UNIVERSITI PUTRA MALAYSIA

THE DEVELOPMENT OF ENERGY HARVESTING SYSTEM FROM THE MOTION DURING MANUAL OIL PALM HARVESTING

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2018/2019

ACKNOWLEDGEMENT

In the name of Allah, the Beneficent and the Most Merciful

Alhamdulillah, my greatest and ultimate the debt and gratitude is due to Allah, Most Gracious, Ever Merciful. I would like to take this opportunity to express my appreciation to all those who work I have consulted and used during my undergraduate final year thesis.

Firstly, I would like to extend my deepest gratitude to my supervisor, Dr. Hazreen Haizi Binti Harith for her support, and encouragement that helps me to go through this project from the beginning until the finish. I believe, without her guidance, I'm not able to finish this project.

My special thanks to my beloved husband, Muhamad Azlan Bin Mohd Shah for his support, morally and financially during my final year project. I am blessed to Allah for giving me a husband that truly understand me. Not to forget to my family members for their support and pray for me to finish this project successfully.

Thanks also expressed to my examiners Dr. Sharence Nai Sowat and Dr. Mahirah Binti Jahari for their valuable comments and contributions suggestion. Lastly, to all my friends from KBP batch 15/19 for their encouragement and inspiration given to me which lead to healthy competition among us.

ABSTRACT

Malaysia is moving toward Agriculture 4.0, and it is expected that more technology such as sensors in IoT will be used. With the application of biomechanical energy harvesting, those IoT wireless sensors can be powered and/or recharged. Therefore, this study aims to investigate the feasibility of harvesting energy from biomechanical work by the human during agriculture activities. Since upper limb movement is one of the greatest movements during agriculture activities, upper limb motion will be the scope of this study. Fabricate the system of a selected type of energy harvesting to get the characterization data for the future development of upper limb energy harvesting system. A system was fabricated with two modes of triboelectric nanogenerator, vertical separation-contact mode and lateral sliding mode. The results indicated that the fabricated TENG system needed large surface area, short wire and best connection for higher voltage. Based on the collected data, system was proposed for energy harvesting system from biomechanical work when performing agricultural activities.

ABSTRAK

Malaysia ke arah Pertanian 4.0, dan ini menjagkakan banyak teknologi seperti pengunaan sensor dalam aplikasi IoT akan digunakan. Dengan mengunakan penuaian tenaga biomekanik, sensor-sensor yang digunakan daam aplikasi IoT dapat di bekalkan atau dicas tenaga elektriknya. Justeru itu, kajian ini dijalankan untuk menilai keupayaan terhadap penuaian tenaga daripada kerja biomekanik yang dihasilkan oleh manusia semasa aktiviti pertanian dilakukan. Oleh kerana gerakan kerja atas bahagian badan merupakan bahagian yang mempunyai paling banyak gerakan ketika melakukan aktiviti pertanian, maka bahagian atas badan ini akan menjadi skop dalam kajian ini. Kerja pembuatan sistem penuain tenaga yang dipilih dilakuakan untuk mendapatkan data pencirian terhadap sistem tersebut bagi kegunaan pembuatan sistem penuaian tenaga bahagian atas badan pada masa hadapan. Sistem ini dibuat untuk dua mod nanogenerator triboelektrik iaitu mod hubungan pemisahan menegak dan mod geseran mendatar. Hasil kajian daripada pembuatan sistem TENG menunjukkan keperluan ruang yang besar, wayar pendek dan penyambungan wayar yang elok untuk menghasilakan voltan yang tinggi. Menggunakan data yang disimpan, sebuah sistem dicadangkan untuk pembuatan sistem penuaian tenaga daripada gerak kerja biomekanik yang dilakukan ketika menjalankan aktiviti pertanian.

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IoT:	internet of thing
TENG:	triboelectric nanogenerator

CHAPTER 1

INTRODUCTION

1.1 Background of study

Many energy sources are used to perform agricultural activities. The energy sources could be from the source of human, animal, and nature. Energy harvester that harvests the wind energy is a windmill, the water flow energy harvester is turbine and energy from the sun, which is solar energy is harvested by the solar panel.

Energy harvesting can be understood as a process which energy from external sources been derived, captured, stored and used by the small, autonomous devices. Biomechanical energy harvesting converts human motion (mechanical energy) into electrical energy (Riemer and Shapiro, 2011). A simple example of energy harvesting is dynamo bicycle that can lighten a bulb when a rider cycles the paddle of a bicycle.

Moving toward Agriculture 4.0, which agricultural industry going to implement the smart farming concept, many smart technologies have been developed and various sensors are used. In most instances, electrical energy is needed in order to use the technologies. Malaysia's number one commodity crop is oil palm. Many research are done to automate and mechanize the task or operations performed in oil palm plantation such as research done by (Aziz, 2018) which review the mechanization in oil palm harvesting and (Shuib et al., 2010) which review the enhancement field mechanization in oil palm management. Yet, the harvesting operation in oil palm plantation is still not fully automated. Manual labor is still needed mainly to cut the fronds and harvest the fruit bunches using a cutter or sickle.

The motion of cutting the frond and fruit bunches involve pushing and pulling of the arm while holding the cutter on a long pole, and it requires a lot of body movements, by the upper limb of the body (M. Faiz Syuaib, 2015). The body movement can be converted to electrical energy by the vibration, friction and other mechanism of the device attached to the subject, and this can be beneficial to power sensors or devices used for precision farming application in the plantation.

In this research, our aim is to determine if is possible to harvest biomechanical energy from human upper limb motion when performing harvesting activities.

1.2 Problem statement

In realizing the future of farming technology toward Agriculture 4.0, efficiency and productivity will increase in the coming years as "precision agriculture" become bigger and farm become more connected. It is estimated that by 2020, over 75 million agriculture IoT device will be used (Clercq et al., 2018).

The uses of IoT in agriculture will help farmers in monitoring their crops from home or instantly at the site. This technology requires electrical energy, such as battery supply, to operate. IoT-based system can be monitored and controlled from home, which means farmer has no need to go to the field to monitor the crop. However, farming activities like harvesting the yield requires farmer to enter the field physically.

In some applications, IoT helps farmers to get more accurate information about the crop to be harvested, such as the maturity of the yield (Nimos Berhad, n.d.). In the oil palm sector, harvesting the crop is still done manually using cutter and sickle. Even though robot harvester was existing in Malaysia, the traditional method is still preferred in this sector because it uses more efficient manpower compared to using the robot because robot only work accordingly with what they were programme.

In agriculture, some of the operations in farming activities cannot be challenged with human power. In order to help farmers in matures yield during harvesting, the application of IoT could be an efficient way. An IoT application could be as simple as using the application that can be installed on a smartphone or another form of wireless sensor.

However, the power supply or battery powering this device will get low after using it for a certain period. This will interrupt the farming operation in the field. How then do we get instant charging in the field other than bringing in an extra battery or power bank to the field? The subject of this study will help to solve the problem.

1.3 Research objective

The main aim of this project is to develop an energy harvesting system which harvests the mechanical energy from the manual harvesting motion during oil palm harvesting. The specific objectives are as follows:

i. To determine the best energy harvesting method for upper limb body motion during oil palm harvesting.
ii. To characterize the fabricated energy harvesting system which is based on triboelectric nanogenerator.
iii. To propose a potential mechanism that allows biomechanical energy harvesting based on the fabricated system during manual oil palm harvesting.

1.4 Scope of research

This study was conducted to develop an energy harvesting system from the motion during manual oil palm harvesting. The energy harvested from the biomechanical motion will measure the feasibility to be converted into electrical energy. The studied aspects were existing biomechanical energy harvesting systems, their methods and applications, selecting the most suitable type of energy harvesting to be applied at upper limb body part, fabrication the selected type energy harvesting, characterize the data get from testing the fabricated energy harvester, propose the idea(s) of potential application in manual oil palm harvesting involve the upper limb motion.

CHAPTER 2

LITERATURE REVIEW

2.1. Energy harvesting

Energy harvesting (also known as power harvesting or energy scavenging) is the process in which energy is captured from a system's environment and converted into usable electric power (Maxim Integrated, n.d.). Energy harvesting allows electronics to operate where there is no conventional power source, eliminating the need to run wires or make frequent visits to replace batteries.

An energy harvesting system generally includes circuitry to charge an energy storage cell and manage the power, providing regulation and protection. Energy source examples include light (captured by photovoltaic cells), vibration or pressure (captured by a piezoelectric element), temperature differentials (captured by a thermo-electric generator) radio energy (captured by an antenna); and even biochemically produced energy (such as cells that extract energy from blood sugar).

2.2. Studies on energy harvesting

There are many methods to harvest the energy to be generated into a form of electrical energy (Kiziroglou and Yeatman, 2012). There are also studies on biomechanical energy harvesting (Donelan, 2008). The researcher wants to harvest the energy from the human body motion because human is moving since they woke up until they sleep.

Some of the studies that have been done in biomechanical energy harvesting are listed in this literature review, under subsection 2.2.1 until 2.2.5.

2.2.1. Electromagnetic induction energy harvesting by leg cyclic (dynamo) (Yang et al., 2012)

From the leg motion of cycling the bicycle, electricity can be generated to light up the bulb of a bicycle. This is an early finding on the application of energy harvesting from biomechanical energy. The type of energy harvesting of dynamo bicycle is a rotary-current generator or electromagnetic induction.

The mechanism of the energy harvesting was based on the cyclic motion of the leg at the bicycle paddle to move the bicycle. When the paddle moves, the tire starts to rotate forward through the power transmission of the chain and sprocket of the bicycle.

A dynamo is placed at the tire which consists of a rotating knob, permanent magnet, and wire coils as shown in Figure 1. The rotating knob is placed against the rim of the tire. When the wheel rotates it rotates the knob which rotates the magnet which is surrounded by the coil. When the magnet rotates its magnetic flux through the coil starts varying which induces an electromagnetic field in the coil according to Faraday's law of electromagnetic induction ("Bicycle dynamo having a rotary-current generator," 1996). The induced voltage is used to power headlights in front of the cycle.

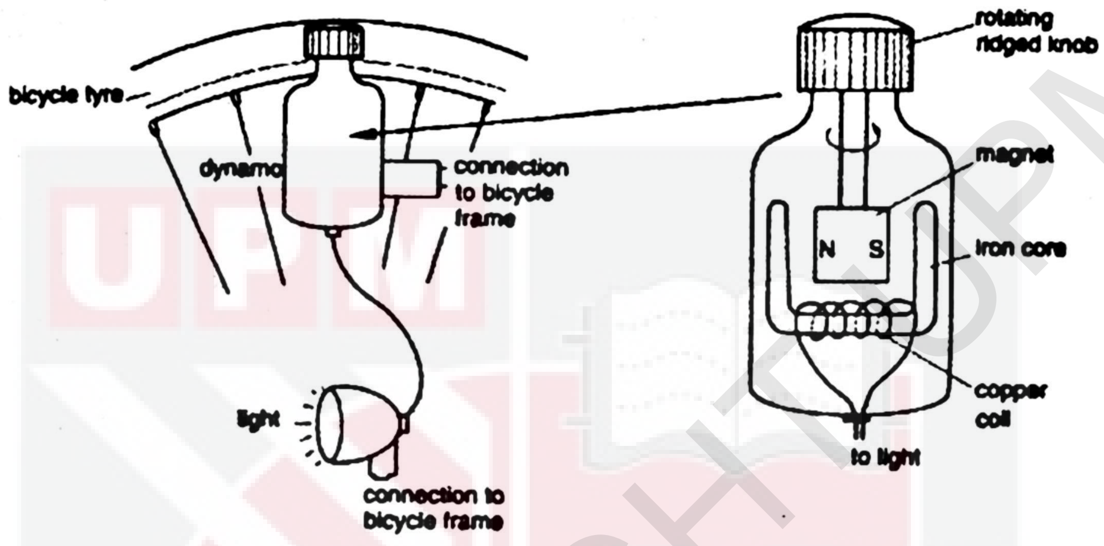


Figure 1: Dynamo bicycle (Yajur Mahendru, 2015)

2.2.2. Piezoelectric energy harvesting from heel strike (Shoes sole) (Howells, 2008)

Heel strike happens when the heel hits the ground surface during walking or running. The method of energy harvesting is using piezoelectric energy, which can be harvested to convert walking motion into electrical power.

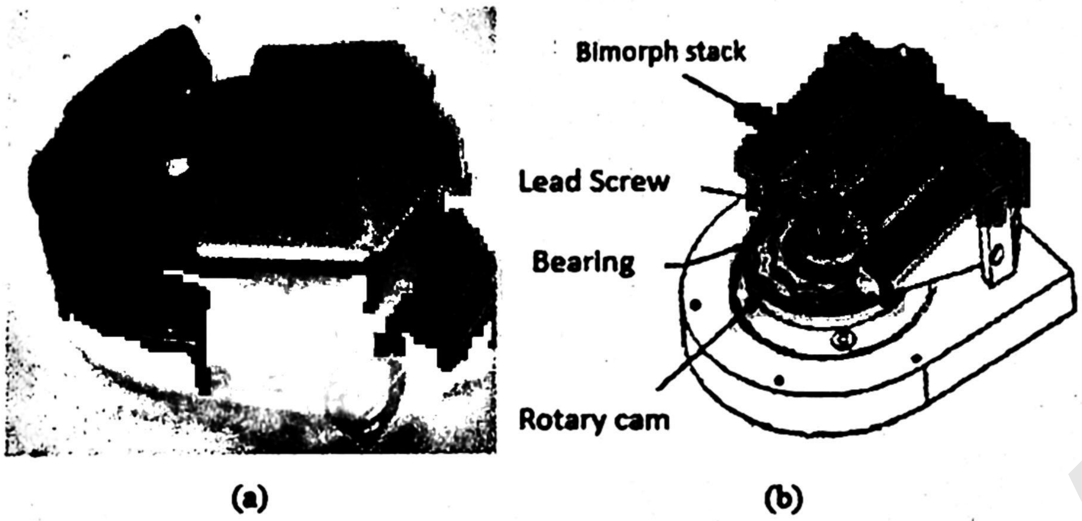


Figure 2: (a) Heel strike generator, (b) Schematic of heel strike generator (Howells, 2008)

The heel strike generator is the device depicted in Figure 2(a), where it has a mass of 0.455 kg and has approximate dimensions of 8.89 cm (L) by 7.94 cm (W) by 4.29 cm (H) (De Marqui, 2016). The Heel Strike Generator uses Lead Zirconate Titanate (PZT-5A) piezoelectric materials to convert biomechanical energy into electrical energy. The input biomechanical energy is transformed into electrical energy through four PZT-5A bimorph stacks as can be seen in the schematic diagram in Figure 2(b). Hence the Heel Strike Generator has four phases of electrical energy generation. The Heel Strike System uses a power electronics circuit to extract, store and regulate the electrical energy output from the four phases and converts it into a 12 VDC pulse.

The operation of energy harvesting starts when the user starts the steps to walk or running and spontaneously compresses the Heel Strike Generator, a lead screw, and gear train convert the linear motion into the rotation of a cam, where the rotating cam causes the PZT-5A bimorph stacks to deflect sinusoidally. The arrangement of the stacks is in such a way that they oscillate 90 degrees out of phase with one another, recycling most of the elastic energy stored in the bimorph crystal stacks. Each sinusoidally oscillating PZT-5A bimorph crystal stack produces an oscillating voltage that is rectified and regulated by a power electronics circuit that is separate from and connected to the Heel Strike Generator. The power electronics circuit takes in the AC voltage signals from each phase of the Heel Strike Generator rectifies them and produces DC pulses that charge a storage capacitor. Any stored charge in the capacitor is then discharged through an AC-DC converter, which converts that stored energy into a regulated 12 VDC output pulse.

2.2.3. Gear power generator energy harvesting by knee flexion (Li et al., 2009)

Knee flexion happens during walking and running. Walking/running starts from the cycle of swing flexion, swing extension, stance flexion, stance extension and pre-swing of the leg. The muscle acts on the joint and can produce positive muscle power and negative muscle power. Therefore, it can be seen externally as positive and negative joint power. Positive knee joint power is a net knee extensor torque while knee joint power is negative due to the flexor torque produced by the knee flexors to slow down the extending knee prior to heel-strike (Li et al., 2009). The period of negative joint power is an effective period for energy harvesting because braking power is generated.

The mechanism of energy harvesting using the gear power generator device is as shown in Figure 3 and can be distinguished into a parasitic and mutualistic method of harvesting energy. Parasitic energy harvesting, the electricity is harvested at the expense of the metabolic energy of the user (Li et al., 2009). In this method, the energy is harvested during the periods when muscles normally perform positive work, causing muscles to perform more positive work than they would otherwise. While for mutualistic energy harvesting is accomplished by selectively harvesting energy at times and in locations when muscles normally decelerate the body. Rather than braking entirely with muscles, a generator would perform some of the required negative work converting the mechanical energy of the body into electrical power. In situation, mutualistic energy harvesting would be like regenerative braking in hybrid cars.

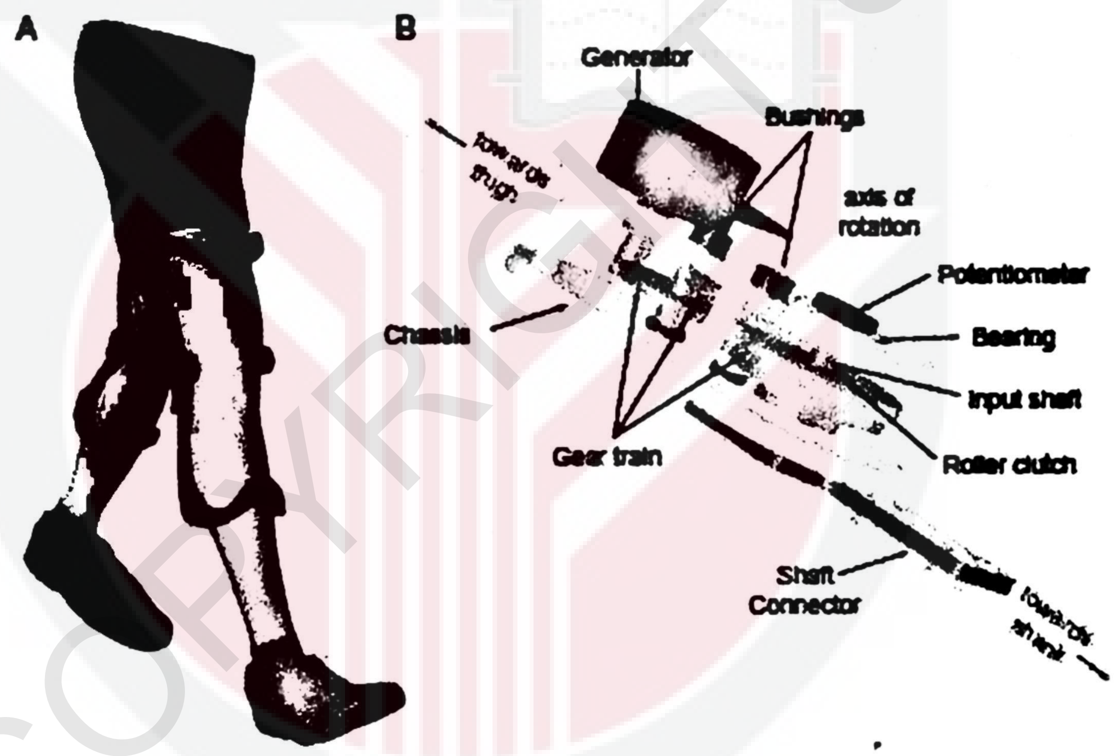


Figure 3: Gear power generator for leg swings (Donelan, 2008)

2.2.4. Gear train generator and vibration energy harvesting by centre of mass (carrying backpack) (Xie and Cai, 2015)

A soldier needs to carry a bag full of their equipment from time to time and backpackers would carry their backpacks instead of luggage. The load of the bag and the walking speed of the person produce kinematic energy. Kinematic energy will be converted for electric energy generation.

The mechanism functions when a person wears the backpack and the body position will move a bit high and a bit low from the static body position due to the changing angle between two legs. The harvesting device is shown in Figure 4, attached at the backpack follows the body movement during walking.

The moving part of the harvesting device consists mainly of a sliding base, springs, gear trains, generators, and linear bearings (Figure 4). The generators and their gear trains are assembled on the sliding base, which can slide along the framework's tubes on linear bearings. The sliding base is also used to support the external suspended load. Springs are assembled between the moving and fixed parts to provide a restoring force.

The harvesting device is designed to be symmetric for maintaining balance. The two symmetrically arranged rack gears mesh with the gear train to transmit the human's body movement to the generators. When the framework is fixed to the person's back and the suspended load is exerted on the sliding base, relative motion occurs between the fixed and moving parts during walking and the sliding base can oscillate up and down. Due to the rack gear mechanism, the up-and-down motion is converted into rotation of the gear trains, and the rotation accelerating through gear train finally drives the generators to produce electricity (Xie and Cai, 2015).

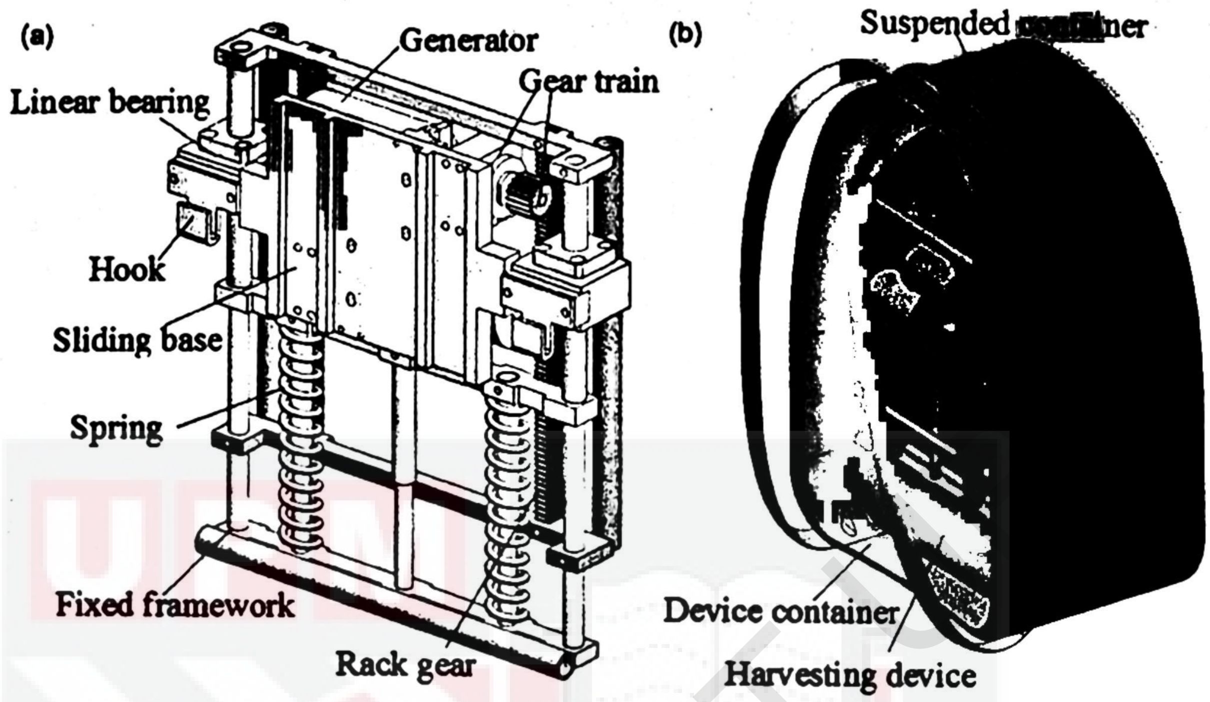


Figure 4: Backpack energy harvester (Xie and Cai, 2015)

Based on the study by (Xie and Cai, 2015), walking velocity and external load mass greatly influenced the power output from the harvesting device. A higher walking velocity contribute to a higher power output for a certain harvester, but there was an optimum load mass for affecting power output at a constant walking velocity.

2.2.5. Triboelectric nanogenerator energy harvesting by wearable fabric (Pu et al., 2016)

Wearable fabric is a cloth that can generate electricity when wearing it due to the human of the body. The type of energy harvesting suitable in this method is triboelectric nanogenerator (TENG). Triboelectric nanogenerator converts mechanical energy into electric power with a coupled effect of contact-electrification and electrostatic induction.

The fabric was woven with two types of polyester cloth, prepared by electroless plating for the Ni-cloth textile and by chemical vapor deposition for parylene on the conductive Ni-cloth with Dichloro- [2,2]-paracyclophane. TENG-cloth was woven with Ni-cloth belts as longitude lines and parylene-cloth belts as latitude lines. All the TENG-cloth belts are connected by copper wire as one electrode, and all the Ni-cloth belts are connected as another electrode.

The TENG-cloth was worn under the arm and at elbow joint like a sleeve. The movement of the arm creates rubbing motion on the TENG-cloth so that they the slide between each woven TENG-cloth longitude and latitude lines as shown in Figure 5. During this phenomenon, the TENG-cloth generated electrical energy from mechanical energy.

Figure 5: A self-charging power textile using supercapacitor yarns, triboelectric nanogenerator (TENG) cloth and wearable electronics (Pu et al., 2016)

2.3. Best criteria of energy harvesting

Based on the list of energy harvesting from 2.2.1 until 2.2.5, it can be summarized that triboelectric nanogenerator is the best mechanisms of energy harvesting with the best criteria for fabrication energy harvesting for upper limb, as shows on Table 1.

Table 1: Criteria of energy harvesting

No	Energy harvesting	Criteria		
		Flexible	Miniature	Commercially availability
1	Electromagnetic induction energy harvesting			✓
2	Piezoelectric energy harvesting		✓	✓
3	Gear power generator energy harvesting			
4	Gear train generator and vibration energy harvesting			✓
5	Triboelectric nanogenerator energy harvesting	✓	✓	✓

2.4. Introduction to Triboelectric

The triboelectric effect is a type of contact electrification in which certain materials become electrically charged after they rub against one another through friction. A simple example in our daily life is rubbing the glass with fur, or a comb through the hair. It can build up triboelectricity. In most of our daily life, static electricity is triboelectric.

2.5. Principle modes of triboelectric nanogenerator

There are four modes in triboelectric nanogenerator (Pan and Zhang, 2019). The triboelectric effect is a type of contact electrification in which certain materials become electrically charged after they meet another different material through friction.

2.5.1. Vertical contact separation-modes

the friction between the two dielectric films creates oppositely charged surfaces with different electron affinity (at least one is insulative). A potential drop between the electrodes deposited on the top and bottom surfaces of two dielectric films is developed once the two surfaces are parted by a gap. Figure 6 shows free electrons in one electrode would flow to the other electrode to balance the electrostatic field if the two electrodes are electrically connected by a load. The potential drop created by triboelectric charges will vanish once the gap is closed, the induced electrons will flow back. The induced electrons are driven by periodic contact and separation between the two materials to flow back and forth between the two electrodes, resulting in an external circuit alternating circuit (AC) output.

In this mode, the process of generating electricity depends on a periodic switch between the two contact surfaces ' contact and separation states, and the output is alternating current (AC). Simple structural design, great device robustness, and high instant power density are features of this mode. However, a cavity with constantly changing volume is an indispensable design of the vertical contact separation mode, making it a challenge for the TENG packaging.

The vertical mode of contact separation is widely used for harvesting energy from finger typing, engine vibration, human walking, and biomedical systems. It is also developed for the construction of self-powered sensor systems, including magnetic sensors, pressure sensors, vibration sensors, mercury ion sensors, sensors for catechin detection and acoustic sensors.

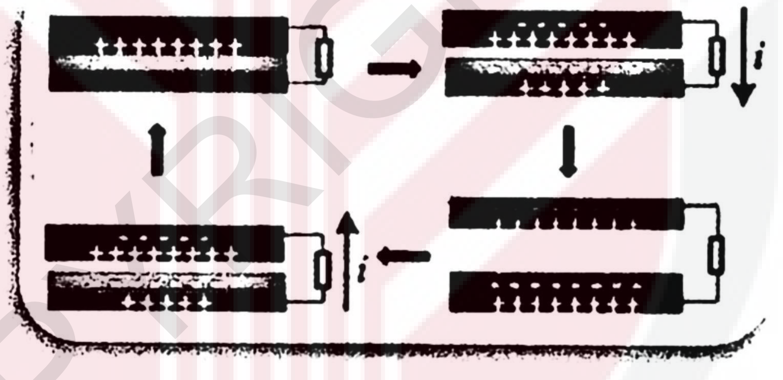


Figure 6: Mechanism of vertical contact separation-modes

2.5.2. Lateral sliding mode

For the lateral sliding mode, the structure is the same as vertical contact-separation mode. Figure 7 shows that a relative sliding parallel to the surface also creates triboelectric charges on the two surfaces when two dielectric films are in connection. A lateral polarization is thus introduced along the sliding direction, which causes the electrons on the top and bottom electrodes to flow to fully balance the triboelectric charges generated by the field. An alternating current (AC) output is generated by a periodic sliding apart and closing. The sliding may be a flat motion, a cylindrical rotation, or a rotation of the disc.

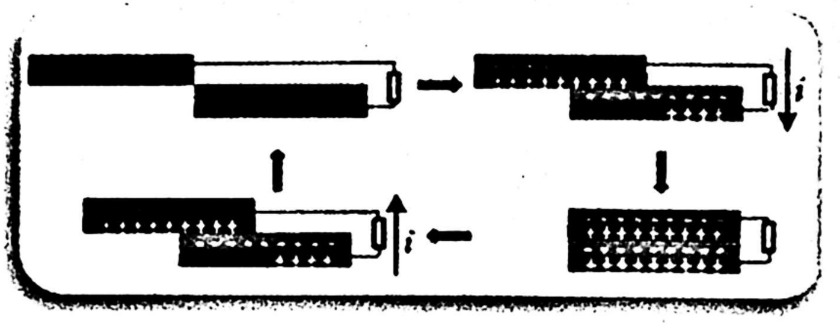


Figure 7: Mechanism of lateral sliding mode

2.5.3. Single electrode mode

The moving objects must be bonded with an electrode and a lead wire for both the vertical contact-separation mode and triboelectric nanogenerators in-plane sliding mode. Such a device configuration largely limits the versatility and applicability of TENGs to harvest energy from an arbitrary, freely moving object, since an interconnector must connect the object to the whole system.

A single electrode mode TENG was developed to solve this problem. Figure 8 shows that, for example, this mode consists of a PTFE moving object and an electrically connected aluminum layer to the ground. PTFE and aluminum are in full contact with each other in the original position, resulting in electrons being injected from aluminum to PTFE as PTFE has higher surface electron affinity than aluminum. Once the negatively charged PTFE slides apart or separates, the positive charges induced on Al will decrease and the electrons will flow from the ground to aluminum until the two plates are completely separated to balance the electrical potential.

Then, when PTFE slides backwards or comes back into contact, the induced positive aluminum charges increase, driving the electrons to flow from aluminum to the ground until the two plates are completely overlapped to restore an electrostatic balance. This is a full cycle of the electricity generation process of the single electrode mode TENG.

Although the induced transmission of electron across the electrode is not effective in the single electrode mode due to the electrostatic screening effect, one of the triboelectric layers can move freely without any restriction. The single electrode mode was applied with this unique feature to harvest energy from air flow, rotating tire, rain drop, and turning the pages of the book. And it was also applied as self-powered displacement vector sensors, visualized touch sensors, active tactile sensors, self-powered trajectories, velocity sensors, angle measurement sensors, acceleration sensors, biosensors, water/ethanol sensors, pressure sensors, sensors for healthcare monitoring, body motion sensors, self-powered identification systems, and self-powered distress signal emitters (Wang et al., 2015).

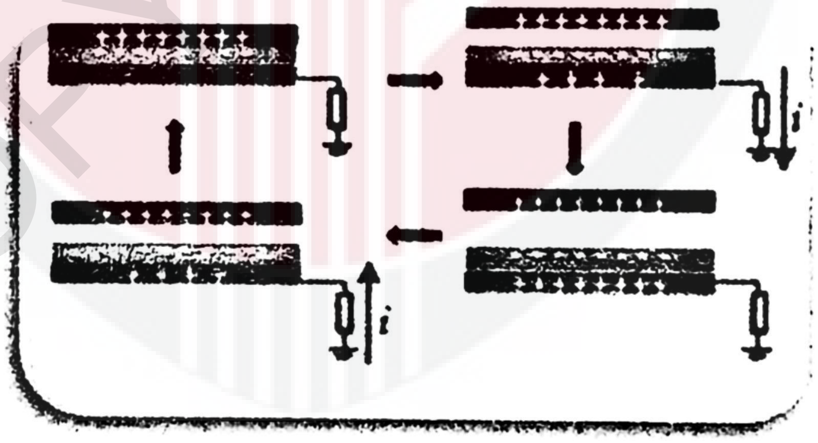


Figure 8: Mechanism of single electrode mode

2.5.4. Freestanding triboelectric layer-mode

In nature, due to its contact with air or other objects, such as our shoes walking on floors that are usually charged, a moving object is naturally charged. The charge remains on the surface for hours and in this period of time contact or friction is unnecessary because the density of the charge reaches a maximum.

If we make a pair of symmetric electrodes below a dielectric layer and the size of the electrodes and the gap between the two are the same as the size of the moving object, the approach and/or departure of the object from the electrode creates an asymmetric distribution of the media charge that causes the electron to flow between the two electrodes to balance the local distribution potential as shown in Figure 9. The electrons oscillating between the paired electrodes generates power. The moving object does not have to directly touch the top dielectric layer of the electrodes so that, without direct mechanical contact, free rotation is possible in rotation mode; surface wear can be drastically reduced.

This is a good approach for extending the durability of the TENGs. Using such a design, we have demonstrated energy harvesting from human walking and a mobile car, showing the potential to harvest energy from a freely moving object without an electrical connection.

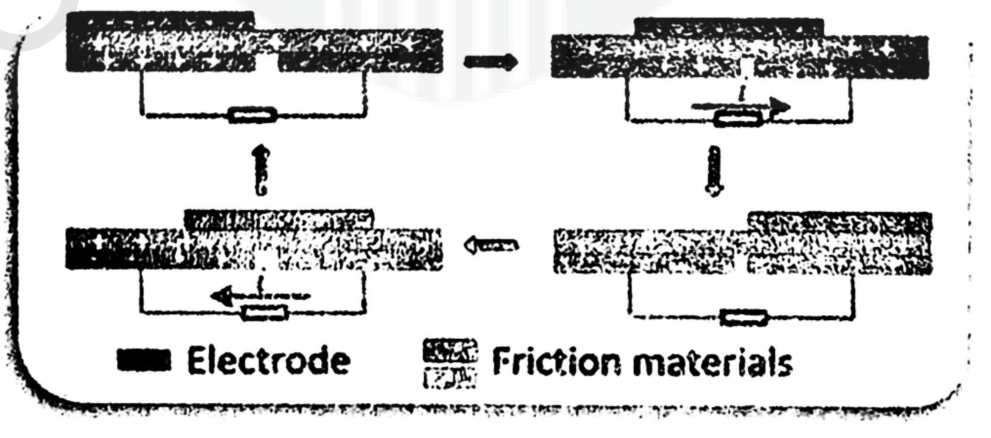


Figure 9: Mechanisms of freestanding triboelectric-layer mode.

2.6. Fundamental theories on the working mode of TENG

In this section, the fundamental theories will only be discussed on vertical contact-separation mode and lateral sliding mode. This is because both of these modes are the suitable mode to be applied for the energy harvesting of upper limb motion.

2.6.1. Vertical contact-separation mode

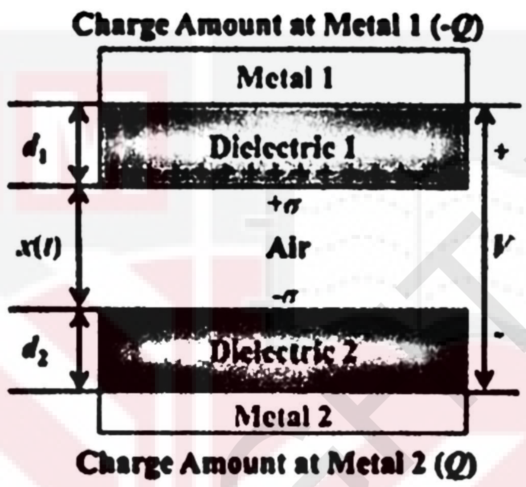


Figure 10: The theoretical model for a dielectric-to-dielectric vertical contact-separation mode TENG

Figure 10 shows the model built for a dielectric-to-dielectric TENG contact mode. Basically, two dielectric plates are placed face to face as two triboelectric layers, with thicknesses of d_1 and d_2 and relative dielectric constants ε_{r1} and ε_{r1}, respectively. Two metal layers are deposited as two electrodes. Due to the external mechanical force, the gap distance x between the two triboelectric layers can be changed periodically.

When the external force brings the two dielectric materials into contact, due to contact electrification, the inner surface of the two triboelectric layers will have opposite static charges with equal density of σ. When the external force separates the two mutually charged surfaces, the two electrodes will induce an electrical potential difference V. The changing V will drive the electrons through the electrodes back and forth. The quantity of charges transferred between the two electrodes is therefore defined as Q. The governing relationship of $V - Q - x$ and the intrinsic output of the vertical contact-separation mode can be expressed as:

$$V = -\frac{Q}{S\varepsilon_0}(d_0 + x(t)) + \frac{\sigma x(t)}{\varepsilon_0}$$

where d_0 is the effective dielectric thickness, and ε_0 is the dielectric constant of a vacuum.

2.6.2. Lateral sliding mode

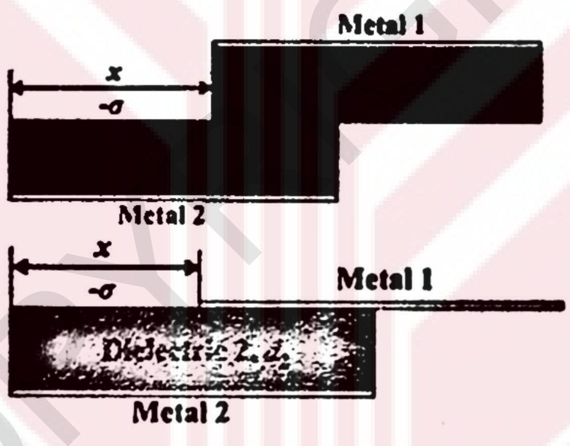


Figure 11: The theoretical models of the dielectric-to-dielectric (up) and metal-to-dielectric (bottom) lateral sliding mode TENG

Figure 11 shows the theoretical models for the dielectric-to-dielectric (up) and metal-to-dielectric (bottom) sliding mode TENG. Two metal electrodes are still attached to the dielectric layers in this mode. The bottom part is fixed while the top can slide through the direction of the longitudinal and the lateral separation distance is defined as x. When the top metal or dielectric layer slides apart, the non-overlapped regions will be charged with different signs. The top metal layer plays dual roles as an electrode and triboelectric layer for the metal-to-dielectric mode. The analytical equation cannot be derived for the general sliding-mode case of TENGs, and rigorous theoretical analysis can only be based on numerical simulations. The *V-Q-x* relationship for the sliding mode TENGs by neglecting the edge effect can be expressed as:

$$V = -\frac{d_0}{W\varepsilon_0(l-x)}Q + \frac{\sigma d_0 x}{\varepsilon_0(l-x)}$$

2.7. Conclusion

Based on the study through this chapter, the objective of determining the best energy harvesting method for upper limb body motion during oil palm harvesting were made. The energy harvesting method using triboelectric nanogenerator were select based on the criteria that have been discussed in subchapter 2.3. After the energy harvesting method was selected, the study on principle modes of triboelectric nanogenerator and the fundamental theories on the system were studied. Through the studies, two modes were selected which are vertical contact separation mode and lateral sliding mode.

CHAPTER 3

METHODOLOGY

3.1. General Overview

The primary objective of this study is to develop an energy harvesting system for upper limb body motion during harvesting activities. The system converts the biomechanical energy used in the agriculture activities into electrical energy. In order to achieve the objective, it is necessary to characterize the selected type of energy harvesting system to get the best configuration of the energy harvesting device for developing the device system later. In Malaysia, this technology is still new since not much research made by Malaysia's researcher. Not much application uses an electrical source from human-sourced biomechanical energy harvesting in agriculture.

3.2. Triboelectric energy harvesting

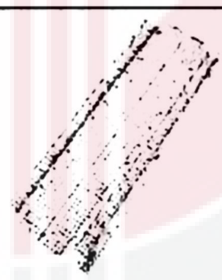
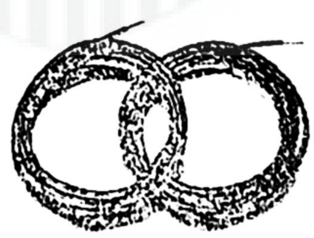
Through the literature review under 2.2 (Studies on energy harvesting) and by the conclusion made under 2.3 (Best criteria of energy harvesting), the most appropriate energy harvesting selected is triboelectric. Triboelectric energy harvesting or triboelectric nanogenerator fit the criteria of cost-effective, lightweight that can be attached at the upper limb without affecting the person.

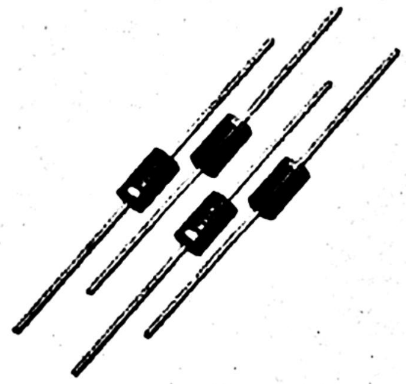
3.3. Material

In this project, the materials used were referred from the journal paper that used for the literature review by (Mallineni et al., 2017). This paper demonstrates the fabrication of U-TENG (ultra-triboelectric nanogenerator) which are simple to refabricate and used the device to get the characterization of the device.

The main material in this fabrication is a dielectric material, indium tin oxide film. Dielectric is an insulating material or a very poor conductor of electric current. When dielectrics are placed in an electrical field, there is virtually no current flowing in them because, unlike metals, there is no loosely bound or free electrons that can drift through the material. Electric polarization occurs. The positive dielectric charges are minutely displaced in the direction of the electric field and the negative charges are minutely displaced in the opposite direction to the electric field. This slight load separation, or polarization, reduces the dielectric's electrical field. (The Editors of Encyclopaedia Britannica, 2011). The materials used show in Table 2.

Table 2: List of materials used for fabrication TENG model

Materials for fabrication			
No	Item	Picture	Details
1	ITO (indium tin oxide) coated with PET (polyethylene terephthalate)		• Thickness: 0.175mm • 50 Ω per sq inch • Weight: 6.68gmm
2	Kapton polyimide adhesive tape		• Thickness: 0.05mm
3	Copper tape		• Thickness: 0.05mm • Double sided conductive roll
4	Breadboard		• Total tie-point: 830 points
5	Single core connecting wire		• Size: 1/0.5mm • Material: 100% pure copper

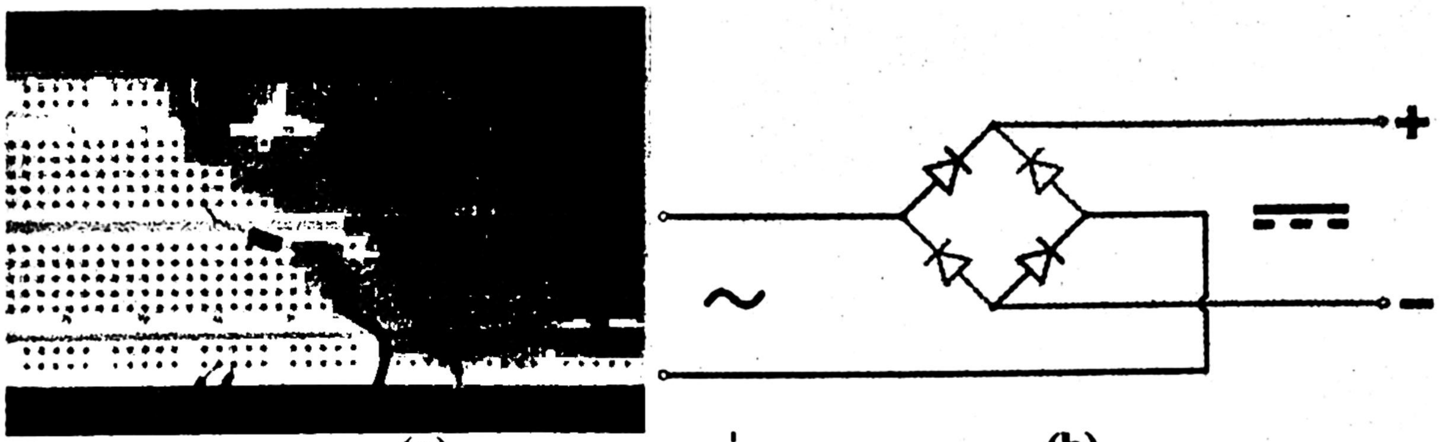
6	Diode		• Forward Current If (AV): 1.5A • Forward Voltage VF Max: 1.16V • Forward Surge Current Ifsm Max: 50A
7	Spacer (double sided tape)		• Thickness: 0.10 mm
8	Conductive silver ink glue		

3.4. Experimental set up

In this chapter, experiments were set up to characterize the simple triboelectric nanogenerator. Figure 12 shows the full setup of the triboelectric nanogenerator, bridge rectifier, and the voltmeter. The triboelectric nanogenerator was build multiple models according to the variable to be measured.

Figure 12: Full set up of vertical contact separation mode-TENG model (left), rectifier bridge (middle), voltmeter (right)

Figure 13(a) shows the actual rectifier bridge setup from four pieces diode used. The function of bridge rectifier is to convert the alternating current from the triboelectric nanogenerator to direct current. The direct current reading shows in the voltmeter. In this experiment, if not using the rectifier bridge, the voltage data shown in positive and negative values. Figure 13(b) shows the schematic circuit of bridge rectifier.



(a) **(b)**

Figure 13: (a) image of bridge rectifier used, (b) schematic diagram of bridge rectifier

Type of bridge rectifier used in this experiment was Uncontrolled Bridge Rectifiers. With this configuration of diodes in the rectifier, power does not vary depending on the load requirement, and is typically used in constant or fixed power supplies (Tarun Agarwal, n.d.).

The amount of voltage harvested based on specific setups of the triboelectric nanogenerator was recorded through the whole experiment session. During the experiment, a single press (external load) applies at the center of the triboelectric nanogenerator device three times to get the average voltage data. This method only applied to the vertical contact separation test, while the lateral sliding test was done by slide the slider piece for a return way. The motion of sliding the slider piece was repeated 3 times to get the average voltage. After all the experiment were done, the recorded video was playback to record the voltage data.

3.3.1. Vertical contact variable with size

The size of the system was varied to analyse the voltage output depending on the size of the energy harvester device. Figure 14 shows three different sizes of big, medium and small respectively (20 x 10) cm, (10 x 10) cm and (3.5 x 2.75) cm. The bigger size of TENG model was determine by the standard size of ITO coated PET film from the supplier, the medium size of TENG model was determine by half of the bigger size which the standard size of ITO coated film were cut half and for the small size of TENG model was determine from the literature study of (Mallineni et al., 2017).

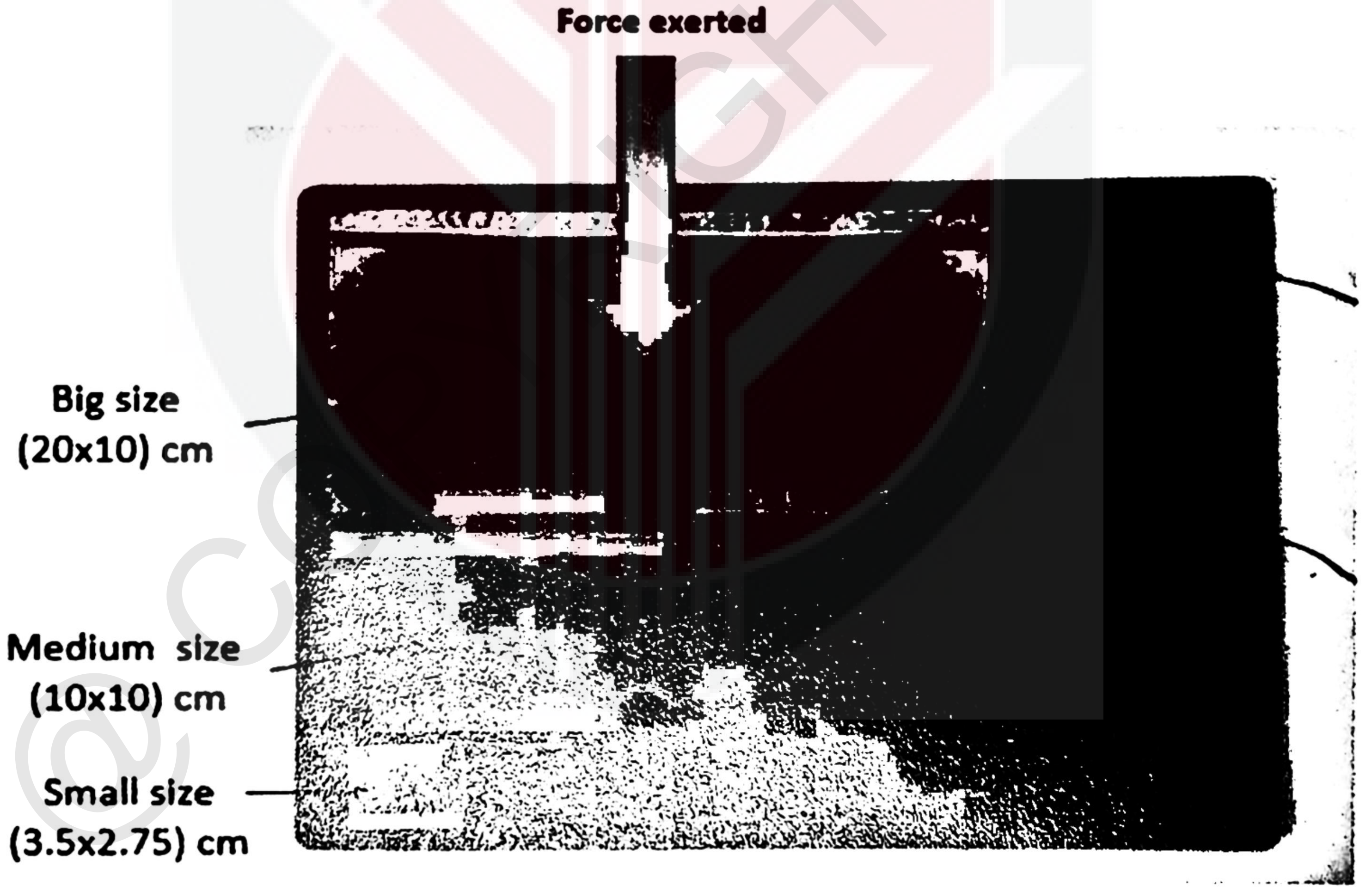


Figure 14:TENG model with three different size of dielectric-to-dielectric material

3.3.2. Vertical contact variable with length of wire

The length of wire core was varied to analyse the effect length on voltage. In order to check the energy loss when passing through the wire core connecting , the wire core connecting length were set up into two length. For the long length is 30 cm and for the short length is 20 cm. Figure 15 shows the two lengths of wire core with the same size of triboelectric nanogenerator device which is (10 x 10) cm.

Figure 15: TENG model with different length of wire connection

3.3.3. Vertical contact variable with type of connection

The type connection is varied to determine the losses of energy harvesting from the triboelectric nanogenerator device passing through the wire core connecting. Figure 16 shows the triboelectric nanogenerator energy harvester one with copper tape connection wire and other with copper tape and glue connection wire.

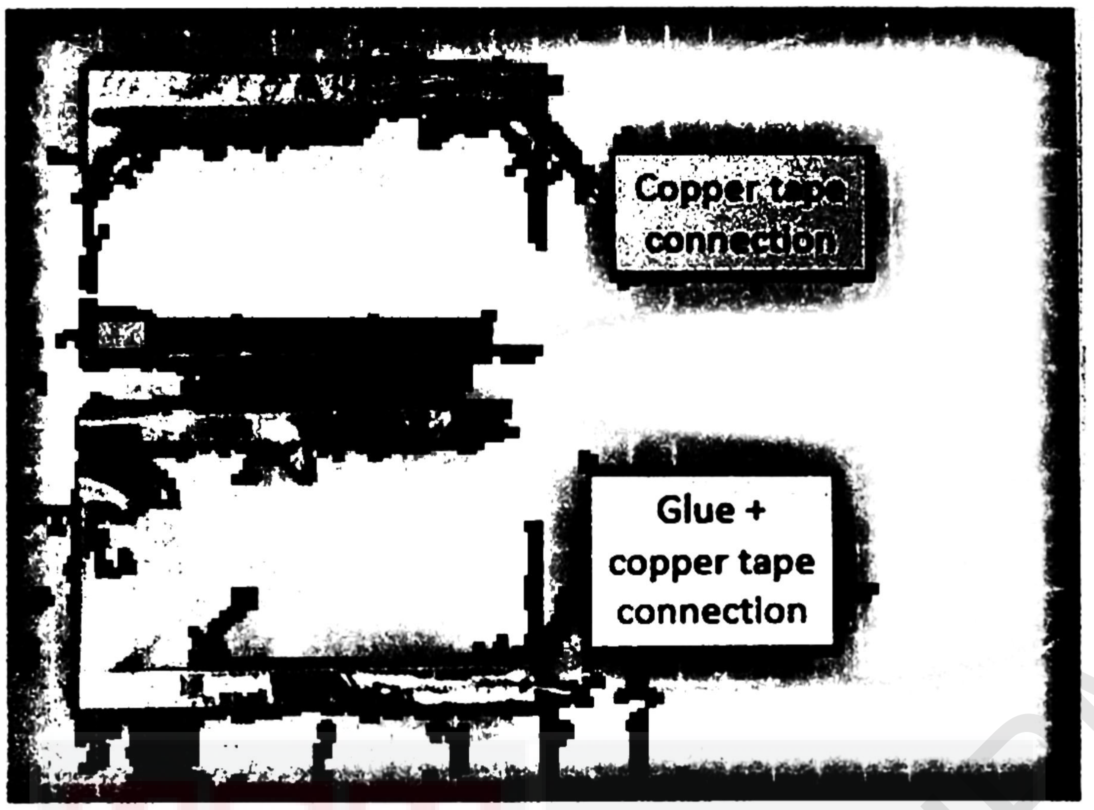


Figure 16: TENG models with different type of wire connection

3.3.4. Lateral sliding variable of air space

The lateral sliding triboelectric nanogenerator to harvest the energy from biomechanical motion. This experiment aimed to measure which mode has better output voltage. Figure 17 shows the fabricated triboelectric nanogenerator for sliding mode. The *A* part was slide forward and then backward as a one complete sliding motion while *B* part remain static.

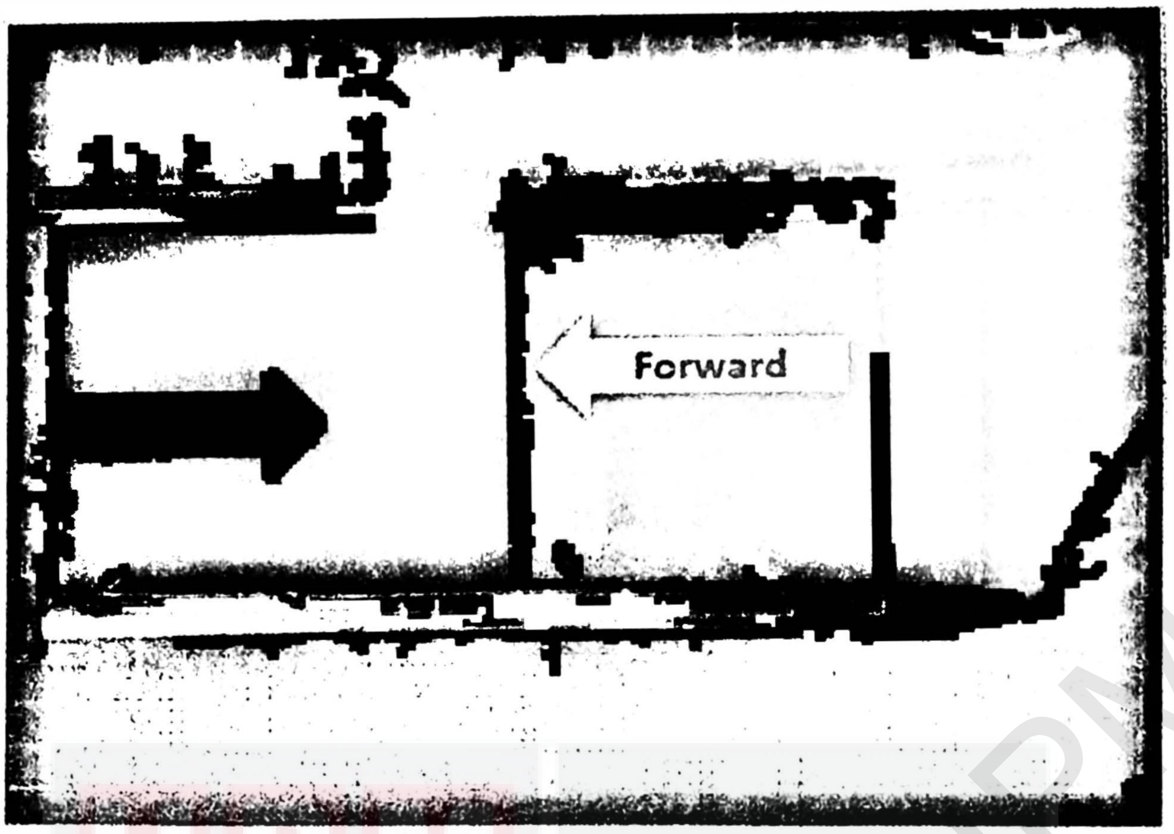


Figure 17: TENG model with no air gap

After experimenting the lateral sliding mode, the voltage output shows different voltage using the same size vertical contact mode system. Hence, another system was fabricated which has extra space gap for air space. The roles of the air space to provide electron in the air particle and friction. Figure 18 shows the fabricated triboelectric nanogenerator with air gap for sliding mode.

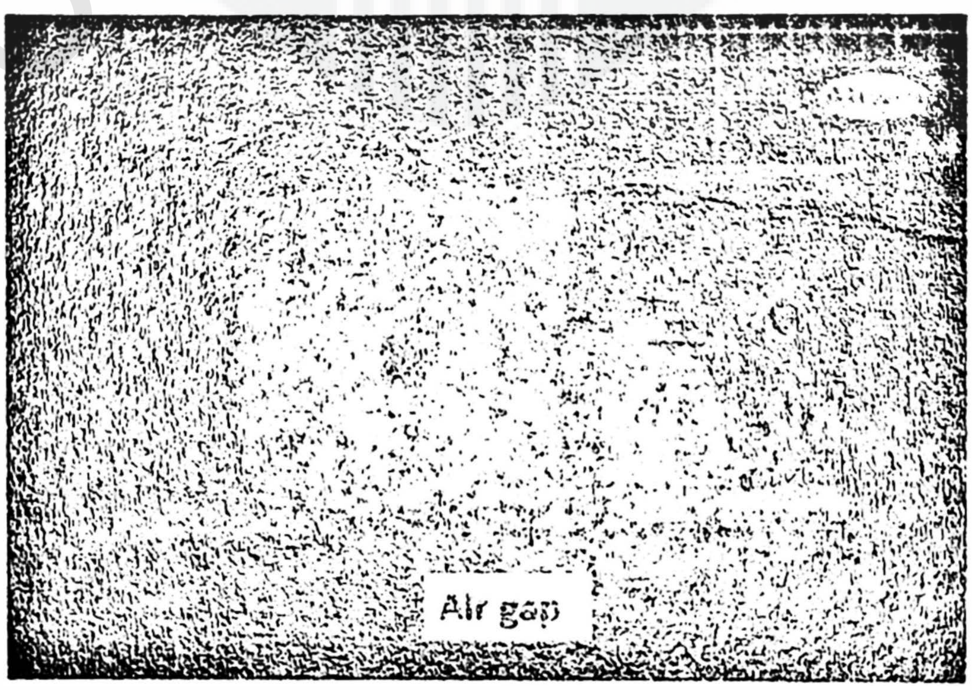


Figure 18: TENG model with air gap

CHAPTER 4

RESULTS AND ANALYSIS

4.1. General Overview

The triboelectric nanogenerator made of simple and commercially available product was fabricated based on (specific reference) and according to the experimental setup for the system characterization. Therefore, the fabricated triboelectric nanogenerator can be characterizing to get the best configuration for assembly on the upper limb, which is the third objective of this study.

4.2. Experimental results and analyses

4.2.1. Vertical contact with varying size.

Table 3: Voltage reading and size of model.

Size area of model (cm)	Voltage reading (volt)			Average voltage reading, V_{ave} (volt)	Standard deviation value, s
	V_1	V_2	V_3		
Small (3.5 x 2.75)	0.537	0.548	0.558	0.547	0.0105
Medium (10 x10)	1.865	1.831	1.837	1.844	0.0181
Big (20 x 10)	2.418	2.330	2.285	2.344	0.0676

From the table 3, it is shown that the size of the device influences the voltage output. A larger the contact surface of dielectric film, produces greater electric polarization and higher voltage.

4.2.2. Vertical contact with varying wire length

Table 4: Voltage reading and length of wire

Length of wire (cm)	Voltage reading (volt)			Average voltage reading, V_{ave} (volt)	Standard deviation value, s
	V_1	V_2	V_3		
Short (20)	1.8650	1.8310	1.8370	1.8440	0.0181
Long (30)	1.6440	1.6950	1.6100	1.6490	0.0428

From Table 4, it can be shown that the of length of connecting wire influences the voltage. A short wire of 20 cm has more voltage harvested at 1.844-volt than long wire of 30 cm has 1.649-volt voltage harvested. Longer wire connection, causes higher resistance for the voltage to reach the voltmeter.

4.2.3. Vertical contact with varying type of connection

Table 5: Voltage reading and type of connection

Type of connection	Voltage reading (volt)			Average voltage reading, V_{ave} (volt)	Standard deviation value, s
	V_1	V_2	V_3		
Copper tape	1.8210	1.8440	1.8300	1.8320	0.0116
Copper tape + glue	1.8650	1.8310	1.8370	1.8440	0.0181

From Table 5, the voltage output from the different types of connection are similar. The type of connection use at the wire connection does not influence the voltage produced. However, the use of copper tape together with conductive silver ink glue give the solderless interconnects and for both rigid and flexible substrates. The connection is tighter and may help prevent energy losses.

4.2.4. Lateral sliding with varying air space

Table 6: Voltage reading and air gap space

Existance of air gap	Voltage reading (volt)			Average voltage reading, V_{ave} (volt)	Standard deviation value, s
	V_1	V_2	V_3		
No air gap	0.2040	0.1840	0.1940	0.1940	0.0100
With air gap	0.1250	0.1360	0.1270	0.1290	0.0058

From Table 6, it is shown that the lateral sliding with air gap produces 0.194-volt and without air gap produces 0.129-volt. The model with no air gap had higher voltage harvested compare to model that have no air gap. The bottom dielectric film was been cut to make a space gap for air flow, however this method had reduced the voltage output. This is because the surface of contact during sliding is less compare to the model that has no air gap.

4.3. Potential Application in Manual Oil Palm Harvesting

In this section, ideas are proposed for future development of TENG model implement for the upper limb. Based on data characterization from the experimental study, a TENG-based energy harvesting system of upper limb motion can be developed.

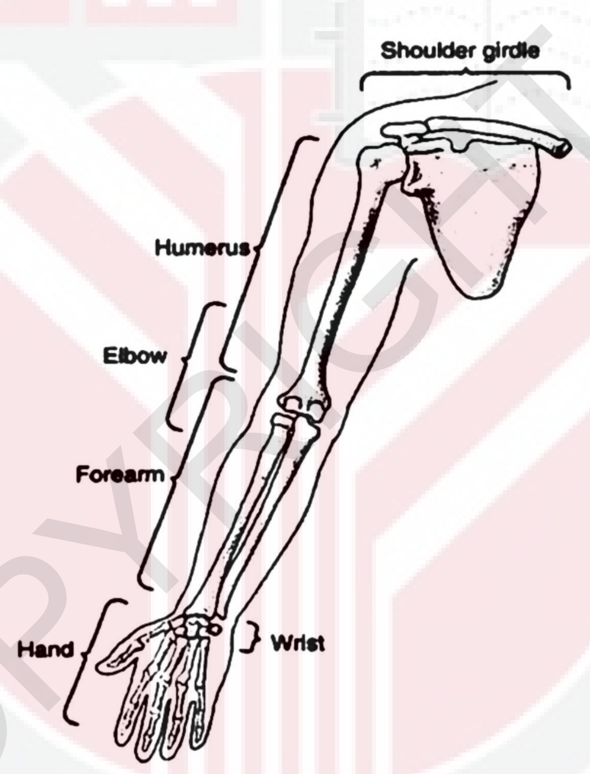


Figure 19: Segments of upper limb.

The upper limb (Figure 19) consists of four segments, which are shoulder, arm, forearm and hand. All this segment moves in the 3D dimension. The movement of upper limb shown in Figure 20.

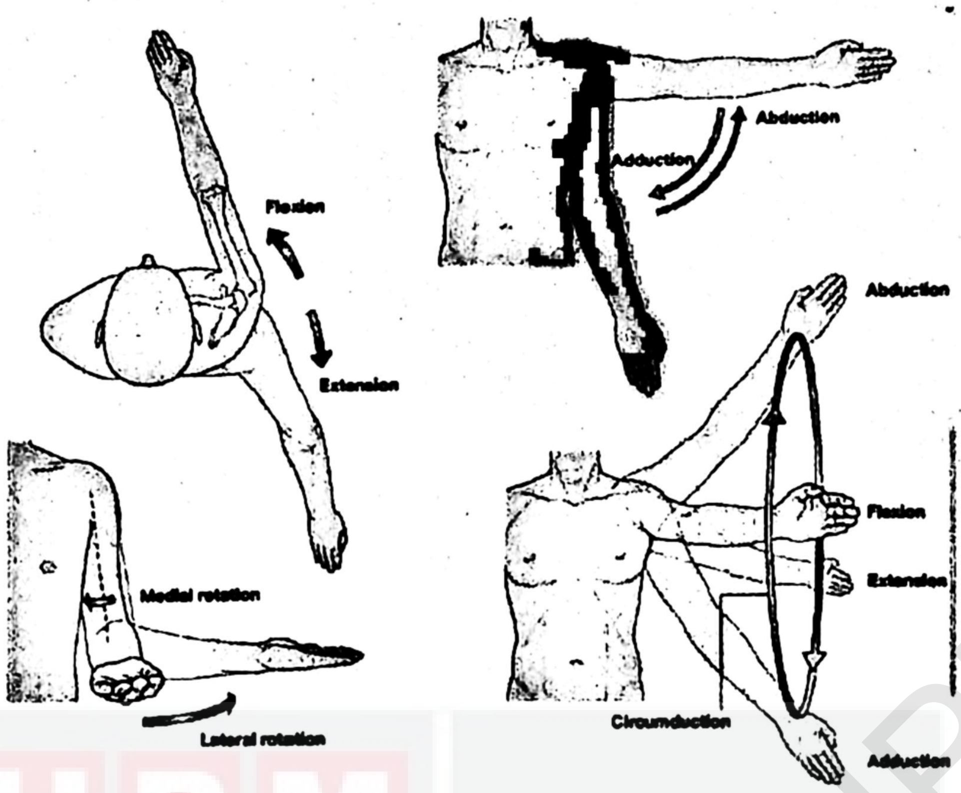


Figure 20: The movement of upper limb (O' and Phd, n.d.)

The experiment tested for both vertical contact-separation and lateral sliding modes (Chapter 3 and Chapter 4). From that experiment, both are suitable to be used to develop the energy harvesting system of upper limb.

A small experiment was setup by placing the TENG model of vertical contact-separation mode at the palm of the hand under the glove while wearing it. Then, pole grabbing by the hand was simulated as a consideration for the use of cutter or sickle for oil palm harvesting. The output from that activity shows that voltage was present while grabbing the pole.

Figure 21: Flow of potential application TENG using vertical contact separation mode

For the lateral sliding mode, the TENG model was placed near the armpit. The lateral sliding TENG model has two pieces of dielectric material. One is placed near the chest lower than armpit and another piece is placed at the triceps of the arm. During pulling and pushing the cutter or sickle to harvest the oil palm fruit brunch, the motion involves flexion and extension of arm. Hence, the sliding motion is created and energy can be harvested through this motion of flexion and extension of upper limb.

Figure 22: Flow of potential application of TENG using lateral sliding mode

These are the potential application for the development of energy harvesting system using TENG for upper limb motion. This study suggests that energy harvesting through the upper limb motion during the harvesting of oil palm is feasible based on the experimental results presented in section 4.2.

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1. Discussion

5.1.1. TENG mode of vertical contact-separation

The fabrication of TENG models are very challenging because it needs the knowledge in triboelectric and materials engineering. The main material used in this project is ITO (Indium Tin Oxide) coated readily with PET (Polyethylene Terephthalate) layer, which is commercially available.

The materials involve are ITO/PET, spacer and Kapton. ITO/PET film and Kapton film act as the dielectric materials. This setup based on the reference in (Mallineni et al., 2017)

Based on the fundamental of theories on the working mode of TENG in subchapter 2.6 and 2.6.1, the voltage output depends on the thickness of dielectric materials, d, the distance of air gap, x, and the dielectric constant and also load exerted on the model. The load applied in this project is by pressing fingers at the center of the dielectric films.

For the upper film which consist of ITO/PET materials, the thickness is about 0.175 mm and for the bottom film which consist of ITO/PET and Kapton film, the total thickness is about 0.225 mm. So, the d_1 and d_2 are 0.175 mm and 0.225 mm respectively. The spacer used in this mode are at 0.1 mm of length. It is representing the x value. the spacer is functionally to provide frictional contact between upper and bottom dielectric materials. The value of dielectric constant for ITO are $\epsilon 1 = 3.3378$ and $\epsilon 2 = 0.011330$ (König et al., 2014).

Q defines as the quantity of charges transferred between the two electrodes. In this project, measuring the Q was not performed.

$$V = -\frac{Q}{S\varepsilon_0}(d_0 + x(t)) + \frac{\sigma x(t)}{\varepsilon_0}$$

However, based on theoretical relationship of *V-Q-x*, voltage can potentially be harvested, and the experiments demonstrated that voltage was present.

5.1.2. TENG mode of lateral sliding

The schematic set up for the lateral sliding mode are same with the vertical contact-separation mode. The different is only at the presence of the spacer. In this mode, spacer was removed as the friction will occur during sliding.

As the parameter are mostly same as the vertical contact-separation mode, the values of thickness of upper film, the thickness of bottom film and the dielectric constant are, 0.175 mm, 0.225 mm and, $\epsilon 1 = 3.3378$ and $\epsilon 2 = 0.011330$ (König et al., 2014), respectively. The x in this mode is define as direction of the longitudinal and the lateral separation distance. Hence, the x value is 100 mm which half from the total length of the bottom plate/film.

$$V = -\frac{d_0}{W\varepsilon_0(l-x)}Q + \frac{\sigma d_0 x}{\varepsilon_0(l-x)}$$

Based on theoretical relationship of V-Q-x, voltage can potentially be harvested and the experiments demonstrated that voltage was present.

5.2. Conclusion

The three of objectives of this study are (i)determining the best energy harvesting method for upper limb body motion during oil palm harvesting, (ii)characterizing a TENG-based energy harvesting using commercially available materials and (ii)developed potential TENG-system for usage during manual oil palm harvesting, were achieved. Triboelectric nanogenerator (TENG) was chosen as it has the best criteria for energy harvesting for upper limb motion. This is because it is flexible, miniature, and commercially available for the fabrication study purpose.

The dielectric material used was indium tin oxide. The material is commercially available. The fundamental of electrical induction occurs between two dielectrically materials get a contact through friction was studied. The fabrication of TENG model was built for two modes, vertical separation-contact mode and lateral sliding mode, and both were characterized.

Based on the characterization studies, potential mechanisms were proposed for future development of TENG system to be implemented during upper limb motion. It is my ambition to see that this technology is further researched as an alternative method to powering/recharging wireless sensors widely used in IoT technologies in Malaysia especially in the plantation which still uses manual labor. In that way, we can utilize the biomechanical energy produced by the human to be converted into electrical energy.

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