertical contact-separation mode and sliding is called lateral sliding mode of triboelectric nano-generator.

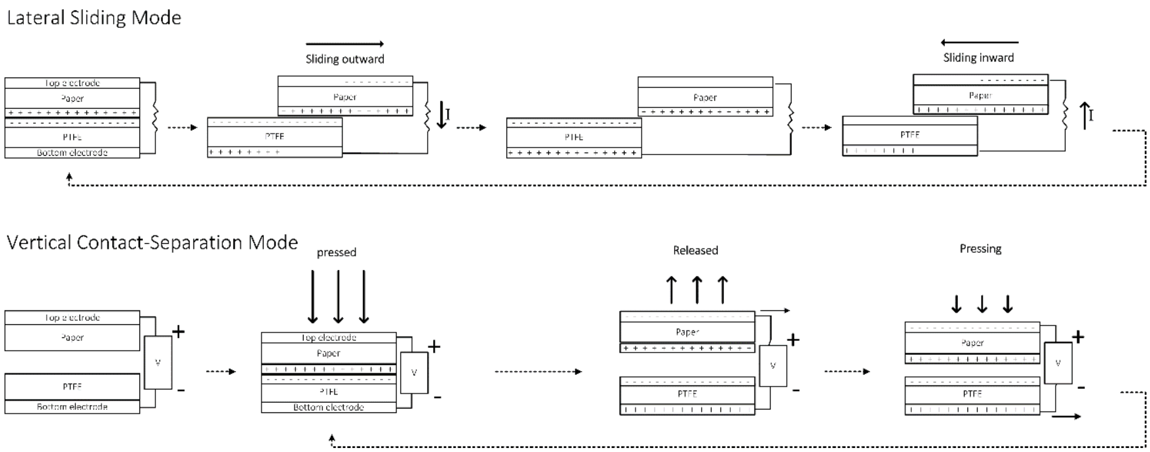


Fig. 5. Interaction Modes – Demonstrating how charged surfaces provide electrical outputs [2][6]

3.3 Three-Dimensional Forms: Origami Structures

A single-direction trigger in contact or sliding modes will limit the application of TENGs in harvesting energy only to one specific direction triggering. To solve this problem, designing multi-layered TENGs is a reliable method to generate more power. In maximizing the amount of harvested energy, 3D multi-layered forms play a key role. The geometric configuration of sheet materials and their periodic contact and separation creates charged surfaces. [3] To achieve an optimized structural form, we have considered several parameters like:

- Maximizing the contact area
- Maximizing the applied force on contact area
- Maximizing the frequency of applying force on contact area
- Choosing material with maximum charge density
- Min. the distance between charged surfaces which periodically are in contact & release
- Maximizing the current flowing in all circuit's components

An accordion origami structure has the potential to increase contact area and is flexible enough to respond to applied external force. By adding such structure into a parallel circuit, we can increase the amount of current flowing into the circuit and consequently, boost power output. Based on a similar case study, in an accordion origami structure current is approximately linearly proportional to the number of connection units. Equation (1) clearly demonstrates that in a parallel circuit flowing current cause exponential increase in output power. In this equation, E is Energy(J), I is Current (A), R is resistance and t is time (sec).

Equation (1) $E = I^2Rt$ $E \sim I^2$

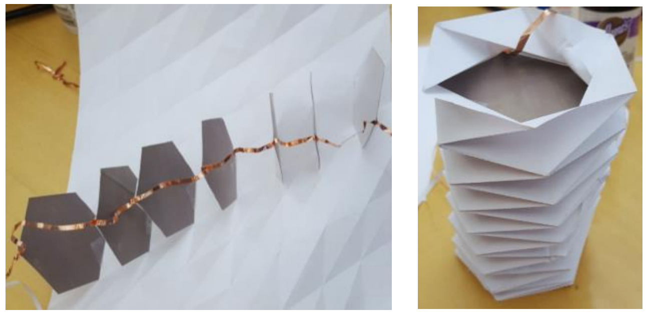


Fig. 6. Left - First test of an accordion origami structure. Center - Adding seven connection units into the paper-based origami form. Right - units consist of paper on top, aluminum foil in between and dark PTFE at the bottom.

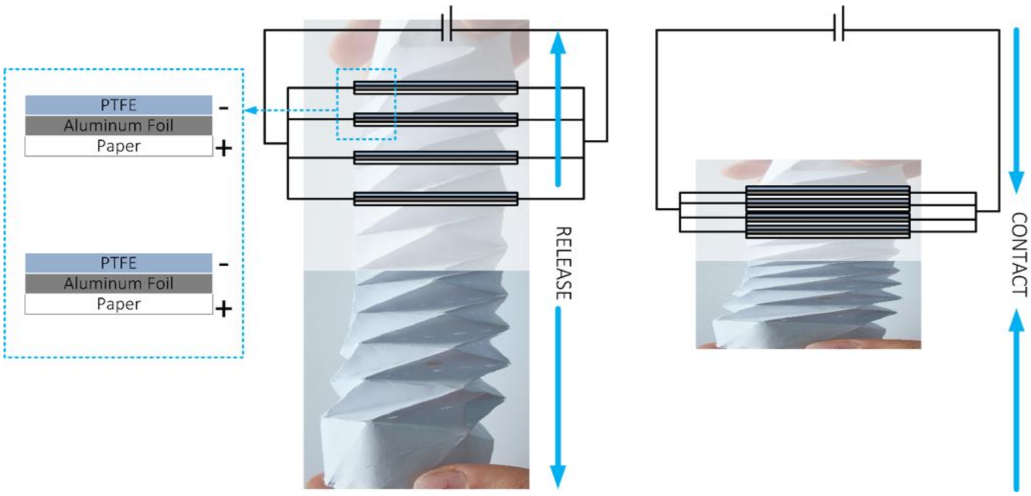


Fig. 7. Simple diagram demonstrating the operation of TENG principle in our accordion origami structure. This diagram presents how periodic contact and separation of paper and PTFE (opposite triboelectric polarities) is happening.

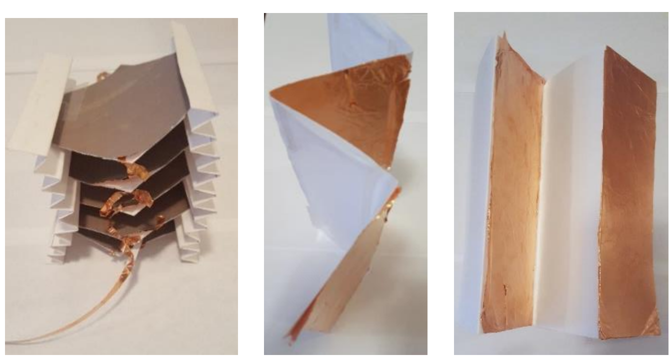


Fig. 8. For quick dirty tests, we made two more accordion structures with different contact areas and we tested them in both series and parallel circuits to observe how the voltage and current changes. (not a successful experiment in terms of electrical output measurements though).

3.4 Experimental Test

To explore how we can power LEDs with the triboelectric effect, we incorporate two electrodes with induced charge relative to each other into the circuit that converts mechanical energy (like tapping or rubbing movements) into electrical energy. To store such electrical energy, we added a capacitor into the circuit to close a switch and then light an LED when enough energy is stored in capacitor. To use the AC voltage generated by TENG in capacitor and LED, we need to convert generated AC voltage into a DC voltage. For such conversion, we added a rectifier bridge into initial circuit which permits current to flow in only one direction. [4]

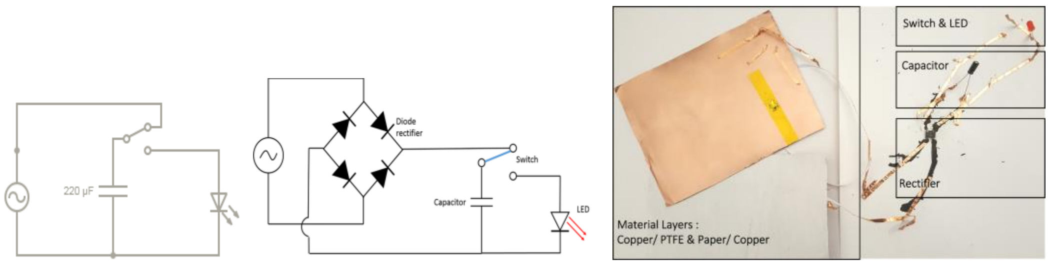


Fig. 9. Left - A circuit diagram shows an AC voltage source connected with a switch to a capacitor and LED. Center - Test 1 Wiring diagram. Adding the rectifier into the circuit. Right - By turning the multi-meter to the 20 V DC setting and tapping on two electrodes, we observed that the volt. across the capacitor was increasing.

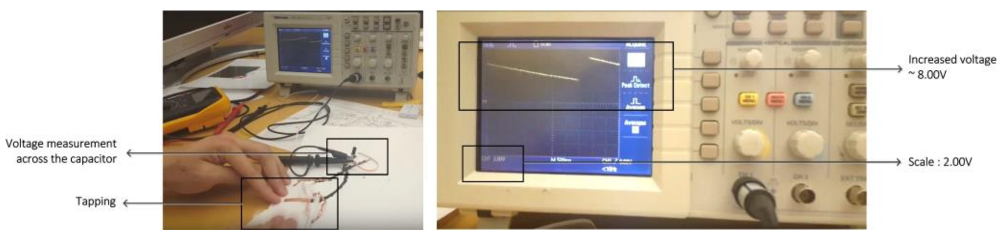


Fig. 10. In test 1, we measured voltage increase across the capacitor with an oscilloscope. By tapping over time, voltage increased about 5.00V.

We were not able to light LED in this experiment. So, in second test, we removed capacitor from circuit. In this scenario, we could increase voltage about 40.00V and observed momentary spark on LED by each tapping. It was a good experiment in that it started us thinking about potential challenges of TENGs - not just about harvesting energy, but storing it too. Since the circuit didn't work based on our presumption, considering two key points in troubleshooting seems necessary:

- Making sure that all components in circuit have minimum required current and such current is flowing in the correct direction.
- Determining if the capacitor stores any energy when tapping on electrodes. And if capacitor is charging enough energy to light an LED.

Another approach in our debugging process was simplifying our experimental test and reproducing a case study in which there is no rectifier and capacitor. According to the case study, the circuit should be able to light up the LED momentarily with each tap. In such experiment, there is no upper layer conductor and the human body acts as such conductor and closes the circuit for turning the LED on.

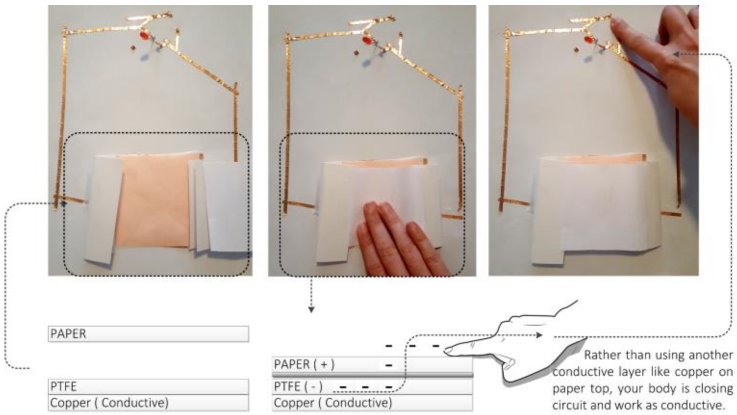


Fig. 11. Test 3 - Reproducing the circuit like [5] to evaluate how electrical outputs will change if body works as conductor for closing the circuit.

4 EVALUATION/DEMONSTRATION (2-4 pages)

Our main proposed goals were first, calculating the amount of harvested energy and electrical outputs for different materials and interaction methods for a baseline and then, exploring origami forms. In these calculations, mechanical movements like tapping and sliding were proposed as interaction techniques. And we also explored different combinations of materials informed by what we knew about each of their charge densities. Our second goal was about optimizing the influential parameters in energy harvesting, based on mathematical simulation of our proposed origami structure.

The second goal is not achieved yet since the proposal wasn't organized realistically in terms of workload and time frame. However, the first goal is almost achieved and at least several errors and challenges were discovered which were totally hidden at the time of proposal submission.

4.1 Measurements

Generally, our experiments were concentrated on the calculation of electrical outputs and amount of harvested energy.

4.1.1 Open-Circuit Voltage

The calculation of potential differences in any experimental test that we conducted was straightforward since all voltage values were easily detected by either a voltmeter as an average value or on an oscilloscope. By using an oscilloscope, we measured potential differences across the capacitor and if no capacitor was in the circuit, we measured such potential difference across the LED. Data is recorded in Table 3.

4.1.2 Short-Circuit Current

The measurement of current was and is still a key problematic issue. The most accurate multimeter in our lab has 200 µA precision. So, we haven't been able to measure the accurate amount of ampere with available instruments in lab, since the flowing current in circuit is much less than this value. There are methods and formula for the calculation of short-circuit current in Equation (2). To calculate the current based on the formula, we need: 1. The values for distance between electrodes in each contact and separation cycle and 2. Charge Density in each charged surface. We still haven't measured the distance between electrodes in each touch and release cycle. Moreover, since we didn't have access to electrometer, we haven't measured the charge density. Thus, we don't have enough data yet to calculate the current.

4.1.3 External Force Applying on Triboelectric Materials & the Speed of Applying Such Force

We still haven't measured the applied external force in any of our experiments. We also, haven't regulated the speed of tapping or rubbing. It is a known fact that increasing the amount of external force and the frequency of applying such force has direct relationship with the amount of harvested energy.

4.1.4 Stored Energy in Capacitor

By measuring voltage across the capacitor, we calculated the amount of energy stored in capacitor. Where E is the energy store in capacitance, C is capacitance and V is voltage measure across the capacitor. The capacitance unit is farads, voltage is volt (V) and energy will be joules (J), equivalently, in watt-secconds (W-s)

Equation (1) $E = \frac{1}{2}cv^2$

Equation (2) = Energy stored in Capacitor by each Tap $E_{tap} = \frac{1}{2}c(v_{before\ tap}^{2} - v_{after\ tap}^{2})$

4.1.5 Collected Data

Table 2. Three circuits that we have tested in our experiment. These circuits are related to the first three experiments in which we familiarized ourselves with research questions.

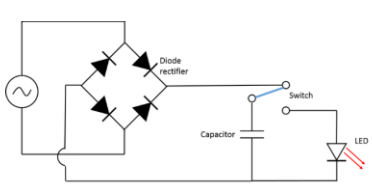
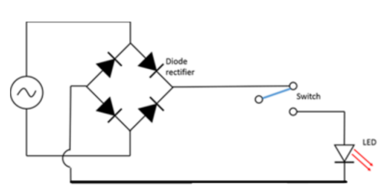
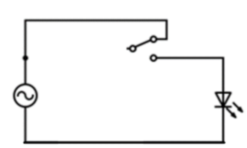
<table>
<tr><td>Test 1</td><td>Test 2</td><td>Test 3</td></tr>
<tr><td>
</td><td>
</td><td></td></tr>
</table>

Table 3. The experimental test results

	Material	Polarity	Geometry	Difference in Voltage	Output power	Current

Test 1	Top layer: Copper-PTFE Bottom layer: Paper-Copper	PTFE (-) Paper (+)	2D sheets (6” * 7”)	**V = ~ 1.25V**	C = 1 μF **E = 0.000001125 J** (Comparing with cellphone which stores about 18,000 J)	Not measured in this test
Test 2	Top layer: Copper-PTFE Bottom layer: Paper-Copper	PTFE (-) Paper (+)	2D sheets (6” * 7”)	**V = ~ 40.00V**	No capacitor in circuit	Not measured in this test
Test 3	Top Layer: Paper Bottom layer: Light PTFE-Copper	PTFE (-) Paper (+)	2D sheets (6” * 7”)	**V = ~ 25.00V**	No capacitor in circuit	Not measured in this test

5 CONCLUSION

In this study, we familiarized ourselves with TENGs and harvesting electrical energy through simple body gestures. We mainly focused on testing materials, interaction techniques and physical forms.

By exploring triboelectric materials and by finalizing our experiments, we chose the combination of photo paper, dark PTFE and aluminum foil. This combination generates higher potential difference in charged surfaces compared with other available materials in our lab.

We found that both proposed gestures; tapping with vertical contact and separation mode and sliding with lateral movement mode are promising interaction techniques. They both are effective and appropriate for many specific applications in terms of generating electrical outputs. Since there is no priority in choosing either one, we will continue our experiments with both techniques.

We have gone through literature in terms of potential benefits in using origami or more general, multi-layered structural forms. We conducted our experiment somehow to maximize the contact area and applied external force in such structures. However, accurate measurements for electrical outputs is not fully accomplished yet.

There are key points that we will consider in next steps:

- Distinguishing between store-release harvesting and unusable momentary harvesting. Such storing is so critical since mostly all applications need a source of stored energy.

- More emphasis on current – voltage characteristics of the energy harvester and characterizing them through measurements.

- Optimizing physical structures that allow us to create effective paper-based TENGs. Such structural forms are in direct relation with specific applications. Regarding applications, we need to consider some limitations existing in the current state of this technology. The first and most important issue in designing any origami structural form and application is the electric energy returned on mechanical energy. In this stage, this is important to design low-powered applications to avoid users' frustration in intentional energy harvesting. It would be also helpful to explore those applications in which human mechanical movements lead to unintentional energy harvesting, like walking.

There are also other limitations like location and situations in which we can or can't use such paper-based structures. For instance, how reasonable is designing a paper-based application for outdoor, humid or wet area? Or how can we substitute paper with another triboelectric material that is appropriate for such environments? The other limitation is about product or application size. Since this study has focused on harvesting energy through human gestures and mechanical movements, the application size can't expand more than specific scale. In this case, we need to evaluate the product size v. amount of usable harvested energy carefully.

REFERENCES

[1] Wang, Zhong Lin, et al. "Harvesting Body Motion Energy." *Triboelectric Nanogenerators*. Springer International Publishing, 2016. 207-236.
[2] Yang, Weiqing, et al. "3D stack integrated triboelectric nanogenerator for harvesting vibration energy." *Advanced Functional Materials* 24.26 (2014): 4090-4096.
[3] Yang, Po-Kang, et al. "Paper-based origami triboelectric nanogenerators and self-powered pressure sensors." *ACS nano* 9.1 (2015): 901-907.
[4] ıge source: 2014 Matthew Zelisko, GK-12 Program, University of Houston https://www.teachengineering.org/activities/view/uoh_piezo_lesson01_activity1
[5] Karagozler, Mustafa Emre, et al. "Paper generators: harvesting energy from touching, rubbing and sliding." Proceedings of the 26th annual ACM symposium on User interface software and technology. ACM, 2013.
[6] Kang, Yue, et al. "Folded elastic strip-based triboelectric nanogenerator for harvesting human motion energy for multiple applications." *ACS applied materials & interfaces* 7.36 (2015): 20469-20476.

Project 2: Exploration of User Interaction with Human Power Generation

THOMAS RYAN, Georgia Institute of Technology
FERESHTEH SHAHMIRI, Georgia Institute of Technology
ALAN ZHANG, Georgia Institute of Technology

By considering the benefits and limitations of TENGs, we explore this technology from a user interface/experience perspective for a broader scope of applications. We proposed different human-environment interactions in everyday activities that can be augmented with multi-layered (origami) TENG structures and eventually chose the most feasible design scenario according to the established causality framework which demonstrates the relations among influential variables. Ignoring variables like 1. Simultaneity in contact-separation in all TENG units and 2. Maximizing the contact area by increasing the number of small-scale units rather than increasing the contact area in each unit necessitates the reevaluation of any designed multi-layered TENG form in this project.

Additional Key Words and Phrases: Energy Harvesting, Paper Electronics, Tangible Computing, User Interfaces, Origami, Self-Powered Sensors, Triboelectric Nanogenerators

1 INTRODUCTION

This project takes what we've learned from project 1 about TENGs to evaluate different user scenarios that we've brainstormed. TENGs create electricity through the triboelectric effect and electrostatic induction. The triboelectric effect describes how some materials can become electrically charged through contact and then separation with other materials. Material properties such as surface roughness, temperature, and others determine how much energy is created through this effect. Therefore, with certain materials the mechanical energy from human motions can be converted to electrical energy. Once converted, this energy can be stored and then used in a simple circuit. Our first project goal is brainstorm a list of user scenarios that would take advantage of the unique characteristics of TENGs.

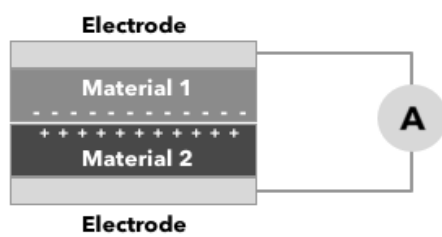


Fig. 1. Basic TENG Structure

1.1 Function

Simple TENGs are made up of thin, paper-like structures stacked together in a way to maximize contact during gestures like tapping, touching, and rubbing. Ultimately the energy harvested from these gestures can be used to actuate LEDs, buzzers, IR transmitters and other low-power devices. In order to operate these simple output devices, TENGs are augmented with energy harvesters to store up enough energy for use. TENGs have a handful of limitations such as low energy generation. During project 1, we explored these limitations. What we learned from that project was transformed into criteria that we used to evaluate our scenarios.

1.2 TENG Structure

Along with the materials and interaction method, the structure of the TENG impacts electricity generation. A couple of simple structures were explored in "Paper Generators", while Wang introduced the idea of exploring more complex structures via origami techniques. Origami structures allow for energy harvesting to occur from multiple TENGs with the same human motion and more force. In addition, this harvesting can be done without any changes to the layering of materials and fabrication of units. Finding a usable and effective energy generating structure for our chosen scenario is one of our last project goals.

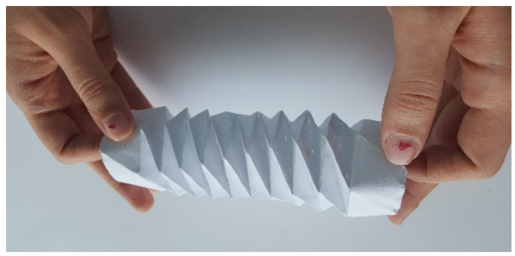


Fig. 2. Example Origami Structure

From our project, we came up with seven different user scenarios that would work well with TENGs. Using our findings from project 1, we evaluated those scenarios to pick the best one. We then explored forms that would work well for that scenario.

2 BACKGROUND

Our project relies heavily on taking advantage of the triboelectric effect in TENGs. We began our work by investing time into understanding the triboelectric nanogenerator. Put simply, a TENG is an energy harvesting device that takes mechanical energy and converts it into electrical energy. It operates via an interaction between two materials: one, an electron donor and the other, an electron acceptor. Contact between these two materials causes electrons to flow. Then, when the two materials are separated, they hold an electric charge. By connecting the two materials via electrodes on the outer edges, a current can be induced. Current flows through the circuit in order to balance the charges. The amount of current flow and the strength of the voltage drop is related to the amount of contact between the two materials. This is a relatively new type of nanogenerator and was first introduced by Prof. Zhong Lin Wang at Georgia Tech. A TENG has three basic operation modes: vertical contact-separation, in-plane sliding, and single-electrode. The choice in operation mode depends on the application. A common choice of materials to create TENGs includes PTFE (Material 1 in Figure 3), paper (Material 2), and aluminum foil (electrodes).

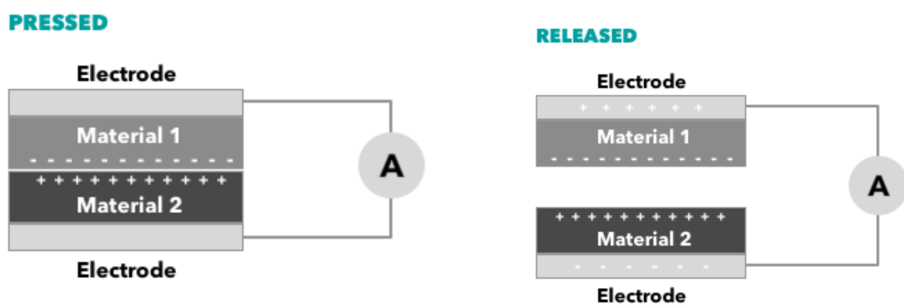


Fig. 3. TENG Operation

2.1 Existing Work

From our literature review, we found multiple papers on this topic. We focused on understanding the work of Disney Research and Prof. Wang. In "Paper Generators" by Disney Research, they present their work on developing, exploring, and evaluating interactive paper-based power generators. The principle of operation for these energy harvesters was explained in detail; this proved to be very useful in developing our understanding of this technology. With this background, they proceeded to design a series of "paper generators" (i.e. energy harvesting structures) and matched them with simple gestures. This part is the most useful contribution of the research paper. Then, these paper generators were used to create a handful of interactive self-powered applications, such as an interactive children's book. The paper from Wang built on existing knowledge about the construction of simple TENGs and explored using origami to more efficiently harvest energy from human motions. According to their research, TENGs are useful for applications in green electronics and sensor networks because of their flexibility, low cost, light weight, and recyclability. They explore slinky and doodlebug-shaped TENGs by using origami techniques to fold printer paper. The paper does a great job of introducing the idea of incorporating origami techniques into the construction of TENGs.

2.2 Origami

Origami is the art of paper folding. It's commonly associated with Japanese culture, but today refers to any paper folding practices. The process starts with a flat sheet of paper and ends with a paper structure made exclusively through folds. One of the primary materials used to create TENGs is paper. Using origami techniques, the paper part of the TENG can be folded into a complex structure and then overlaid with the second material (PTFE commonly) and the electrode material. The energy generation of TENGs can be amplified through studying origami structures that maximize contact between the paper and PTFE. In addition, each TENG module can be connected to the circuit either in parallel or in series depending on the application requirements. Finally, origami techniques result in structures that provide an unique affordance that works well with TENG technology - namely how these structures can be built in such a way that simple human motion transforms the structure. Some styles of origami structures have two states to transform between - one is a closed state where different parts of the structure have a lot of contact while the other is an open state without contact. These two states map well to the Pressed and Released states in Figure 3. Also, in general the transformation just requires a simple human motion.

3 TECHNOLOGIES AND IDEAS EXPLORED

Since the beginning for this research, we have considered both the technology side of harvesting electrical power from TENG technology and the user side / applications that harness ambient mechanical energy from normal human physical motion and his or her daily routine activities. As it is demonstrated in detail in P1 report, we have explored triboelectric pair materials and figured out that an intentional design of the form and interaction techniques can increase the rate of energy harvesting and conversion efficiency. However, there were key limitations in fulfilling and regulating the required electrical output, storing useful harvested energy, etc. To evaluate the reasons behind these limitations and to conduct the research more scientifically and systematically, we decided to establish a Causality/Correlation framework [1]. In this framework, we classify different types of variables and moderators that influence the strength of the relationship between those variables, as well as mediators that explain how the relationship between such variables should work. Establishing causality and identifying these relationships (Table 1), will allow us to neutralize any potentially confounding variables in future steps. While manipulating one or more variables, this framework assists us in controlling and measuring any changes in variables [1, 2]

By putting bases on proposed table, we re-evaluate our potential design scenarios in which TENGs can be applied to self/low-powered applications and devices.

Table 1. Causality/Correlation Framework

Predictor (Independent)	Mediator/ Mechanism	Output (Dependent)	
Construct **Human Activity** (like walking, sitting, sleeping, hand gestures, etc.)		Construct **Harvesting Electrical Power**	Construct **Usability of harvested energy in self-powered applications**
Variable **Interaction Techniques** ▪ Contact-Separation Mode ▪ Lateral Sliding Mode	Variable ▪ **Form/Structure** (Modular, multiplied unit cells, multi-fold, Number of units) ▪ **Material** (Triboelectric pairs materials) ▪ **Circuit** (Parallel v. Serial)	Variable **Electrical Outputs**	Variable ▪ **Amount of useful electrical power** ▪ **Output** (for Actuation, communication, etc.)
Measure (Quantitative) ▪ Cyclic frequency of external mechanical force ▪ Amplitude of external		Measure (Quantitative) ▪ Open Circuit Voltage (V_{oc}) ▪ Short Circuit	Measure (Quantitative) ▪ Stored energy in energy harvester

mechanical force (Depend on mechanism, maximizing three following measures, improve current output) ▪ Effective contact area ▪ Relative velocity of the contact or separation of two plates ▪ Density of the surface electrostatic charge		Current (I_{sc})	component ▪ Regulated Voltage ▪ Load Resistance

Moderator	Control Variables	Alternative Explanation
Context ▪ Environmental Limitation (indoor v. outdoor, humid, rainy, particles contamination in air, imperfection in device fabrication process, difficulty in synchronizing all the device units, etc.) ▪ Frequency of applying external force	It is not considered yet.	It is not considered yet.

4 EVALUATION/DEMONSTRATION

Through a brainstorming process, we came up with a list of user scenarios where TENGs could be used. Each scenario has a short description, harvesting method, contact area, energy usage timing (simultaneous or delayed), interaction method, actuation/output, and exposed or hidden form. While the scenarios were brainstormed with what we learned from P1 in mind, we tried to not be entirely constrained by our previous findings about the capabilities and limitations of TENGs.

Scenario 1

Description: Track usage of a space by embedding a circuit inside a chair that is powered by a TENG. When a user sits on the chair, the TENG structure is actuated and generates energy to power an IR LED to send out an unique code for that chair. An IR sensor embedded in the space receives the code and keeps track of chair usage in the space.

Harvesting Method: Unintentional

Contact Area: Inside chair rod (TENG contact area)

Simultaneous v. Delayed: Simultaneous

Interaction Method: Sit, once

Actuation/Output: IR LED

Form: Hidden

Scenario 2
Description: Embed a TENG structure inside a doormat or the push bar of a door to roughly track how many people enter and exit a space. Each TENG would be connected to some type of wireless technology - either a BLE module or an IR LED.
Harvesting Method: Unintentional
Contact Area: Doormat or Door Push Bar
Simultaneous v. Delayed: Simult.
Interaction Method: Step or push, once
Actuation/Output: IR LED or BLE module
Form: Hidden

Scenario 3
Description: Embed TENG technology inside running shorts. The rubbing of the inner mesh and outer shorts layer would generate power to light up parts of the shorts for enhanced visibility during night runs. Currently running shorts have reflective parts that light up when flashed by light, but these reflective parts do nothing for visibility when there's no external directed light.
Harvesting Method: Unintentional
Contact Area: Inner and outer fabric inside running shorts.
Simultaneous v. Delayed: Simult.
Interaction Method: Running motion rubbing, multiple
Actuation/Output: Light (LED?)
Form: Hidden

Scenario 4
Description: TV remotes work using IR LEDs to send codes to the TV sensor. Embed a TENG structure inside a couch arm rest to allow users to change the volume of the tv or turn on and off the tv. Users can either rub or tap the armrest to control the tv.
Harvesting Method: Intentional
Contact Area: 4 in x 4 in segment of fabric on couch armrest.
Simultaneous v. Delayed: Simult.
Interaction Method: Rubbing or Tapping, multiple
Actuation/Output: IR LED
Form: Hidden

Scenario 5
Description: Children's light up shoes typically use batteries to power LEDs embedded in the shoes. Instead of relying on batteries for power, use TENGs to convert the mechanical energy of each step into electricity for the LEDs.
Harvesting Method: Intentional
Contact Area: Entire foot and insert in shoe
Simultaneous v. Delayed: Simult.
Interaction Method: Stepping, multiple
Actuation/Output: LED
Form: Hidden

Scenario 6
Description: There's a lot of contact and rubbing that occurs between someone's bed sheets and their pants. Build a pair of pants and matching bed sheets enhanced with fabrics that can be used to build a TENG made out of wearable materials. For cold climates, the TENG-enhanced pants

can generate electricity from the rubbing between a user's pants and bed sheets and convert that into heat to warm the user.
Harvesting Method: Unintentional
Contact Area: Legs and/or feet with bed sheets
Simultaneous v. Delayed: Simult.
Interaction Method: Rubbing, multiple
Actuation/Output: Heat of some form
Form: Exposed

Scenario 7
Description: Create a toy that requires a user to pump part of the toy in order to light up another part of the toy. For example, a lamp that has a pump made out of an origami TENG structure which powers an LED in the toy somewhere. This is similar to the Disney interactive story books but for a 3D toy.
Harvesting Method: Intentional
Contact Area: Depends on application.
Simultaneous v. Delayed: Simult.
Interaction Method: Depends on application.
Actuation/Output: LED or power a switch to turn on power for the toy.
Form: Exposed or Hidden.

While we avoided limiting our brainstorming by what we learned from our first project, we ultimately chose a scenario by formally evaluating each scenario based on the criteria and lessons from P1. Using Table 1, we evaluated each of these scenarios and chose Scenario 4. More details on this Scenario are in Figure 4.

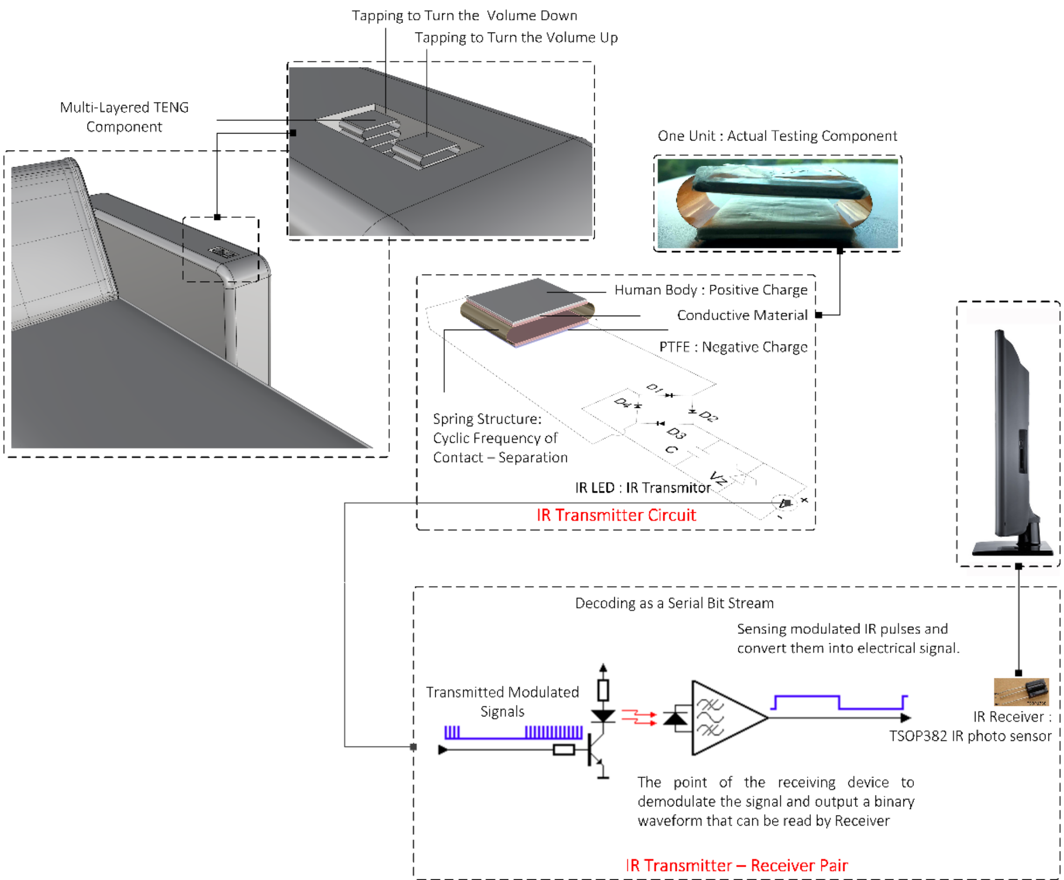


Fig. 4. Scenario 4 Details

We chose this scenario using the criteria from Table 1, which summarizes what we learned from project 1. A couple of reasons we chose the couch scenario include: it uses tapping (this interaction generates a lot of energy), it's novel, and it's feasible from what we learned about TENG energy generation limitations.

We then explored forms that would work well for this scenario. The form in Figure 5 shows a form that works great for TENG structures because the outer edges are springy and help with separation (contact & separation are fundamental to the operation of TENGs). Part of our future work will explore how to effectively stack this form to create a multi-layered TENG structure.

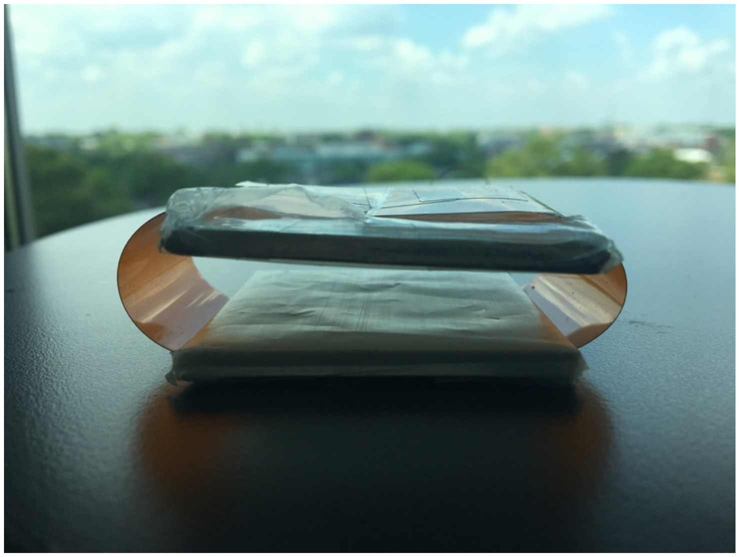


Fig. 5. Single Unit Form

5 CONCLUSION

In this study, our main reason for choosing three dimensional multi-layered (like origami structure) TENGs, was solving the challenge of low output current in applications with a single-layer structure [3]. Although, there have been promising results in effectiveness of such modular-multi-layered TENG structures in terms of current output enhancement [4], our experimental research still is unable to generate enough and accurately measure this electrical output.

By assuming the fact that such technical parts can be solved in collaboration with material science groups here in GT [5], in second part of the project, we approached the concept of self-powered applications from user perspective and his/her daily routine activities, which harvest ambient mechanical energy. We proposed several design scenarios which illustrate methods for both harvesting and momentary usage of energy in interaction between a user and his/her surrounding environment.

To reevaluate our approach and progress, we created a causality framework to study the relationship between variables, moderators and mediators in a more systematic and scientific way [1]. In this reevaluation process, we noticed that we have missed a key point in creating effective forms and interaction techniques. Although we had considered the influence of variables like contact area, frequency and amplitude of external force on our multi-layered structures, we had ignored that the contact and separation should happened simultaneously in all units. We need to synchronize the output of all TENG units, so that the instantaneous output power can be effectively maximized [3, 4, 6].

In those multi-layered origami forms' scales/sizes that we have designed and studied our applications and interactions, such simultaneity is impossible. Through more in-depth research and review of literature [3, 4, 7, 8, 9], we noticed that this parameter is the reason that in most successful applications, maximizing the contact area happens by increasing the number of small-sized units not necessarily by increasing the contact area in each unit [10, 11]. At the current state of this project, we conclude rationalizing TENG modules' form and size, responsive to above requirements, is the key point in progressing the project. However, we still don't have a solid outline to push the project forward by having this approach.

REFERENCES

[1] Hayes, Andrew F. "Beyond Baron and Kenny: Statistical mediation analysis in the new millennium." Communication monographs 76.4 (2009): 408-420.

[2] Bauman, Adrian E., et al. "Toward a better understanding of the influences on physical activity: the role of determinants, correlates, causal variables, mediators, moderators, and confounders." American journal of preventive medicine 23.2 (2002): 5-14.

[3] Yang, Weiqing, et al. "3D stack integrated triboelectric nanogenerator for harvesting vibration energy." Advanced Functional Materials 24.26 (2014): 4090-4096

[4] Wang, Zhong Lin, et al. "Harvesting Body Motion Energy." Triboelectric Nanogenerators. Springer International Publishing, 2016. 207-236.

[5] http://www.mse.gatech.edu/faculty/wang

[6] Yang, Ya, et al. "Human skin based triboelectric nanogenerators for harvesting biomechanical energy and as self-powered active tactile sensor system." ACS nano 7.10 (2013): 9213-9222.

[7] Lee, Sanghyo, et al. "Triboelectric energy harvester based on wearable textile platforms employing various surface morphologies." Nano Energy 12 (2015): 410-418.

[8] Wu, Changsheng, et al. "Paper-based triboelectric nanogenerators made of stretchable interlocking kirigami patterns." ACS nano 10.4 (2016): 4652-4659.

[9] Dhakar, Lokesh, et al. "An intelligent skin based self-powered finger motion sensor integrated with triboelectric nanogenerator." Nano Energy 19 (2016): 532-540.

[10] Yang, Po-Kang, et al. "Paper-based origami triboelectric nanogenerators and self-powered pressure sensors." ACS nano 9.1 (2015): 901-907.

[11] Kang, Yue, et al. "Folded elastic strip-based triboelectric nanogenerator for harvesting human motion energy for multiple applications." ACS applied materials & interfaces 7.36 (2015): 20469-20476.