Measurement and Survey of Energy Harvesting using Human Locomotion

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***Abstract*—From 2011 to 2021 smartphone ownership in the United States has grown from 35% to 85% [1] and is becoming an ever increasing part of the daily lives of many. On average a phone under moderate usage, such as web browsing, will last ∼ 10 hours [2] which is more than enough when you have ready access to a USB device charger. But given the ubiquitous use of smartphones, including during extended trips where a standard power supply is not available, other means of charging a mobile device need to be identified. In this study we will highlight the amount of potential kinetic and vibrational energy generated through walking and running using accelerometer measurements at the ankle, hip and wrist. Using this experimental data we then discuss potential current technologies that could be used for energy harvesting to charge a mobile personal device.**

I. Introduction

With the ongoing advancement in technology and reducing manufacturing cost, the computing devices are becoming ubiquitous and pervasive. The current model of using a battery to power each device cannot be sustained. There is a need to find sustainable source of power for these devices and identify alternative energy source to power these devices. Based on the environment, the energy can be harvested from several sources including, but not limited to, electromagnetic waves, heat and vibrations [3]. Figure 1 displays the taxonomy of potential sources of energy harvesting from the surroundings and external sources [4] [5].

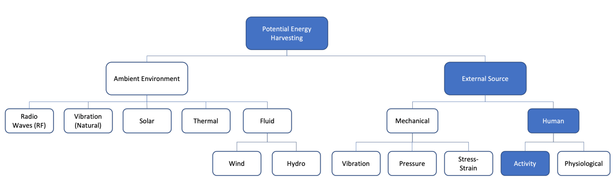

Fig. 1. Taxonomy of potential energy harvesting sources

Human body generates enormous amount of energy doing various activities which can be harvested. As established by Shi et al [6] by studying various human activities, the human body motion produces the most energy and can be harvested to power computing devices. This paper would focus on the energy harvesting technology from the Human activities specifically hiking. This paper will explore the landscape of the existing technologies to harvest energy based on human activities and verify it based on the data collected by the hiking activities.

II. Overview And Current Technologies

Energy harvesting based on the human walking provides opportunity to harvest both kinetic and potential energy and translates to mechanical energy (foot steps), inertia energy (body movement) and vibration energy.

Shi et al [6] summarized four different categories of technologies to harvest energy from human motion:

1) *Smart Materials Based Harvester:* Piezoelectric materials are example of smart material based harvester. Piezoelectric materials have the ability to generate electrical charge along the surface when applied with mechanical stress.
2) *Triboelectric Generator (TENG):* Triboelectric generators work based on the triboelectric effect which is electrification of two dissimilar materials after first coming into contact with each other and then separated.
3) *Electromagnetic Induction Generator:* Electromagnetic induction is the primary way to generate electricity by the creating an electromotive force across an electrical conductor in a changing magnetic field.
4) *Electrostatic Generator:* Electrostatic generator produce static electricity and can be leveraged to convert vibration energy into electricity [7].

Goal of this paper is to explore current technologies and propose energy harvesting approach to charge mobile phone while doing hiking as the human activity. As an example Openmoke Neo Freerunner (Android) phone uses 68.6 mW in suspended state, 268.8 mW in idle state and 320 mW for audio playback [8].

III. Methodology

A. Approach

The approach to achieve the goals for this paper is to first collect the data from hiking activities at different locations on the body and then use a model to convert that into an equivalent of the energy that can be harvested. The energy generated can then be compared with the total energy required to charge the mobile phone.

B. Data Collection and Measurement

To record our data, we attached a phone to the body with an elastic bandage to hold it in place. We attached the phone to three positions: 1) outside of the left lower leg just above the ankle, 2) outside of the left lower leg just below the knee, 3) outside of the left forearm just above the wrist. Each time we took approximately 40 steps in a fairly level parking lot.

In order to understand the potential energy accessible through various forms of human movement, experimental data was captured using an accelerometer. The accelerometer used had a sample rate of 400Hz and was used to gather data at the ankle, knee and wrist. The magnitude of the acceleration was calculated as $v = \sqrt{a_x^2 + a_y^2 + a_z^2}$ and a sixth order low pass Butterworth filter with a 5 Hz cut off [9] was applied to reduce the amount of noise created by extraneous effects such as sensor shaking (fig 1-6). The parameters for the Butterworth filter were derived by analyzing the lowerpass filter frequency response (fig 7). In order to understand the frequency of the accelerometer's motion the filtered data was analyzed using a Fast Fourier Transform (FFT) (fig 8-13). All of this analysis was combined into a single script give a more holistic view of the interactions between the sensor placement and the movement type [10].

C. Results

Using the Fast Fourier Transform to identify the frequency with the highest magnitude (table 1) showed that the different locations didn't have much effect on the most prominent frequency domain. What was interesting though was that when the sensor was on the knee while jogging there were also large spikes around the 2.5 Hz and 8.25 Hz domains whereas the sensor on the ankle while jogging showed a large spike only around the 2.5 Hz domain. There is the potential that certain energy harvesting techniques could harness this broader range of frequencies more efficiently and take advantage of the higher Hz found in the secondary spike found in the knee placement data. The maximum output power is calculated using general second-order spring mass systems [11] [12] [13] with the following assumptions that the frequency of the activity matches with the natural frequency of the system. Based on this formula the maximum power is directly proportional to the acceleration levels and inversely proportional to the frequency. With our experimental data, it was found that the sensor placed on the knee while jogging produced both the highest mean magnitude (24.15 m/s^2) and the highest frequency (5.04 Hz).

Table 1: Average Magnitude (m/s^2)

Sensor Position	Activity	Average Magnitude (m/s^2)
Ankle	Jog	17.79
Ankle	Walk	13.06
Knee	Jog	24.15
Knee	Walk	13.11
Wrist	Jog	13.62
Wrist	Walk	10

Table 2: Charge Time Based on FFT Frequency and 3500 mAh Battery

Sensor Position	Activity	FFT Frequency (Hz)	Max Current	Charge Time
Ankle	Jog	4.9	807 mA	4.3 hrs
Ankle	Walk	3.5	609 mA	5.7 hrs
Knee	Jog	5	1458 mA	2.4 hrs
Knee	Walk	3.5	614 mA	5.7 hrs
Wrist	Jog	4.9	473 mA	7.4 hrs
Wrist	Walk	3.6	347 mA	10.1 hrs

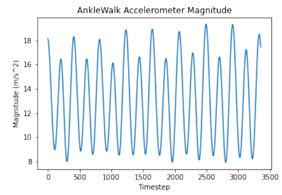

Fig. 2. Filtered data from the accelerometer placed on the ankle while walking

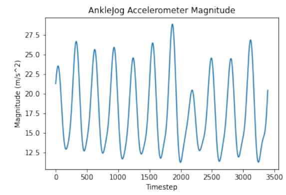

Fig. 3. Filtered data from the accelerometer placed on the ankle while jogging

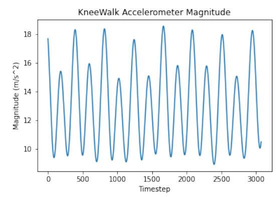

Fig. 4. Filtered data from the accelerometer placed on the knee while walking

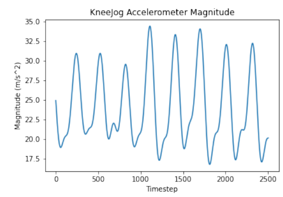

Fig. 5. Filtered data from the accelerometer placed on the knee while jogging

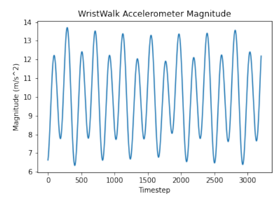

Fig. 6. Filtered data from the accelerometer placed on the wrist while walking

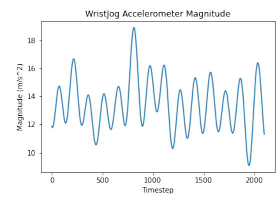

Fig. 7. Filtered data from the accelerometer placed on the wrist while jogging

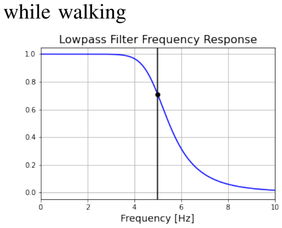

Fig. 8. Low Pass Frequency Response graph based on the ankle-jog accelerometer data

$$P = m\xi_e A^2 / 4\omega_n(\xi_e + \xi_m)^2$$

Fig. 9. Maximum Output Power Calculations

IV. Energy Harvesting Techniques and Energy Conversion

According to the standard of USB interface, the minimum operating voltage and current are 5V and 0.5A [14]. Therefore, it is important to convert the harvesting energy into this range, when we would like to charge the power-bank or mobile device via a USB cable. As described in earlier section, the total power requirement to charge the mobile phone is 1200mAh, 3.7 V, which is 4.44 Wh.

The following are the current energy harvesting techniques that can be leveraged to harvest energy from human activities.

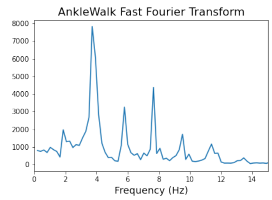

Fig. 10. Fast Fourier Transform from the accelerometer placed on the ankle while walking

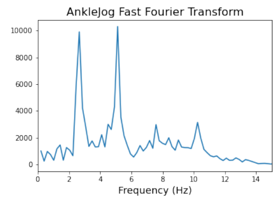

Fig. 11. Fast Fourier Transform data from the accelerometer placed on the ankle while jogging

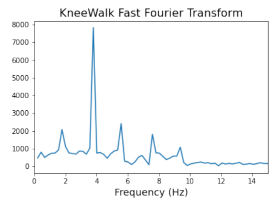

Fig. 12. Fast Fourier Transform from the accelerometer placed on the knee while walking

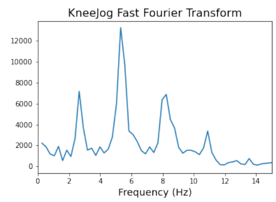

Fig. 13. Fast Fourier Transform from the accelerometer placed on the knee while jogging

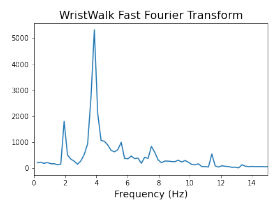

Fig. 14. Fast Fourier Transform from the accelerometer placed on the wrist while walking

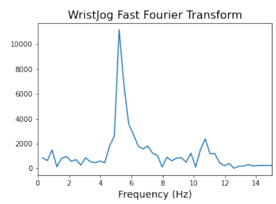

Fig. 15. Fast Fourier Transform from the accelerometer placed on the wrist while jogging

This section summarizes potential of each of these techniques to support the goal of charging the mobile phone while hiking.

A. Triboelectric Nanogenerator

Piezoelectric Materials vs Triboelectric Generator (TENG): Ahmed et al. [15] established that the TENG has higher potential for energy harvesting for frequency less than 4 Hz. [16] has demonstrated that the acoustic energy can be harvested at a rate of 0.144V/s, delivering a maximum power density of 121mW/m2 with a paper-thin TENG thickness of 125 µm and load resistance of 800kΩ. The mechanism is that the sound induced membrane vibration and vibration induced electricity generation. However, the experiment setting in the research showed that harvesting acoustic energy requires high frequency of 250Hz which does not fit to our use case. In order to solve this issue, we can build up an additional power management circuit to convert generated AC energy to DC power at low frequency [17]. With such setting, the generator is able to harvest random biomechanical energy at a constant of 1mW to charge electronics at 1 Hz of palm tapping.

B. Piezoelectric Energy Harvester

With piezoelectric energy harvester, the body motion can be efficiently converted into power. We have to consider the following criteria: 1) Mechanism of piezoelectric effect; 2) Energy conversion efficiency; 3) Proper selection of suitable materials; 4) Assembly of harvester; 5) Smooth the power output and 6) Coupling the power storage [18]. From the experiment, the harvester is able to harvest maximum current and voltage of 40nA and 0.25V, for an available total power output of 0.01mW at a tapping frequency is 3.2Hz. On the other hand, [19] has demonstrated the principle of converting kinetic energy into AC voltage using a piezoelectric transducer. The cantilevered beam is fixed one side and free on the other side. The AC voltage can be generated by the beam oscillation and a rectifier circuit converted it into regulated DC as useful power. Example shows that maximum of 0.01V are generated from such transducer. Although piezoelectric materials can generate voltage with light-weight device, it is not enough to power up a battery or a cell phone.

C. Mechanical Energy Harvester

Xie and Cai [20] propose a backpack harvester to harvest mechanical energy. For example, a backpack-based harvester can generate 10.6 W at a walking speed of 5.5km/hour with a 30kg external load / 0.353W per kg of load. Although the harvester is heavier and may cause burden to the hikers, it can ensure the power generation to the cell phone. As an alternative, the researcher also proposed a light-weight harvester prototype with only 95 grams, which can embed in a shoe. As a result, it can generate power of 1.15W at a higher walking speed of 125 steps/minutes.

Zeng and Khaligh [21] built an energy harvesting prototype using a permanent magnet sliding on a rail between two linear stators. Their prototype was 150mm x 27mm x 36mm and produced 497 mW, which is 3.4 mW per cm3. They proposed making a smaller version of the machine mounted in the sole of a shoe along the heel-toe axis. The machine could be made small enough to fit into the sole of a shoe with a reduction in the power output proportional to the decrease in volume.

D. Thermoelectric Generator

Yap et al [22] explored a thermoelectric generator, specifically the TEG1-4199-5.3 model manufactured by Tecteg. This TEG produced 30 microwatts per sq cm. Since it is 4cm x 4cm it can produce approximately 0.5 mW. As shown on the research, maximum voltage of 150mV can be harvested from single TEG. In order to reach the workable charging voltage, 2 step-up converters are used to convert voltage from 0.25V to 5V and it is useful to charge a mobile device. Several TEG modules could be used to increase power output, but they are noticeably cold to the touch by the user. When the skin temperature is cooled through thermal transfer, the TEG modules lose efficiency due to needing a minimum temperature difference between the hot and cold sides of the module.

Table 3: Charge Time @ 5V with 3500 mAh Battery

Energy Harvester	Current	Charge Time
TENG, Niu et al	0.2 mA	17500 hrs
Piezoelectric, Qi et al	2 mA	1750 hrs
Mechanical, Xie and Cai	230 mA	15.2 hrs
TEG, Yap et al	0.1 mA	35000 hrs

V. Discussion & Reflection

Our estimates of the maximum kinetic energy that can be harvested at the ankle, knee, and wrist are two to three orders of magnitude higher than actual values found in our research. This indicates a significant inefficiency in current harvesting technology. Comparing technologies found in the research, Triboelectric Nanogenerators [17] and Thermoelectric Generators [22] underperformed Piezoelectric [18] by at least 10 to 1. Mechanical harvesters proposed by Xie and Cai [20] were the best charging technology that we found, which outperformed Piezoelectric by more than 100 to 1. The disadvantage of mechanical harvesters is that they use permanent magnets which are very heavy.

A. Reflection

At the initial stages of our projects, we planned to research on different energy harvesting techniques and propose a hardware prototype based on our findings. We have chosen to use our smart phones as experiment devices to collect sensors data. We used that as our baseline reference since they could collect information for calculating corresponding kinetic and potential energies generated at different body locations. We were excited to apply what we have learned from the course in analyzing sensors data. However, we faced a challenge that only the acceleration data are useful in our collected data, and we had to spend extra effort to work on data processing and calculations due to the data noise and inconsistency. Considering the remaining time for our project, we decided to adjust our project plan and focused on solving the challenges instead of proposing a hardware prototype. At the end, we come up with a preliminary result, that today harvesting technologies are insufficient to provide power for mobile devices efficiently. We also explored a lot about the latest energy harvesting innovation in this project. This topic is highly related to ubiquitous computing as it helps resolving the frequent charging issues of wearable devices. Despite the limited time, this project could have further exploration on the hardware aspects, such as using different sensors and building prototypes to collect and analyze the actual generated powers.

VI. Conclusion

In this project, we determined the best body location for scavenging biomechanical energy into useful power for charging mobile devices. We collected sensors data at different body locations, preprocessed and converted the data into useful power, and analyzed the feasibility of charging a mobile device using the generated power and current technologies. According to our evaluations on human walking behaviors, energy harvester attached on someone's knee while jogging would generate the highest current of 11.65 mW. However, that level of generated power is insufficient, as it would require 1500 hours to charge a phone with 3500 mAh completely, according to our calculation. Nevertheless, the most efficient biomechanical energy harvesting gadget nowadays is the mechanical energy harvester, which can generate the highest current of 1.15 W, still needs 15.2 hours to charge the same phone completely. We concluded that today technologies are not matured enough to generate sufficient power to charge large mobile devices in a short period of time. However, they are still capable to support smaller devices such as sensors and actuators. This is useful for maintaining IoT devices, which is the trend of the future technical development.

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