Kinematic wearable energy comparison

Nicolas Ballesteros-Velasco[1*], Stephanie Garcia[1*], R. Lyle Hood[1,2], Gold Darr Hood[1]

[1]Department of Mechanical Engineering, *University of Texas at San Antonio*, San Antonio, TX 78249; [2]Joint Biomedical Engineering Program, *University of Texas at San Antonio* and *UT Health San Antonio*, San Antonio, TX 78249

Abstract: The growing consumer demand for sustainable energy has prompted the exploration of alternative energy systems. One technique that has recently been exploited is the harnessing of mechanical vibrations to produce clean, stable, and portable energy. The present research analyses two different methods that harness kinetic energy and convert it to electrical power: piezoelectric and inductive charging. Comparative analysis was conducted through experimentation with two representative designs, wherein the prototypes were attached to a volunteer and the power output was measured during ambulatory movement. It was hypothesized that energy harvesting through inductance would have a higher efficiency and power density than piezoelectrics. The final results exhibited that the piezoelectric converters were more efficient per weight in harvesting energy, refuting the hypothesis and claims from previous studies. The overall power output per weight results demonstrated that piezoelectric strips were the most efficient prototype during participant running with respect to power density, which was measured at 0.553 W/kg. In contrast, the inductance-based prototype had a measured power density of 0.0091W/kg. Piezoelectrics are a more marketable and effective mechanism, due to their greater portability and flexibility in configuration. Electromagnetic inductance suffers by comparison due to design and manufacturing complexity. As the cost associated with piezoelectrics declines, this technology has the potential to build a new market in both attire and charging solutions for handheld devices.

1. Background

Embedded wearable technology is an exciting and relatively new application of smart materials, seeking to harvest the energy of human movement to increase battery life of electronics. The two leading technologies currently researched today for kinetic energy harvesting through wearable technology are piezoelectrics and electromagnetic inductors [1]. Piezoelectric generators create electricity when they are subjected to mechanical stress, creating a charge during strain resulting in an electric field. Piezoelectric research shows that energy can be harvested from ambient vibrations to generate sustainable power. Several studies and experiments have been conducted to investigate the efficiency of harvesting energy via piezoelectric generators. Experiments conducted by Swallow *et al.* leveraged an innovative, custom-built piezoelectric generator, which was tested by mounting onto a vibrating beam structure. Results showed that piezoelectrics produce sufficient voltage output to power wearable microsystems. The team proposed future work seeking to integrate their design into an energy harvesting glove [2]. In 2013, Zu and Su published an investigation studying piezoelectric energy harvesting from oscillating beams [6]. The research showed that a piezoelectric generator mounted on a simply supported beam can produce electrical power when subjected to compressive dynamic loading [6].

Currently, the most commonly employed kinetic energy harvesters are based on electromagnetic inductance. Electromagnetic generators leverage induction, which is voltage production from the relative motion of the magnetic flux gradient caused by a conductor's movement. This induced voltage is proportional to the temporal rate of change in the magnetic flux [5]. A study published by Janky *et al.* in 2004 investigated harnessing electrical energy produced by the ambient vibrational motion of moving vehicles through conversion into electromagnetic power [4]. These types of ambient vibration generators have resulted in numerous issued patents to the aforementioned research team and may offer the ability to substantially extend battery life for many electrically powered devices, particularly in wearable or handheld applications. In another example, Steve Vetorino of Applied Innovative Technologies developed the first magnetic-force flashlight. Vetorino's straightforward approach induces current and stores it in a capacitor through simple manual oscillation of the flashlight. The capacitor then delivers the power to an LED, yielding 20 minutes of light for 30 seconds of manual perturbation [8]. These are just a few examples of inductor-based energy harvesting, which is becoming increasingly more feasible and correspondingly increasing in market circulation.

Although both piezoelectric and inductor-based energy harvesting have been extensively studied, few researchers have compared the two energy production methods directly. Specifically, this investigation seeks to ascertain which generator can yield a higher power output efficiency, in terms of power output per weight (controlled for cost), when used to harvest energy from human motion. Drawing from prior studies, the study hypothesis is that dynamic induction will harvest and convert electrical energy from the kinetic motion of an ambulatory subject more efficiently than a piezoelectric generator [3]. This hypothesis was assessed through attaching inductance and piezoelectric prototypes to a volunteer during semi-controlled ambulatory movement.

2. Methodology

2.1 Study Design

Generated power was measured during the ambulatory motion of a consistent volunteer. For these experiments, the electrical mechanisms were wired directly into a multimeter that simultaneously recorded the voltage, current, and power output during each trial. Specifically, the data recorded monitors output from a subject exercising on a treadmill. Exercise was conducted by consistent pacing on a treadmill (8-minute mile pace) for 1-minute intervals, a total of 8 runs were recorded. Measurement began once critical speed was reached and maintained constant.

2.2 Generator Hardware Selection

To properly control for commercial applicability, each of the electromagnetic inductance or piezoelectric prototypes were constrained to a nearly identical cost. All the materials used in order to evaluate the power of the piezoelectric generators, two different forms of hardware were used. The first was a piezoceramic disk (GOE-3301, manufactured by Geodrum) with 35x0.58mm dimensions, weighing 9.9g. This prototype produced voltage derived from pressure applied from the subject's heel. The second was a piezo film (605-000004, manufactured by Parallax,) with dimensions of 0.98x0.52mm and a weight of 1.7g. The film was made from flexible, synthetic polymers and was attached to the subject's hip to produce power from distortion generated during locomotion. Analyzing the behavior of the voltage produced by both normal (perpendicular) pressure and flexion allowed for variability in measurement when testing the piezoelectric energy generation method. Both of these mechanisms were selected due to their ability to harvest energy from weight transfer and vibrational movement while the test subject was running.

2.3 Generator Placement

To provide power generation without disturbing gait, the piezoelectric ceramic disks were placed beneath the test subject's right and left plantar fascia. Previous studies have demonstrated that the anatomy of the plantar fascia provides maximum pressure density directed to propulsion that is needed for the experimental running gait, which is likely to result in maximum energy transfer [6].

The piezo films were secured at the subject's right hip and are activated by lateral flexion. These were positioned at different local maxima of torque while the human body is in motion to compare which location resulted in higher energy production: the mid-bicep or hip. As seen in *figure 1A*, the piezoelectric generator, denoted as "S", was attached to the deltoid of the test subject.

Kinetic energy is directly related to velocity and acceleration of the runner's body mass. The hip was chosen as one of the focal points for measuring the energy produced by the piezoelectric strip due to the range of hip motion increasing as the gait lengthens, thus increasing energy expended. It should be noted, however, that at a steady pace, an increase in flexion results in a decrease in total leg extension. The piezoelectric generator attached on the hip of the test subject, denoted as "H", is shown in *figure 1B*. The only physical modification made to both S and H generators was a pair of Magcraft Rare Earth 19.05x3.18mm magnets placed on the ends of the piezoelectric films to provide additional momentum during movement without piercing the generator.

As inductors generate energy most efficiently via linear translation, the ankle was selected as a stable point of maximum translation on which to affix the prototype, as shown in *figure 1C*. To properly secure the prototype to the subject under dynamic constraints, sweat resistant athletic scotch tape was used as additional support to minimize energy loss from reactionary vibration. The inductive generator was custom designed and built with common off the shelf (COTS) components in order to accommodate for the geometric and physical limitations of the design. The design was constrained to efficiently harness single axis movement. It was placed horizontally on the side of the foot (talus), parallel to the sole of the test subject. The inductive coil was housed in a cylindrical casing 3D printed using polylactic acid (PLA). The casing accommodated a 1-inch diameter copper coil spanning 4 inches in length made from a 14 American Wire Gage (AWG) copper wire. The electromagnetic inductor design is exhibited in *Figure 2B*. The composition of the design was intended for effective energy production while maintaining a feasible level of comfort for the test subject.

2.4 Data Collection

In order to render each prototype wearable for the test subject, a 14 AWG copper wire was soldered to each generator tested and wired to a Morris Products Digital 600-voltmeter (Model #57030). The voltmeter was directly connected to a system running data capture software. These measurements were recorded and plotted in LabVIEW 2017 SP1 (64-bit). The multimeter was also connected directly to a system running MATLAB R2016a to record data, including highlighted peak values, into a matrix for analysis.

3. Results and Discussion

3.1 Results

Experiments sought to determine the amount of power produced by each harvesting technique. *Figure 3* depicts the power produced for each modality during the subject's motion. *Figure 4* and *Figure 5* depicts the raw data for the inductors and piezo strip generators, *Figures 6-9* exhibit the peak values in voltage and current measured over time. These demonstrate a clear demarcation in output for the energy harvesting methods: the piezoelectric ceramic disks produced the least amount of power, equating to 0.19 mW per minute trial. The piezoelectric strips on the shoulder equated to 0.55 mW per minute trial. The piezoelectric strip placed on the hip harvested 0.94 mW per minute trial. The Inductor produced 1.96 mW per minute trial. Normalized per weight, the power density values were calculated to be 0.01, 0.02, and 0.55 W/kg for the inductor, piezoelectric disk, and piezoelectric strip, respectively.

	Kg	mW/min	W/kg/min
Inductor	0.215	1.96	0.00910
Piezo Disk	0.00907	0.193	0.0209
Piezo S	0.00170	0.547	0.321
Piezo H	0.00170	0.940	0.552

3.2 Discussion

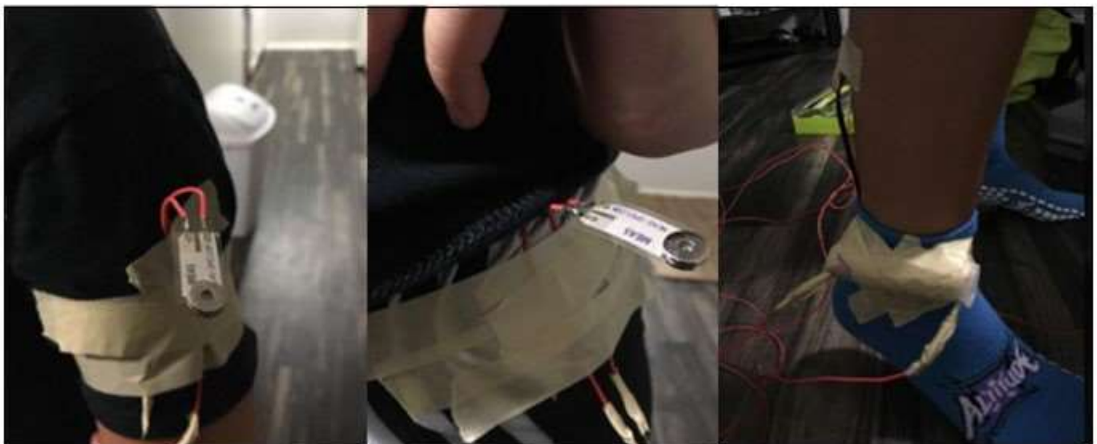
The generators were very sensitive to placement, as irregularities or difficulties in proper isolation of movement may have resulted in some deviation in recorded data. For example, the electromagnetic inductor was attached to the ankle of the test subject, which follows a pendulum- like path of motion during running. As the inductor's axis was parallel to the sole of the foot, the out of axis effects of gravity and momentum caused losses of kinetic energy. Although controlled for both total time and pace, the length of generator path traveled is variable with stride length, resulting in fewer oscillations per unit time for the inductor relative to the piezoelectric strips. This difference in operational frequency between the generator modalities can be observed in *Figures 4* and *5*. The study demonstrated that although the inductor did in fact generate more overall power, the power to weight density was far superior for piezoelectric technology as shown in *Figure 3*. It is noted that other studies mainly focused on obtaining the power harvested due to the frequency, however analyzing the power density by weight in order to determine efficiency yielded better results. The prototype produced in this study had a mass of 0.215 kg, length of 10.2 cm, and generated 1.96 mW. The inductor described in DePasquele *et al.* had a length of 6.6 cm, and generated 2.1 mW/min [3]. The in-house manufactured inductor produced nearly 3X the power given a little less than twice the length of the other inductor. Of greater import is that the piezoelectrics tested had a far greater power to weight ratio. The piezo sensor S generated 0.321 W/kg and piezo sensor H produced 0.552 W/kg, relative to the DePasquele *et al.* device which produced 0.23 W/kg [3]. One limitation to note is that, due to the exceptionally high resistance within the piezoelectric disks, some voltage readings were minorly differentiated or potentially not recorded, as they were at the edge of the voltmeter sensing threshold. In *Figure 10*, it can be seen that the current to voltage ratio of the disk is extremely low.

4. Conclusion

This study provided a direct comparison on the energy harvesting capability of inductors and two different varieties of piezoelectrics. Results demonstrated that the inductance harvester generated more energy over the course of 1 minute of running. However, the study hypothesis was that the inductance harvester would generate more power per weight, and as the inductor was far heavier, analysis showed that the piezoelectric strips were more than 50 times more efficient by this metric. These findings have important implications for design choices in the development of wearable electronics.

Appendices

Activity Pictures



A. Piezoelectric strip attached at deltoid. | **B. Piezoelectric strip attached at hip** | **C. Inductor attached at ankle & Piezo disk connected at heel.**

Figure 1.

A. Sensors and Materials. | **B. Internal copper coil inside of the inductor.**

Figure 2.

Data

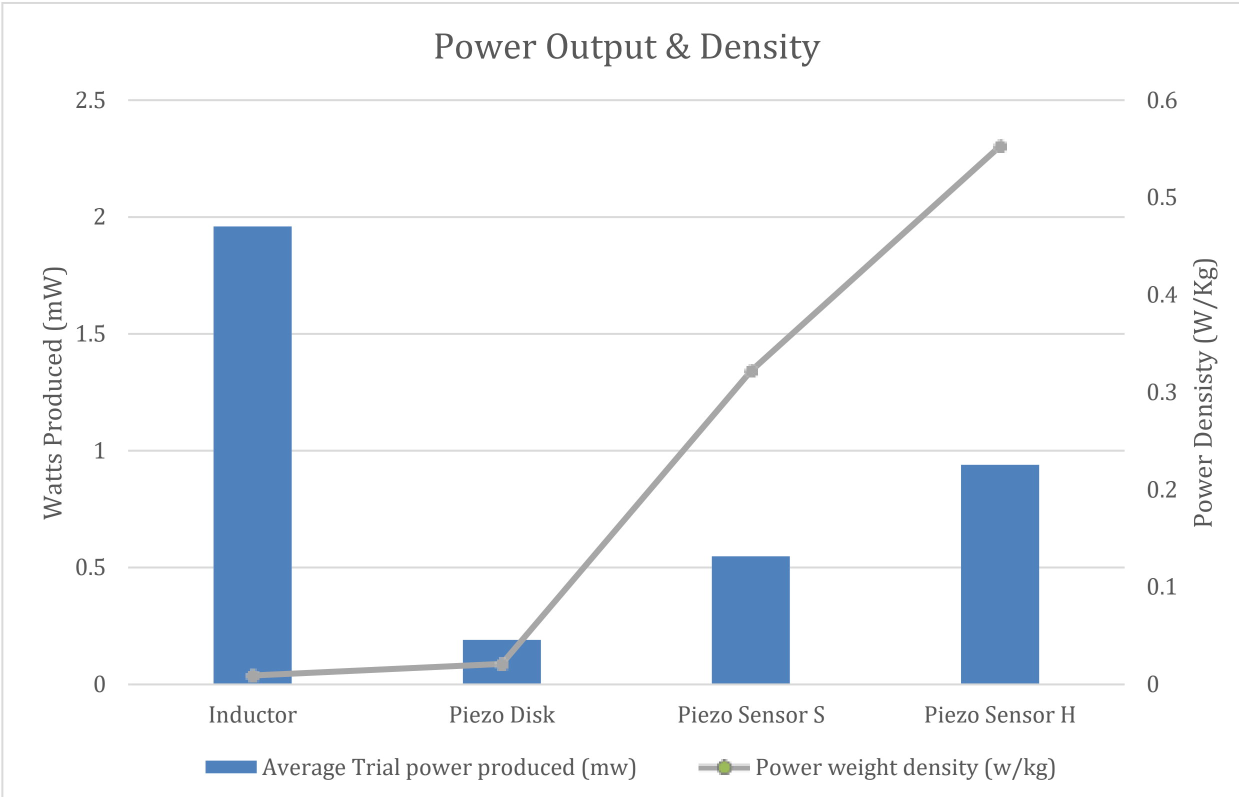


Figure 3. *Total power output comparison chart of the tested generators*

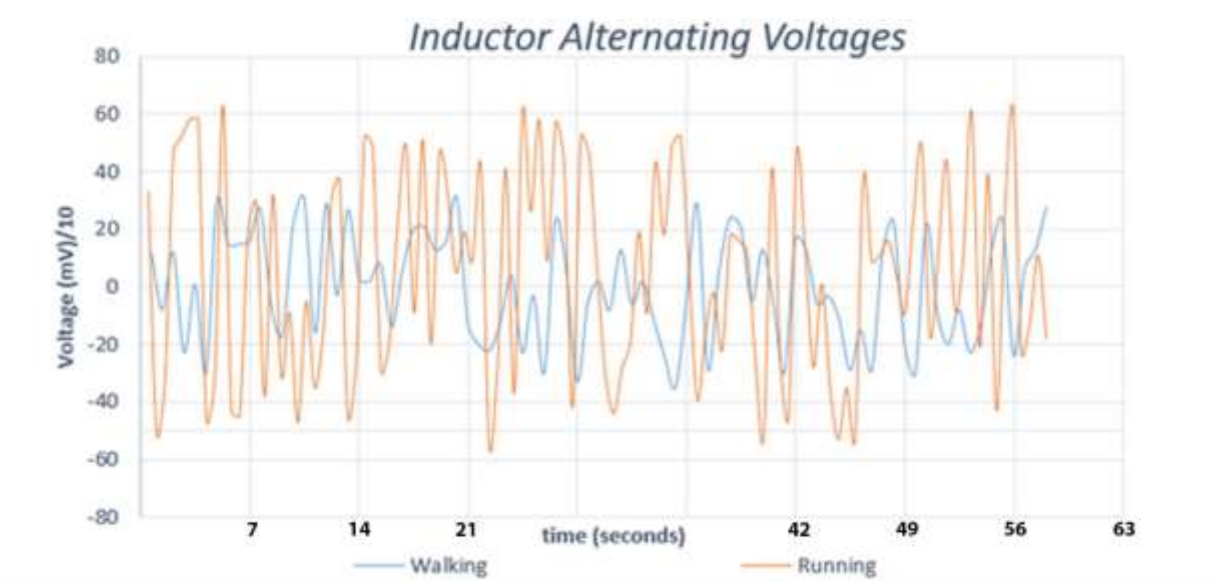


Figure 4. *Raw Inductor Voltage signal chart, average data for all 8- 1min trials.*

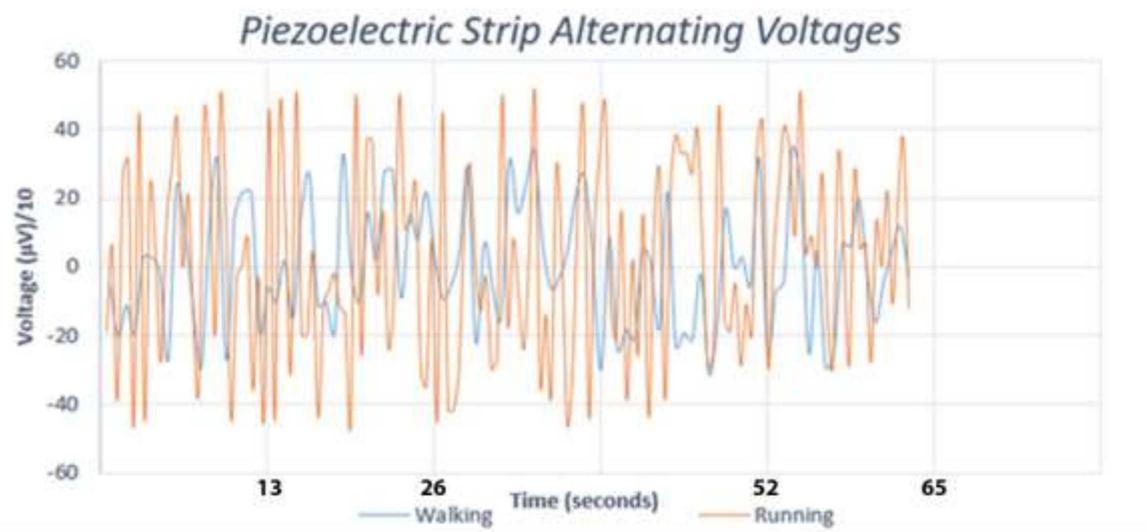


Figure 5. *Raw Piezoelectric strip signal chart, average data for all 8- 1min trials.*

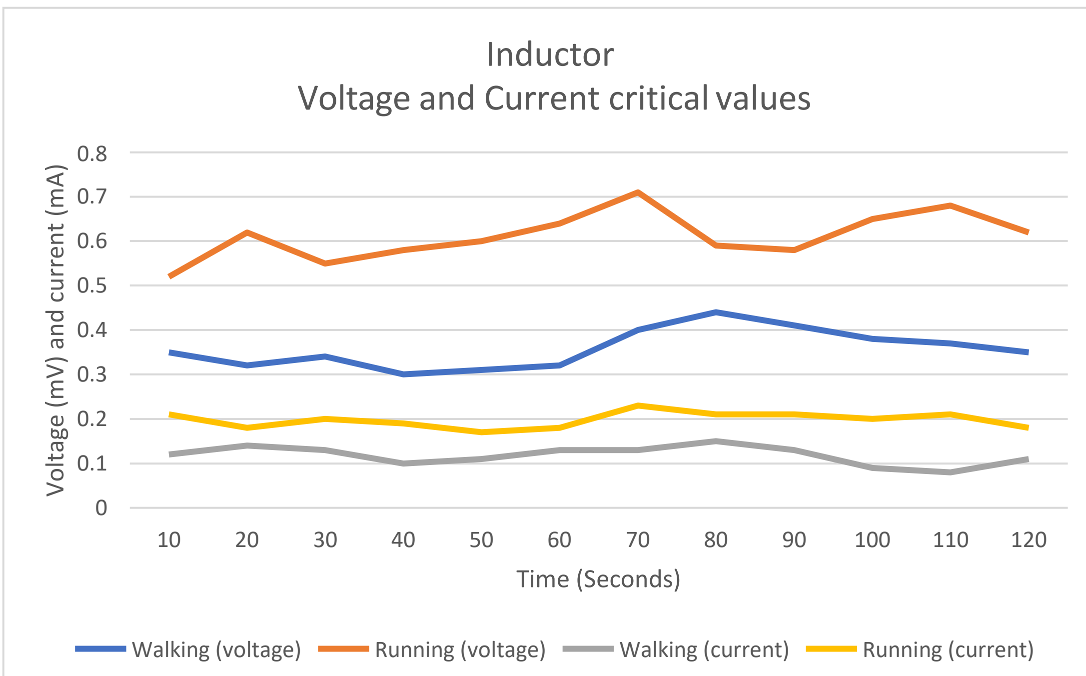


Figure 6. *Critical Values of Inductor*

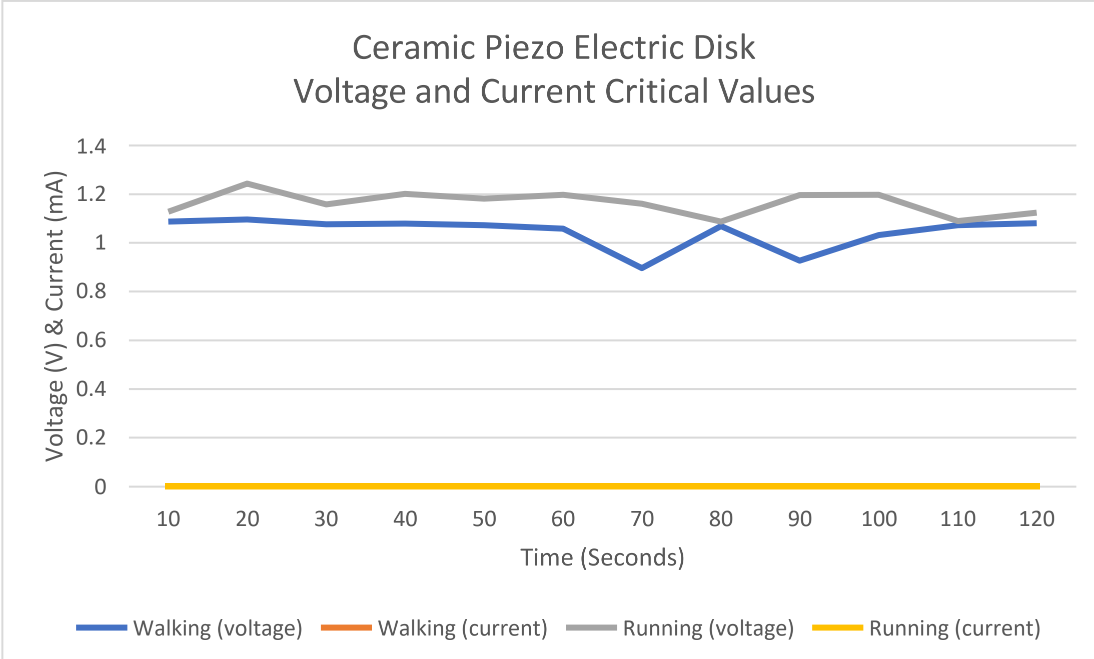


Figure 7. *Critical Values of Piezoelectric disk*

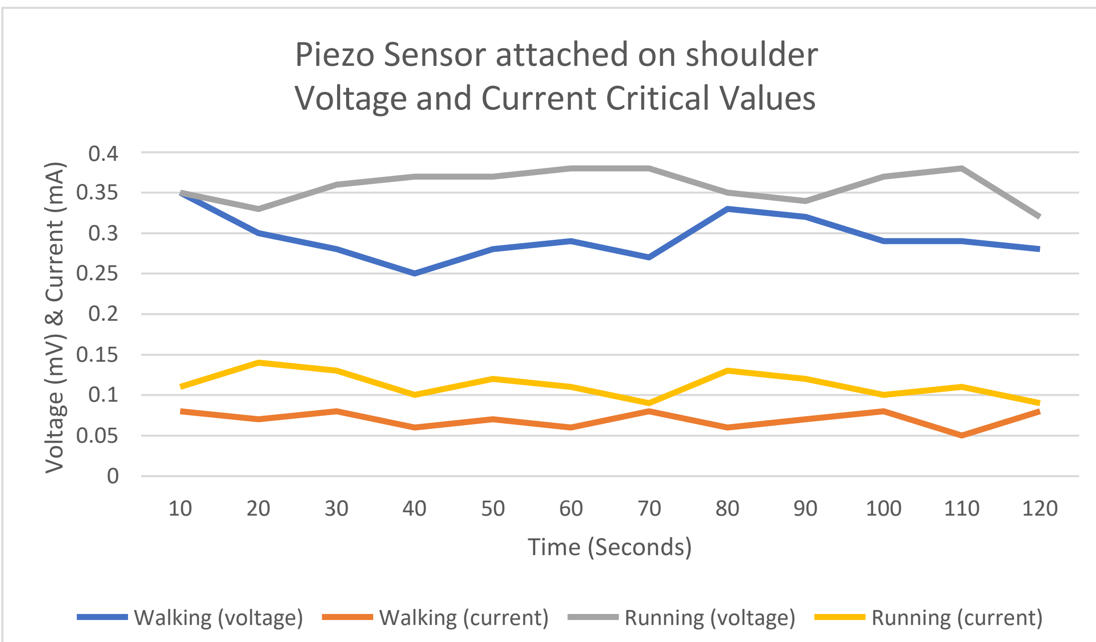


Figure 8. *Critical Values of Piezoelectric strip attached on shoulder*

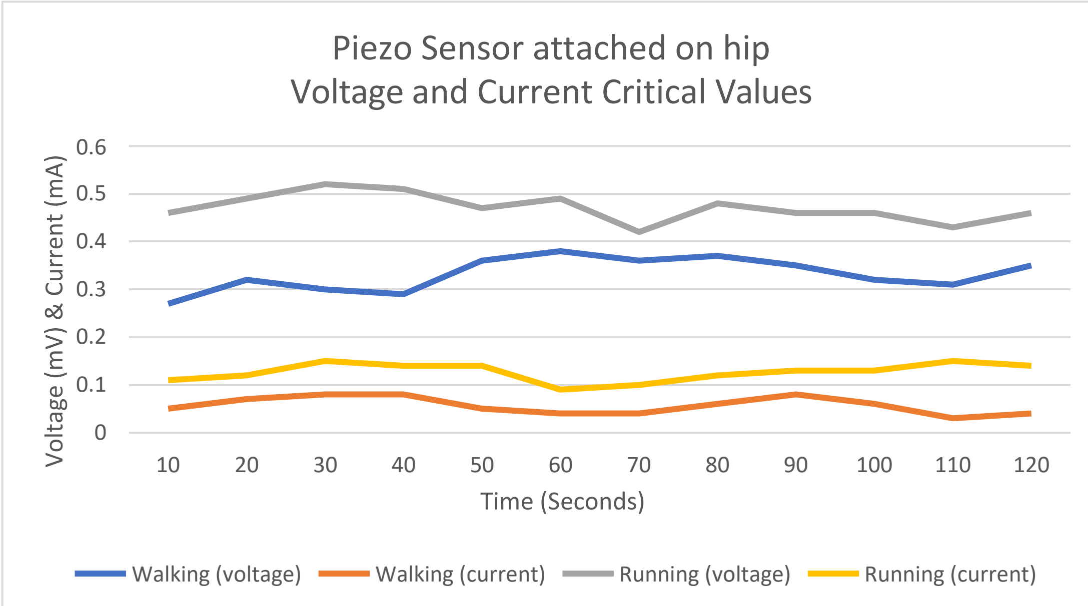


Figure 9. *Critical Values of Piezoelectric strip attached to hip*

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