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BIOMECHANICAL STUDY AND ANALYSIS ON HUMAN MOTION USING PIEZOELECTRIC SENSOR FOR SCAVENGING ENERGY

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ABSTRACT

Research on the new technology of the potential of human body part to provide mechanical energy to convert to electrical energy has been rapidly performed by some researchers from well known universities. This paper described the research that focus only on toe as a source of mechanical energy and by using piezoelectric sensor as a mean of converting mechanical energy into electrical energy to power electronic devices. In order to complete the project, the data has been taken from a subject that performed a stationary run on the force sensor with piezoelectric sensor attached to the toe. Voltage output from piezoelectric sensor is in alternating form is then connected to a non-adaptive harvesting circuit

Keywords: *Piezoelectric sensor, harvesting energy, human body, non-adaptive harvesting circuit.*

1.0 INTRODUCTION

The rapid growth technology in electronic devices has led to massive usage of electrical energy. This phenomenon has led to the need for new alternative power source since the current approaches for powering portable devices are battery which has some drawbacks such as weight, recharging and replacing it and etc. Scavenging energy is nowadays receiving attention by researchers in biomechanical energy harvesting field where the general idea is to convert mechanical energy from human movement to electrical energy. The idea of scavenging energy has long been applied, for example the scavenging energy from windmill, solar, biomass, ocean wave and etc. Scavenging energy from human motion is renowned as a potential source of energy for replacing battery [1 - 6]. More recent works are focused firstly on which part of the body while in motion that will produce high mechanical energy and secondly on how to develop and improve the efficiency of the scavenging device in converting the mechanical energy to electrical energy.

Studies at the MIT Media Laboratory explored scavenging waste energy from human and have developed parasitic power harvesting in shoe using piezoelectric [1-2]. Based on study conducted by Niu *et. al.* [3], there are four main methods in converting mechanical energy to electrical current or voltages which are piezoelectric actuation, electrostatic actuation, electroactive polymers and magnetic actuation. Piezoelectric and EAPs are shown to have similar characteristics which are having high impedance, sharp output voltage, and

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very low energy conversion efficiency. Niu and Chapman [4] continued the research on designing and analyzing linear biomechanical energy conversion devices by considering three human motion namely arm swing, horizontal foot movement and up-down centre of gravity movement. Design and optimizing procedure of a biomechanical energy conversion device were addressed in details in [5].

Penglin [5] discussed about designing and optimizing procedure of a biomechanical energy conversion system. He focused on the center of mass motion which is identified as an energetic motion where the model of hip as an inverted pendulum. It is observed that during walking, the hip where the center of mass for our body is located resembles a sine wave with amplitudes of 2.5 cm when it follows an up and down motion. In the study, firstly the characteristics of center of mass motion were investigated. The hip can provide a reasonable speed in the vertical direction where faster walking can produce a higher vertical velocity. Secondly this motion could not provide a large amount of direct force but piezoelectric and EAP actuations require a big amount of direct force to generate power and therefore they can be eliminated from the application and magnetic actuation method utilizing inertial energy was more suitable as a scavenging device.

Li *et. al*. [6] have developed a knee mounted devices where power generation occurred at the end of the swing phase when knee flexor muscles acted to brake knee motion. On the other hand, Saha *et. al*. [7] presented electromagnetic based generator for harvesting energy from human motion. Howel [8] developed electric generator conversion of mechanical motion into electrical power. Donelan *et. al*. [9] in their research explained the physiological that guided the design process of energy harvesting and its performance. . Like the previous paper, they also do some research on walking mechanics and energetic. The fact is, muscle require metabolic energy to perform negative work. In order to perform positive mechanical work, active muscle fibers shorten while developing force, converting chemical energy into mechanical energy.

Most researches are focusing on heel strike application with piezoelectric. But apparently, the electrical current or voltages generated are very average [10]. Sodano *et. al*. [11] studies concluded that piezoelectric material has shown the capability to recharge a discharged nickel metal hydride battery from scavenging energy through vibration. In their studies [12], three types of piezoelectric devices were tested to determine each of its ability to transform ambient vibration into electrical energy.

There are basically three basic types of foot strike while running namely mid foot strike, fore foot strike and heel strike. For fore foot strike, part of the foot between forward and toe touch the ground. Strikers, mid distance runners and some athletes tend to prefer running on fore foot strike because of extra speed obtained. Lastly, in heel strike, the heel strikes the ground in front of the body.

In this research, scavenging wasted energy from human motion and converting it into useful electrical energy is further studied and analyzed. In the study, several joints lower parts of human body are analysed. In analyzing these joints, inverse dynamic method is used to calculate and determine negative work produced. Then, the study concentrates on the potential of the lower part of human body while in motion, in particular, the toe, that has potential for scavenging energy. Experiment was conducted in finding values of voltage produced from human motion using piezoelectric transducer that converts the mechanical energy into electrical energy.

The paper is organized as follows, section 2 reviews on related topics to the study including biomechanics of human motion and piezoelectric transducer. Section 3 describes the experimental setup of the study and section 4 is the results and discussion on the study. The conclusion summaries the main contributions of the paper.

2.0 REVIEWS ON RELATED TOPICS

This section presents related topics of the study which are the biomechanics of human motion and scavenging energy device using piezoelectric transducer.

2.1 Biomechanic of human motion

Study of biomechanics can be applied in many fields such as sports, ergonomics and etc. In research field nowadays, many researchers have decided to study on renewable energy based on biomechanics human motion such as arm swing, heel strike and center of mass motion. Most of the study focused on converting mechanical energy into a useful electrical energy. As the name implies, biomechanics is defined as the study of living things using the sciences of mechanics [13]. For example, the understanding of biomechanics human motion is used to increased athletes performance [13]. Word biomechanics was built from two different parts which are bio and mechanics. Usually, prefix bio is related to living things while mechanics is an analysis of force and it does involve calculation [14].

Since this project is about to harvest energy from human motion during walking, it is important to know a little bit about walking mechanics and muscle activity. In order to produce energy, muscle needs metabolic energy from food and oxygen to perform work [3]. At constant speed, there are no mechanical work produced by the body since the kinetic energy and the potential energies are in equilibrium condition since kinetic energy and potential energy initial and final are the same [6]. In other words, to produce high energy, big differences of potential energy and kinetic energy are needed [6]. Main source of mechanical power for biomechanical energy harvesting is located at human muscle. There are two types of work performed by the body which are positive and negative work. Positive work will be produced by muscle only while negative work is from air resistance, damping in the shoe sole and movement of soft tissue [6]. In order to produce maximum electricity from human motion, every gait cycle of human motion should be studied. There are many parts of human body that found to be flexible for harvesting energy purpose for example arm swing, horizontal foot movement and up and down movement of the center of gravity [10]. There are five phases during walking which are swing flexion, swing extension, stance flexion, stance extension and pre-swing. It can be concluded that highest power is produced during stance flexion phases. For harvesting energy from human motion, the lower body segments are the best part to harvest the wasted energy [3]. From the previous research, it is found that knee have the high potential as a scavenging energy source since it can produce high energy [3]. In this study, the analysis are about to calculate the work produced by human motion using data from previous researcher [16]. The calculation of force and work produced from human joint was discussed and the focused is on toe.

2.2 Piezoelectric transducer

Piezoelectric transducer can be divided into two which are piezoelectric sensor and piezoelectric actuator. Basically, piezoelectric sensor is converting mechanical energy to electrical energy while piezoelectric actuator is vice versa. Piezoelectric is an active sensor since it responses to a mechanical load indicated by yielding electric charge with their transduction element such as quartz and $PbZrO_3$ [17]. Piezoelectric sensors have an extremely high rigidity where it shows almost zero deflection or typically in μm range. The sensitivity of piezoelectric depends on the piezoelectric coefficients $d_{i\lambda}$. With its unique characteristics, piezoelectric sensor is widely used in many applications such as in quality assurance and process control. Converse piezoelectric effect can be defined as mechanical stress is proportional to an acting external electric field in the piezoelectric material. However, direct effect of piezoelectric can be seen when proportional changes in electric polarization of the material is produces from mechanical deformation of the piezoelectric material. Converse piezoelectric effect has been applied in ultrasound and communication technique due to the simple principle where elements with piezoelectricity properties will deform periodically in alternating electric field. This situation will produce an electrical energy when the material is stressed [7].

2.2.1 Mathematical Equation

Based on principles of piezoelectric material, voltage will be generated when the piezoelectric material was compressed or bent. For compressed condition, voltage that will be produced by piezoelectric material can be calculated from the equation below [3]:

$$V = \frac{d_{33}}{\epsilon}\frac{Ft}{LW} \tag{1}$$

where d_{33} is a constant of piezoelectric in thickness direction, F is the applied force for piezoelectric material. l and w are width and thickness of piezoelectric material while t is the thickness. Meanwhile, in order to calculate electrical energy, the following equation are used:

$$W = \frac{1}{2}CV^2 = \frac{1}{2}d_{33}^2F^2\frac{t}{\epsilon LW} \tag{2}$$

Where d_{33} and ϵ are fixed by piezoelectric material.

For bending mode, it is assumed that strain is given to the piezoelectric material which has given the equation to calculated voltage as followed:

$$V = \frac{3FLg_{31}}{2Wt} \tag{3}$$

Where g_{31} is a voltage coefficient. This equation is only valid if force is applied at the free end of piezoelectric material. The total available energy is:

$$E = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\epsilon LW}{t}\frac{9F^2g_{31}^2}{4W^2t^2} \tag{4}$$

where$= K_{stiff}\Delta x$. Δx is free end deflection and K_{stiff} is equivalent stiffness of the bender.

3.0 METHODOLOGY

The methodology of this study is divided into two phases. Initially, biomechanical study was conducted to find a potential of human motion to produce mechanical energy. Section 3.1 provides the mathematical calculation to determine amount of work produced by the joint using human motion data by previous study [16]. Next, section 3.2 provides the development of the energy scavenging device with hardware needed for analyzing the developed device.

3.1 Work Calculation

Since the force and Δy which is the difference between *y* coordinate initial and final for toe can be calculated, the amount of work produced while walking at different speed is calculated. In order to measure the work, force needed to change the coordinate of every joint must be known first. Here, the focus is on toe, knee, ankle and hip. The maximum ground reaction during heel contact, F_s , can go approximately 1.2 times body weight [5]. To calculate work produces the definition of work as the force acting with linear displacement is going to be used [3].

$$F_s = 1.2 * m * g \tag{5}$$

Where g = 9.81 m/s^2 and *m* is the mass of the subject. In this study, the mass of the subject is 57 kg. Work produced during heel strike is calculated using equation below [3]:

$$W = \int_{s_0}^{sf} F_s(s)\,ds \tag{6}$$

where: s_0 = Toe initial coordinate
s_f = Toe final coordinate

The data coordinate is in pixel coordinate. In order to convert the pixel unit to unit meter, the equalization between body length in pixel unit and in meter is used to synchronize the measurement. Figure 1 is the body fraction estimation due to the human height [17]. For this project, the height of the subject is 160 cm. In order to calibrate the pixel unit and meter unit, the actual distance between one human joint is to be considered.

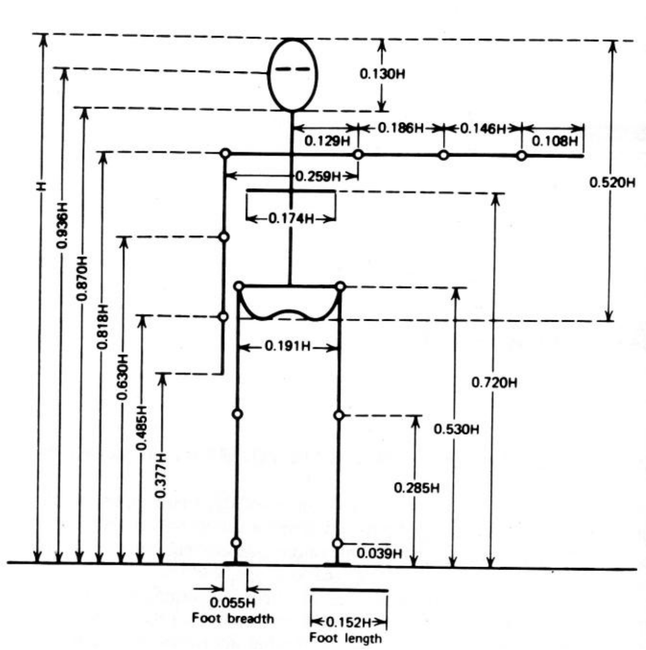


Figure 1: Body segment lengths as a fraction of the body height, H [16]

For example, from subject with height of 160 cm, the calculation to get the distance between knee and hip are:

Knee = 0.285H = 0.285(160) = 45.6cm
Hip = 0.485 H = 0.485(160) = 77.6cm
Hip – Knee = 77.6cm – 45.6cm= 32cm

Figure 2 show the location of every point of human joint marked by MATLAB as shown in Table 1. The initial coordinate of every point is a reference point to do the calculation of displacement when the subjects start to walk. By using the data given in Table 1 below, the distance between hip and knee in pixel unit can be calculated.

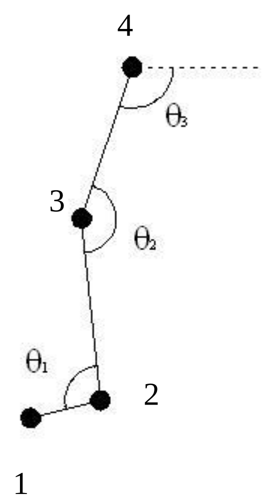


Figure 2: Two dimensional body reference point [16]

Table 1: The origin point of every joint [16]

Marker	Area	x-coordinate	y-coordinate
1 (toe)	131	214	429
2 (ankle)	175	286	411
3 (knee)	520	267	222
4 (hip)	611	319	65

Same as in meter unit, the difference between hip and knee in pixel unit need to be measured.

Hip – knee = 222-65 = 157 pixel

After getting the value of hip and knee distance in pixel unit and meter unit, the calibration is the equalization of the two units:

32 cm = 157 pixel
1 pixel= 0.203 cm

In order to get the distance value in meter unit, the difference between pixel units at one point is needed. For example, maximum ground reaction force for speed 1 km/h occurs at frame 21. At this frame, y-coordinate is at 428.55. The frame before which is at frame 20 indicate that the y-coordinate at this frame is 432.86. The difference between these points is:

$428.55 - 432.86 = -4.31$ pixel

Since the difference unit is in pixel, the force reaction is cannot be calculated. To convert the pixel unit in meter unit, the calculation below is needed:

$-4.31 \times 0.203cm = -0.875cm$

Next, the example to calculate work is as following:

$$F = 1.2 \times m \times g$$
$$W = 1.2 \times 57 \times 9.81 \times \frac{-0.875}{100}$$
$$W = -5.87N.m$$

3.2 Development of scavenging energy device

Piezoelectric sensor gives voltage in alternating form when given a force. Since many electronics devices use direct current to power them, the circuit to rectify an alternate current to direct current is needed. In this project, the circuit from [18] for non-adaptive harvesting circuit and [19] for adaptive harvesting circuit are considered initially for piezoelectric sensor. After doing a simulation using simulation software [20], the non-adaptive harvesting circuit is chosen as the signal conditioning for the piezoelectric sensor since it gives better value of output voltages. Moreover, non-adaptive harvesting circuit consists less components compared to adaptive harvesting circuit.

Figure 3 shows the MULTISIM software that has been used to test the circuit before developing it. After completely develop the virtual circuit, the circuit has been run using different sets of input voltage value (V_i) and constant frequency (f) to investigate the validity of the circuit and for comparing with the real circuit to be used in the experiment.

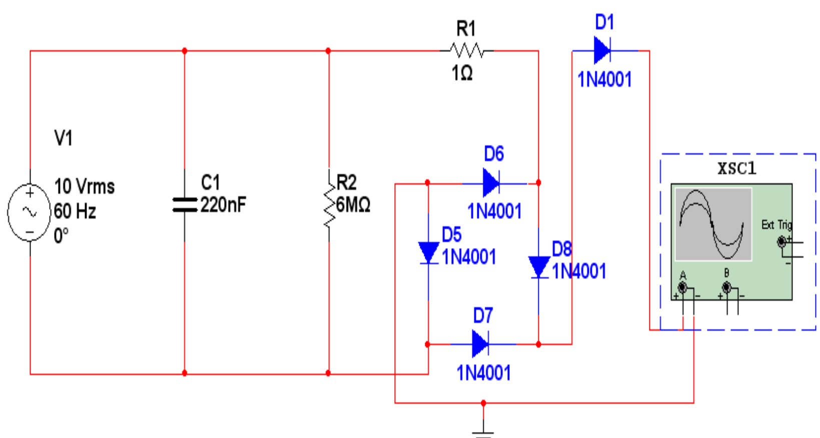


Figure 3: Circuit development using software

Figure 4 shows graphs of the adaptive harvesting simulation circuit with voltage output increases when frequencies increase. In relation to human motion, the results indicate that as the motion becomes faster, the voltage produced increases. To verify the simulation results, the circuit is built and tested using function generator as the input with the maximum voltage generated is 10 V. The frequency is varied to indicate the variation speed of human motion using the same frequencies and Figure 5 shows the graphs.

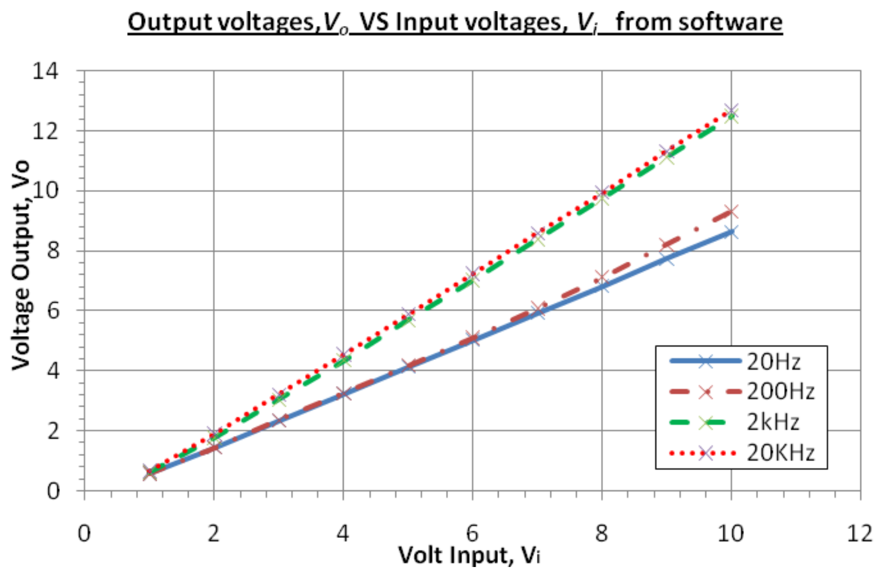


Figure 4: Voltages output vs. voltage input for different frequency using software

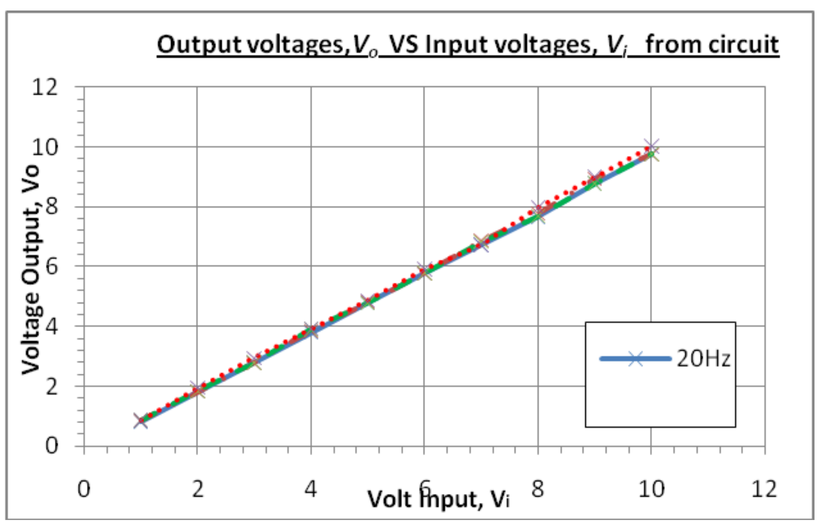


Figure 5 Output voltage outputs (*Vo*) vs. input voltage (*Vi*) for different frequency using circuit

3.3 Experimental Set-up

Initially, force sensor will be connected to KISTLER charging amplifier which already connect to DEWE-41-T-DSA. This hardware is connected to computer which has DEWESOFT 6.6.2 in order to measure the force produce while running on the force sensor. On the other hand, electronic parts like piezoelectric sensor attached to the subject's toe and the signal conditioning circuit were connected to National Instrument (NI) data acquisition (DAQ) along with its LabView software. The subject who performs stationary run on the force sensor with varies speed. The subject who performs a stationary run on the force sensor for this experiment is a male with 60 kg body weight. Since there is no speedometer used in this experiment, the velocity of the runner could not be constant and it is the drawback of this experiment. The polarity of the foot step may change during running. Figure 6 shows the experimental flow for the project.

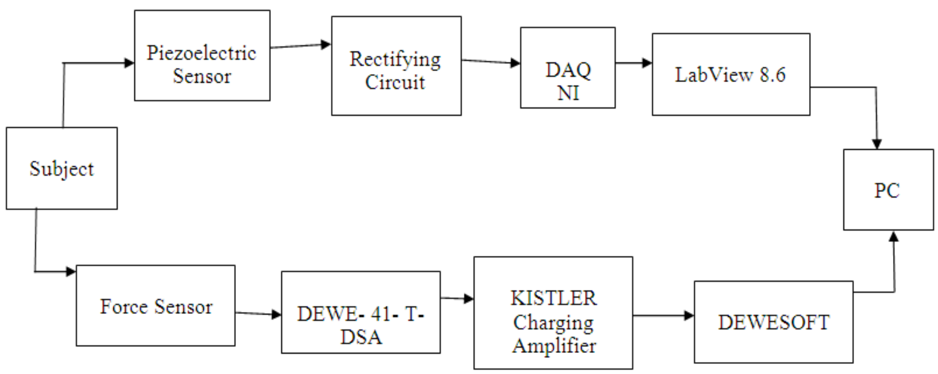


Figure 6: Schematic diagram for the overall experiment

4.0 RESULTS AND DISCUSSION

This chapter is basically the discussion about the result obtain from the theory calculation and actual experiment in section 4.1. The result of work calculated is used as comparison with the actual data obtains from experiment using piezoelectric device. In section 4.2, the experimental setup, results and data analysis on the developed scavenging energy device are presented.

4.1 Comparative studies

From the total data of 400 frames for three different speed adapted from [16], maximum reaction force occurs is determined. Tables 2 to 4 show the work data calculated from the formula of work as the force acting linear displacement using equation (5). Figures 7 to 9 show the graphs plotted from the work calculated. However, due to some limitation, only the work when the whole foot is on the ground can be measured. By comparison, work at speed 3 km/h shows the highest negative work which is 9 Nm compared to work at speed 2 km/h which is 8 Nm and at speed 1 km/h which is 6 Nm. In addition, maximum ground reaction force at speed 3 km/h can be found at more points compared to speed at 1 km/h and 2 km/h.

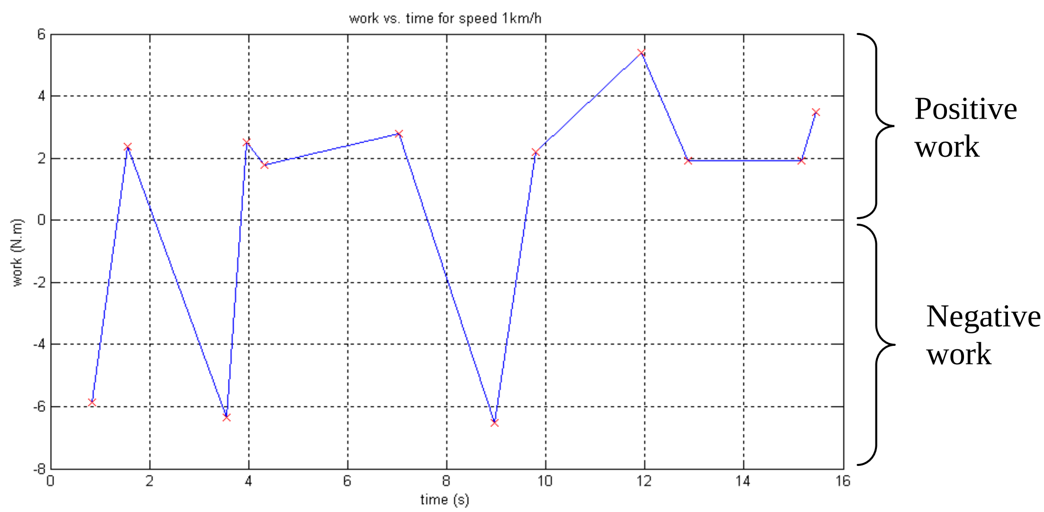


Figure 7: Work vs. time at speed of 1 km/h

Table 2: Work (Nm) generated at toe for speed 1 km/h

Time, s	Δd (pixel)	Δd (m)	$W = F \times \Delta d$
0.84	-4.31	-0.0087493	-5.8708
1.56	1.73	0.0035119	2.3565
3.56	-4.65	-0.0094395	-6.3339
3.96	1.84	0.0037352	2.5063
4.32	1.31	0.0026593	1.7844
7.04	2.04	0.0041412	2.7788
8.96	-4.8	-0.009744	-6.5382
9.8	1.61	0.0032683	2.1930
11.92	-3.97	-0.0080591	5.4077
12.88	1.41	0.0028623	1.9206
15.16	1.41	0.0028623	1.9206
15.44	2.55	0.0051765	3.4735

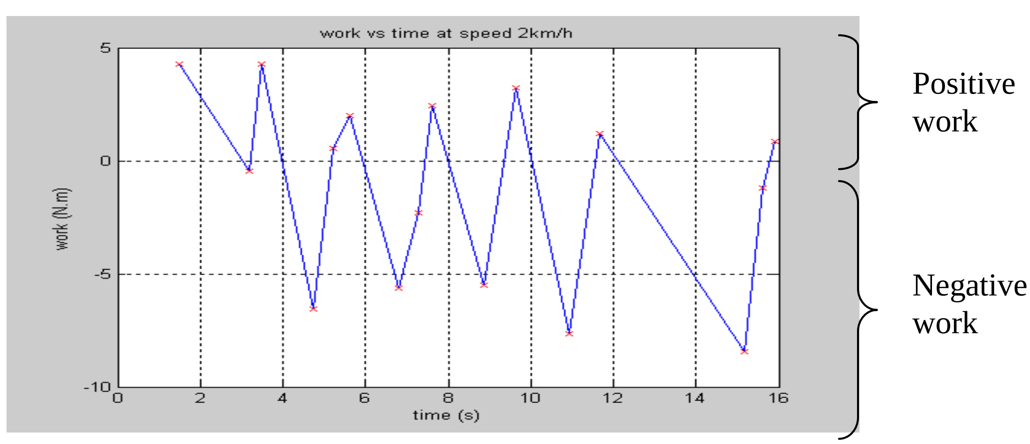


Figure: 8 Work vs. time at speed of 2 km/h

Table 3: Work (Nm) generated at toe for speed 2 km/h

Time, s	Δd (pixel)	Δd (m)	$W = F \times \Delta d$
1.48	3.14	0.0064	4.2944
3.2	-0.38	-0.000714	-0.4791
3.48	3.15	0.0064	4.2944
4.72	-4.83	-0.0098	-6.5758
5.2	0.4	0.000812	0.5449
5.64	1.5	0.003	2.0130
6.8	-4.13	-0.0084	-5.6364
7.28	-1.66	-0.0034	-2.2814
7.6	1.7	0.0036	2.4156
8.88	-4.03	-0.0082	-5.5022
9.64	2.37	0.0048	3.2208
10.92	-5.6	-0.0114	-7.6494
11.68	0.91	0.0018	1.2078
15.16	-6.2	-0.0126	-8.4547
15.6	-0.87	-0.0018	-1.2078
15.92	0.66	0.0013	0.8723

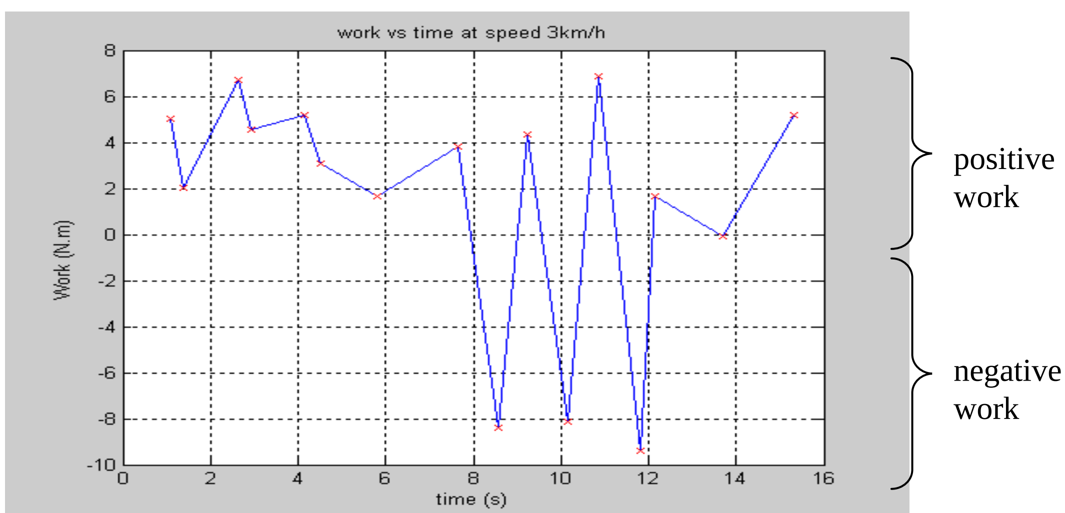


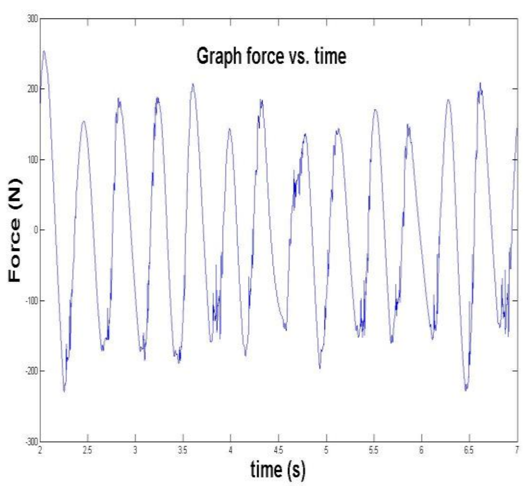
Figure: 9 Work vs. time at speed of 3 km/h

Table 4: Work (Nm) generated at toe for speed 3 km/h

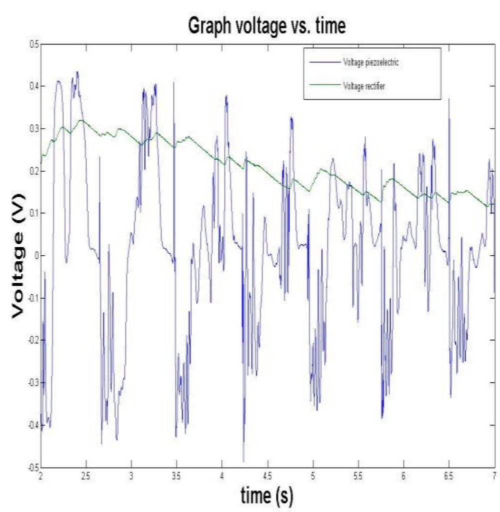
Time, s	Δd (pixel)	Δd (m)	$W = F \times \Delta d$
1.08	3.67	0.0075	5.0325
1.4	1.47	0.0030	2.0130
2.62	4.94	0.0100	6.7100
2.92	3.35	0.0068	4.5628
4.16	3.79	0.0077	5.1667
4.52	2.29	0.0046	3.0866
5.8	1.25	0.0025	1.6775
7.64	2.83	0.0057	3.8247
8.56	-6.15	-0.0125	-8.3875
9.24	3.21	0.0065	4.3615
10.16	-5.96	-0.0121	-8.1191
10.84	5.03	0.0102	6.8442
11.8	-6.89	-0.0140	-9.3941
12.16	1.25	0.0025	1.6775
13.68	-0.06	-0.0001218	-0.0817
15.32	3.81	0.0077	5.1667

4.2 Experimental Analysis on Scavenging Energy Device

After capturing force and voltage produce using DEWESOFT 6.6.2 and LabView, the data need to be analyzed and interpreted. In software setting, every one second time, 1000 data will be captured. Data from DEWESOFT and LabView are imported to MATLAB 6.5.1 for graph plotting. In order to analyze and compare, the data has been categorized into three parts according to the velocity of the runner. Using DEWESOFT, the step of the runner has been observed and it is found that the step speed varies from 1 step/sec, 2 steps/sec and 3 steps/sec



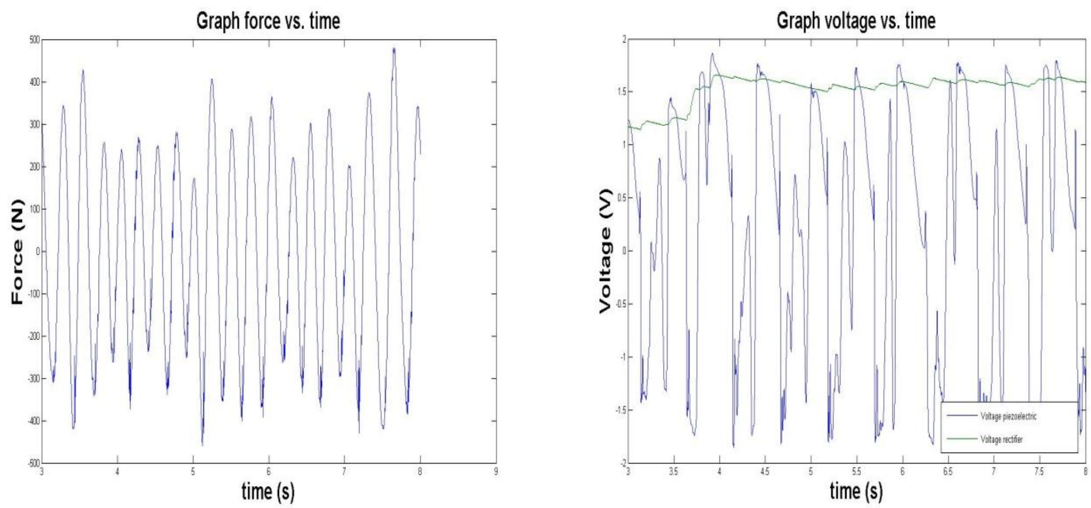
(a)



(b)

Figure 10: Force and voltage produce at speed of 1 step/sec

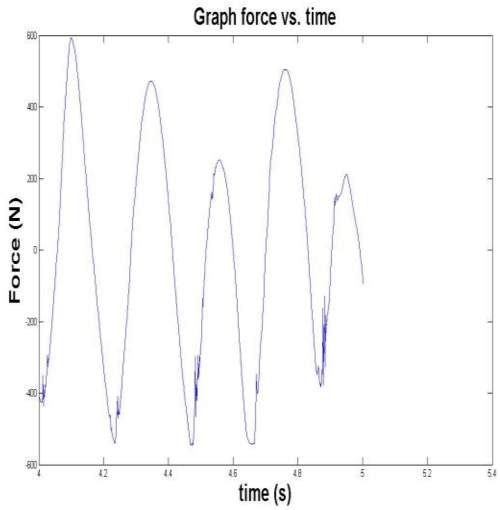
Figure 10a and 10b, show the force and voltage produce when subject run at speed 1 step/sec. Since the running speed of the subject is considered slow, the maximum force is about 200N. The voltage produced by piezoelectric also depends on the motion of the subject while running and thus it can be seen that the voltage produce is only about 0.4V. After rectifying, the voltage supplied to the capacitor is around 0.3V. Since the capacitor is used in this project, it is important to know the properties of a capacitor first. The current through a capacitor depends on the changing of voltage with time. Voltage rectifier is depending on voltage produce by piezoelectric sensor.



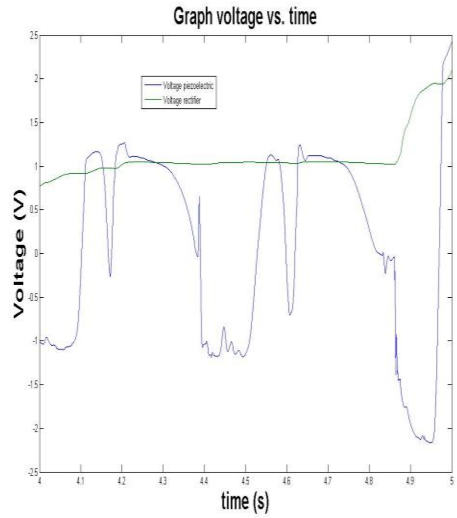
(a) (b)

Figure 11: Force and voltage produce at speed of 2 steps/sec

Figures 11a and 11b show the result of speed 2 steps/sec. As expected from based from previous data, the result that appear in this experiment is approximately the same like experiment before. The force produce is around 500N. At t = 3s to t = 8s, it can be seen that voltage through rectifier increase at this time and we expect it to keep increasing as time increase. The voltage between these times is constantly around 1.5V. However, with this value of voltage it is not enough to recharge a rechargeable battery.



(a)



(b)

Figure 12: Force and voltage produce at speed 3 steps/sec

Figure 12a and 12b show the force and voltage produced at speed of 3 steps/sec that occurred at t = 4s to t = 5s. Since the speed is increasing, it will give effect on the force value. This can be seen in the graph above. Comparing on data when 1 step/sec and 2 steps/sec, the force value at speed 3 steps/sec is very high which is around 600N. The voltage value suddenly increases from 0.7V to 2V. This data is different from others because the time taken for voltage to increase is very short. It may be because of the speed increase so it will stimulate the piezoelectric to vibrate faster than before.

5.0 CONCLUSIONS

The main objective of this project is to study and analyze the potential of piezoelectric sensor as a mean of scavenging energy from human daily motion. Some experiments have been conducted with a piezoelectric sensor being attached to the toe of the running subject and data are collected. The results show that the higher speed of running person, the more voltage is generated from piezoelectric sensor thus increased the voltage generated from rectifier to capacitor.

This study provides an initial understanding of scavenging wasted energy from human motion and converting into useful electrical energy. The study can be further extended to develop the energy conversion device by designing the actuator device. The device is then tested with different material, different motions with different human characteristics and activities.

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