Energy Harvesting From Piezoelectric Materials Fully Integrated in Footwear

J. G. Rocha, L. M. Goncalves, P. F. Rocha, M. P. Silva, S. Lanceros-Méndez

Abstract- **In the last few years it has been an increasing demand of low power and portable energy sources due to the development and mass consumption of portable electronic devices. Further, the portable energy sources must be associated with environmental issues and imposed regulations. These demands support the research in the areas of portable energy generation methods. In this scope, piezoelectric materials become a strong candidate for energy generation and storage in future applications. This article describes the use of piezoelectric polymers in order to harvest energy from people walking and the fabrication of a shoe capable of generating and accumulating the energy. In this scope, electroactive β–PVDF used as energy harvesting element was introduced into a bicolor sole prepared by injection, together with the electronic needed to increase energy transfer and storage efficiency. An electrostatic generator was also included in order to increase energy harvesting.**

I. INTRODUCTION

As low power and wearable electronic devices are more and more present in our every-day life, there is a growing need for the delivery of power to different points of the human body. Table 1 shows the approximate energy consumption for one hour of operation of some portable devices that can be considered as possible applications of the energy generated by our system.

Table 1 Approximated energy consumption for one hour of operation of some portable devices

Device	Energy
Heart rate meter	3 J
Respiratory rate meter	3 J
MP3 Player	350 J
Mobile phone (conversation)	2800 J
Mobile phone (standby)	150 J

Another interesting application is a posture monitoring system of the human body presented by Silva et. al. [1]. The posture monitor system is composed of five sensing modules; two located on upper-members, two on lower member and one on the spine, as shown in Fig 1. The detection algorithm uses the gravitational force to detect inclination, and the earth magnetic field to measure the rotation of the body about the axis perpendicular to the gravity field. The total energy consumption of the suit is near 20 J per operating hour.

The delivery of power to different points of the human body can be performed by batteries and wires, which incentivizes the development of more efficient, light and long lasting batteries.

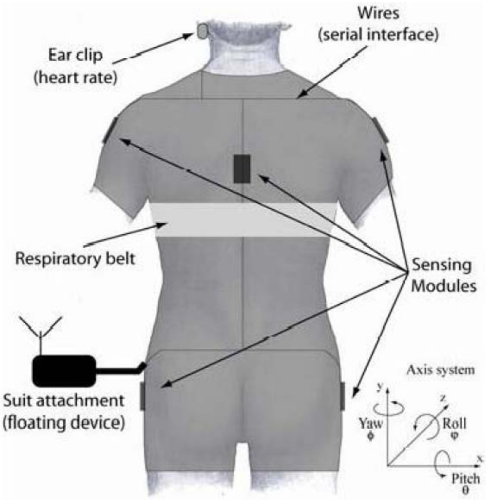

Fig. 1: Location of the sensing modules in suit[1].

It can also stimulate the research in the field of energy generation, in order to produce energy close to the point in which it will be used. In this case, energy storage might not be necessary at all.

As power requirements of most modern electronic portable devices are decreasing, it becomes possible to use the energy harvesting from human body activity, in order to power these devices. Table 2 compares the main characteristics of several portable power sources [2, 3].

II. MOTIVATION

As it is shown in table 2, vibration-based devices compare well to other potential energy-scavenging sources, including batteries, fuel cells, and solar, temperature, and pressure devices.

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Table 2: Comparison between portable energy and power sources [3].

Power Source	**Power ($\mu W/cm^3$)**	**Energy (J/cm^3)**	**Power/yr ($\mu W/cm^3/yr$)**	**Need of secondary Storage**	**Need of Voltage regulation**	**Commercially available**
Primary battery	N/A	2880	90	No	No	Yes
Secondary battery	N/A	1080	34	N/A	No	Yes
Micro fuel cell	N/A	3500	110	Maybe	Maybe	No
Ultracapacitor	N/A	50-100	1.6-3.2	No	Yes	Yes
Heat engine	10^6	3346	106	Yes	Yes	No
Radioactive (^{63}Ni)	0.52	1,640	0.52	Yes	Yes	No
Solar (outside)	15000[1]	N/A	N/A	Usually	Maybe	Yes
Solar (inside)	10[1]	N/A	N/A	Usually	Maybe	Yes
Temperature	40[1,2]	N/A	N/A	Usually	Maybe	Soon
Human power	330	N/A	N/A	Yes	Yes	No
Air flow	380[3]	N/A	N/A	Yes	Yes	No
Pressure variation	17[4]	N/A	N/A	Yes	Yes	No
Vibrations	375	N/A	N/A	Yes	Yes	No

[1] Measured in power per square centimeter, rather than power per cubic centimeter.

[2] Demonstrated from a 5ºC temperature differential.

[3] Assumes an air velocity of 5 m/s and 5 percent conversion efficiency.

[4] Based on 1 cm^3 closed volume of helium undergoing a 10ºC change once a day.

Researchers have successfully built and tested vibration-based generators using three types of electromechanical transducers: Electromagnetic [4], electrostatic [5], and piezoelectric [6, 7]. All of them are based on the same principle: To convert mechanical energy into electrical energy one should be able to realize a movement between the mechanical parts of the generator (e.g. the rotor and the stator of a macroscopic generator). Vibrations consist however of a travelling wave in or on a solid material and it is often not possible to find a relative movement within the reach of a small generator.Therefore one has to couple the vibration movement to the generator by means of the inertia of a seismic mass. Fig. 2 shows a seismic mass connected to an energy generator. The mass is also connected to the outside world by means of a suspension/damping system.

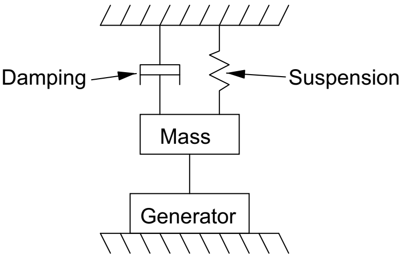

Fig. 2: Schematic diagram of a vibration scavenger [8].

A. *Electromagnetic generators*

In electromagnetic generators an electromotive force (emf) is induced across a coil if the magnetic flux coupled to the inductor changes as a function of time. The relationship between this emf and the displacement of the mass depends on the design of the system. An expression that relates the emf with the displacement (z) can be written as [8]:

$$emf = K\frac{dz}{dt} \tag{1}$$

where K is a constant that depends on the number of turns of the coil, their length, area and shape, and the magnetic field intensity. A similar relationship exists between the mechanical force on the coil and the current through it:

$$F = Ki \tag{2}$$

Notice that the factor K in equations (1) and (2) needs to be identical for energy conservation. Compact systems for low power applications based on small magnets have been demonstrated, including capacitive energy storage components [9, 10].

B. *Electrostatic generators*

An electrostatic generator consists of a capacitor whose value changes as a function of the displacement. The electrical current is given by [8]:

$$I = V_o\frac{dC(z)}{dt} + C(z)\frac{dV}{dt} \tag{3}$$

where V and V_o represent the voltage across the charged capacitor and its initial value respectively. The first term at the right side of equation (3) represents the electromechanical coupling, while the second term describes the electrical behavior of the capacitor. Notice that the electromechanical coupling is enhanced when the capacitor is biased with a voltage V_o. This polarization of the capacitor can either be reached by pre-loading the capacitor [11], by using electrets [12], or by using piezoelectric elements, which is the main innovation of this work and will be analyzed in the following sections of this article.

C. *Piezoelectric generators*

There are two types of piezoelectric signals that can be used for technological applications: the direct piezoelectric effect that describes the ability of a given material to transform mechanical strain into electrical signals; and the converse effect, which is the ability to convert an applied electrical solicitation into mechanical energy. The direct piezoelectric effect is more suitable for sensor applications, whereas the converse piezoelectric effect is most of the times required for actuator applications [13]. So, it can be stated, that a material is called piezoelectric when it shows the ability to transform electrical into mechanical energy and conversely, mechanical into electrical energy.

Mathematically, the piezoelectric charge (strain) coefficients predict, for small stress (or strain) levels, the surface charge density originated by external stress. In the charge mode and under conditions approaching a short circuit, the generated charge density is given by:

$$D = \frac{Q}{A} = d_{3n} F_n, \quad (n = 1,2,3) \tag{4}$$

where D is the surface charge density developed, Q the charge developed, A the conductive electrode area, d_{3n} the appropriate piezoelectric coefficient for the axis of applied stress or strain and X_n the stress applied in the relevant direction. The mechanical axis n of the applied stress (or strain), by convention, is 1 for length (or stretch) direction, 2 for width (or transverse) direction and 3 for thickness direction.

In the voltage mode, the emf is given by:

$$emf = g_{3n} F_n t, \quad (n = 1,2,3) \tag{5}$$

where g_{3n} is the appropriate voltage piezoelectric coefficient for the axis of applied stress and t the film thickness [14].

Table 3 compares the three generator principles on the basis of two energy densities [2, 3]. Practical values represent what is currently achievable with standard materials and processes, while aggressive values represent what is theoretically possible. In addition to energy density, three further considerations affect transducer technology selection: electrostatic transducers are more readily implemented in standard micro-machining processes; electrostatic transducers require a separate voltage source (such as a battery) to begin the conversion cycle; and electromagnetic transducers typically output AC voltages well below 1 volt in magnitude.

Table 3: Energy storage density comparison.

Type	**Practical Maximum (mJ/cm^3)**	**Aggressive Maximum (mJ/cm^3)**
Piezoelectric	35.4	335
Electrostatic	4	44
Electromagnetic	24.8	400

Based on the data presented in Table 3 and on the constraints of the application, we decided to focus our work on both piezoelectric and electrostatic generators.

III. SYSTEM DESCRIPTION

The idea to use footwear to produce energy has been pursued for a long time. Several patents based either on electrical, mechanical and piezoelectric systems [15-19] have been registered. In the following subsections, the basics on piezoelectric polymers will be discussed and their suitability for harvesting energy will be demonstrated through the construction and test of a sole prototype. This work shows an integrated way to include the piezoelectric material into a sole, its geometry and harvesting of the energy. In the next subsections, the different steps: development and preparation of the electroactive material, positioning of the material into the sole of the shoe, readout electronics design and preliminary test results of the system will be presented.

A. Polymer preparation

The piezoelectric films used for the energy generation are constituted by a polymeric material coated in both sides by a conducting material, which form the electrodes. The polymeric material is based on the polyvinylidene fluoride (PVDF) polymer in its electroactive (β) phase. It can be processed in the form of a film by extrusion, injection or from the solution, usually in the non electroactive α phase. In order to obtain the electroactive β phase, the α phase films must be submitted to mechanical stretching at temperatures below 100ºC and with a stretching ratio (ratio between the final and the initial lengths of the sample) from 4 to 7. After getting the electroactive β phase, the material must be activated by poling. This is done by subjecting the film to an electric field with amplitude larger than 60 MV/m along the thickness direction [20, 21].

The main advantages of using polymeric films instead piezoceramics or single crystals are that polymer films are flexible and can be fabricated in the desired shapes and sizes through simple processing processes. Further, electroactive polymers are very cheap in comparison with their ceramic and single crystal counterparts, making them more suitable for mass production systems and devices.

For the present work, high performance films, prepared by a method patented by us have been used [20, 21]. Unoriented films exclusively in the β phase were obtained from the crystallization of PVDF from solution with N,N-Dimethyl Formamide or Dimethyl Acetamide at temperatures below 70ºC. The electromechanical properties of the film were improved by a treatment that consists on pressing, stretching and poling at high temperature [20]. A final step of stretching at a temperature around 80ºC results in oriented films, which further increases the material performance. Final film thickness ranged from ~20 to 60 μm.

B. Electrode deposition

Once the material is prepared, electrodes are deposited on both sides either by magnetron sputtering or by thermal evaporation. Silver and aluminum has been used as electrode materials for the present tests.

The thermal deposition system consists in a vacuum chamber where the pressure reaches 10^{-6} mbar. An evaporation boat containing the material to be evaporated is placed in its interior. The boat is heated by means of an electric current ranging between 100 A and 200 A. At the top of the chamber the β-PVDF film, where the deposition is performed, and two mass sensors are placed. In order to deposit the electrode on the thin β-PVDF polymer, the electrical power applied to the boat must increase slowly. When the temperature of evaporation of the silver is reached, the mass sensors will indicate a variation of the mass attached to them –proportional to the film thickness. At this point, the electrical power must be kept constant. When the mass sensors indicate that the electrode thickness is equal to 30 nm, the power supply is switched off and the deposition of the electrode is complete. The second electrode is deposited by turning upside down the β-PVDF film and repeating the previous procedure.

C. Positioning of the piezoelectric material

As piezoelectricity is a dynamic process, the material should be positioned in the places were larger and more variable pressure is exerted during walking. Those places are shown in Fig. 3, together with the first prototype. In this prototype single layers of electroactive material were placed on the top of the sole.

Fig. 3: First prototype of the energy generator: two piezoelectric polymer films above the sole.

D. Performance tests

As a dynamic process, the material reacts to pressure variations and the generated voltage changes when the pressure on it increases or decreases. Fig. 4 shows the experimental set-up developed for testing the material performance: a shaker applies force to the piezoelectric material at different frequencies and forces. The voltage is recorded on the digital oscilloscope and the energy stored in a battery.

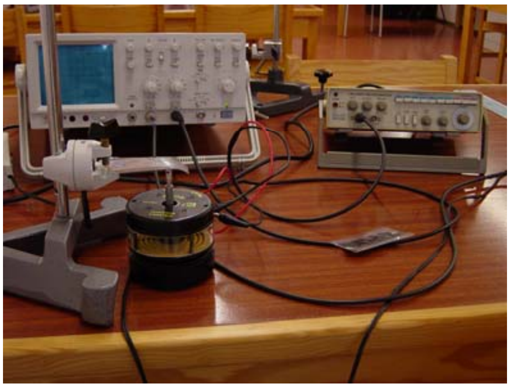

Fig. 4: Experimental set-up for material testing.

After the placement of the piezoelectric films into the soles, preliminary test are performed by simple jumps. Fig. 5 shows the voltage change when a single jump is applied to a 28 μm thick PVDF sample.

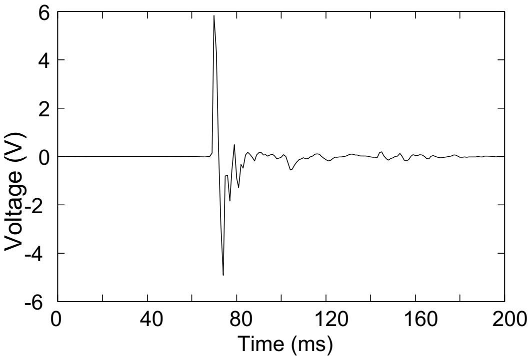

Fig. 5: Voltage change for a single impact applied to the sample.

E. Electronic circuit

In order to maximize the energy transfer to a charge or to a battery, in the case of energy storage, it is necessary a rectifying circuit in order to obtain a single polarity voltage. This circuit consists of a rectifier bridge based on four Schottky barrier diodes. These diodes have a forward bias voltage drop near 0.33 V, which is an advantage for this application, as it means that for potential values larger than 0.66V (two diodes) it is possible to use the full wave configuration. With p/n junction diodes, this value would be approximately 1.4V.

The circuit board of the full wave rectifier is then connected to the piezoelectric element placed in the sole giving origin to the first prototype 3(Fig. 6). The whole system is implemented into a shoe (Fig. 7) and further tests are performed in real walking situations (Fig. 8).

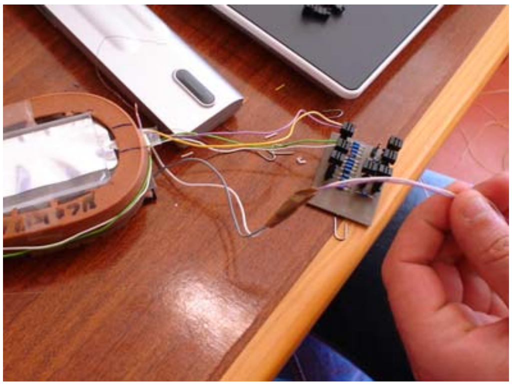

Fig. 6: Connection of the circuit board to the piezoelectric material.

Fig. 7.Sole and electronic circuit placed in the shoe

Fig. 8 shows the values of the rectified signal, for a single step situation.

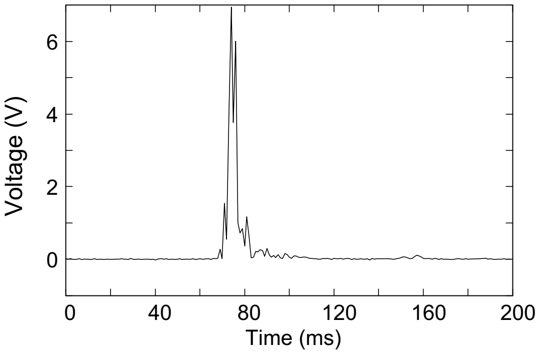

Fig. 8: Voltage versus time after rectification for a single impact applied to the generator.

Once the system was tested and verified, the circuit board was minimized in order to be fully integrated within a real shoe. Fig. 9 shows a photo of the final circuit. As it can be seen, its dimensions are less than a one Euro cent coin.

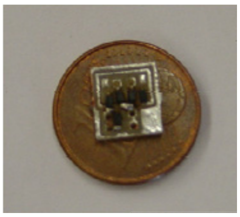

Fig. 9. Circuit implemented in the final prototype shown on a 1 cent Euro coin.

F. *Addition of an electrostatic generator*

In order to increase the power generation, an electrostatic generator was also coupled to the sole. It consists basically in two metallic plates separated by a flexible dielectric material (foam), which changes its thickness every time a pressure is applied, i.e. when the person puts his/her foot on the floor. Fig. 10 shows a photo of the test setup. The steady-state capacitance of this electrostatic generator is 20 pF. When the person steps with the foot on the floor, the capacitance increases about two times, which means that the voltage decreases to one half. At this time, the piezoelectric voltage is higher than the one at the electrostatic generator terminals, so, its capacitance will be charged. When the person raises the foot, the capacitance of the electrostatic generator decreases and the voltage increases. In this case, the load is an energy storage device (battery of 3 V), so, when the voltage of the electrostatic generator exceeds the one of the battery, the charge of the first is transferred to the second.

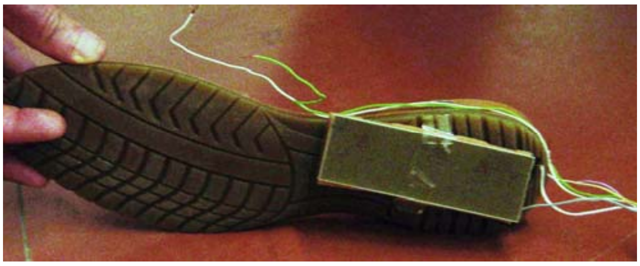

Fig. 10: Electrostatic generator placed below the sole for test purposes.

Fig. 11 shows the schematic diagram of the electrical connections between the piezoelectric element, the electrostatic generator and the load.

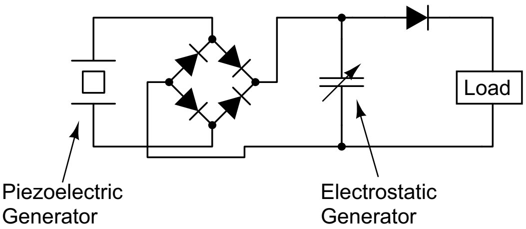

Fig. 11: Schematic diagram of the connections between the piezoelectric film and the electrostatic generators.

G. *Energy storage*

A thin-film rechargeable lithium battery can be used to store the energy generated. All-solid-state lithium batteries, fabricated entirely of thin-film components, achieve capacities over 35 uAh/cm^2, with current densities above 200 μA/cm^2, in less than 10μm of thickness. A layered structure, as presented in Fig. 12 is being prepared to implement the proposed battery. On top of a polymeric flexible substrate where the metal current collector was previously prepared (a platinum layer provides external cathode connection), $LiCoO_2$ cathode is deposited, followed by a Li_3PO_4 (LiPON) electrolyte, both by reactive sputtering. The Li cathode is then deposited by thermal evaporation. The anode current collector is deposited on top of the battery, providing the external connection to the anode. The final step is the deposition and patterning of a parylene or Si_3N_4 protective coating.

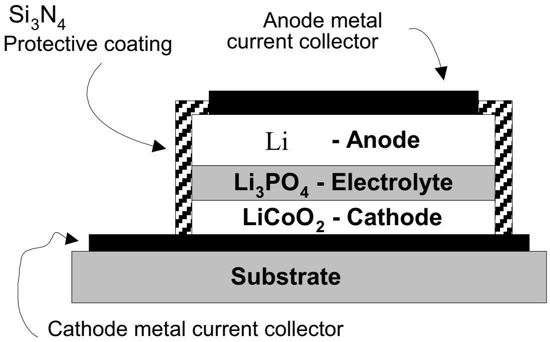

Fig. 12: Cross section of a thin-film lithium battery.

IV. EXPERIMENTAL RESULTS

After testing the foils and the readout electronics, the system was introduced in a bi-color sole of a shoe prepared by injection molding (Fig. 13). It is important to notice that during this process, temperatures higher than 160 ºC are reached at certain points of the sole. This process did not affect the performance of the electroactive set up.

The power generated by the PVDF foil within the shoes ranges from tens to hundreds of milliwatts, depending on the area, the placement, the geometry and the numbers of foils. Especially important is the system allowing stretching and not just pressing of the foil, as the longitudinal electro-mechanical coupling of PVDF (k31) is more efficient that the k33 mode [14]. In this way, the PVDF foils are more efficient in the electromechanical conversion when they are introduced within the sole in the form of a bimorph. A bimorph converts the foot pressure towards the bottom into a combination of pressing and stretching of the PVDF films, making use in this way of the k33 and k31 electromechanical conversion.

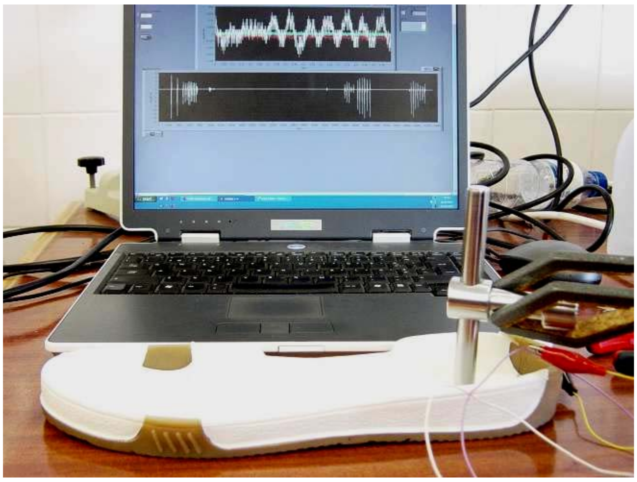

Fig. 13: Performance test. A handspike system was used in order to apply constant pressure impulses to the sole.

Important for the generation of energy is also the number of polymer layers in each piezoelectric element. Fig. 14 shows the voltage generated by a person walking.

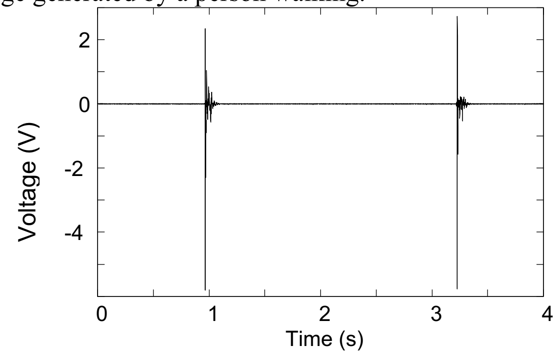

Fig. 14: Voltage generated by a person walking.

The voltage generated in a system with two superimposed layers of piezoelectric material was also tested. The generated voltage was approximately double that of the one generated by the single layer system.

Fig. 15 shows the whole system (piezoelectric + electrostatic) performance. It is possible to see that the output peek voltage value is greater in the case that uses the electrostatic generator. Moreover, its time response is slower, which means that the associated piezoelectric-electrostatic generator supplies energy to the load during a long time interval.

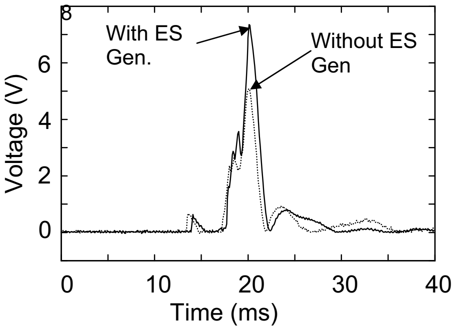

Fig. 15: Voltage generated by a person walking with and without the electrostatic generator.

Fig 16 shows the average energy generated in one hour, by a running person (four steps per second), when the generator is coupled to a resistive load.

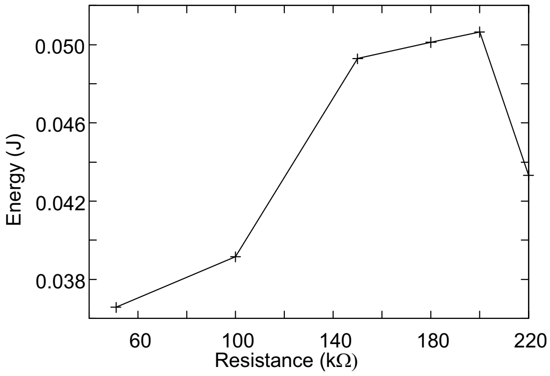

Fig. 16: Energy generated in one hour by a person applying four steps per second, when the generator is coupled to a resistive load.

When we compare the results of Fig. 16 with the data of table 1, the conclusion is obvious: the amount of energy generated is less than the one needed by the described applications. This means that the work is far from being concluded. Instead of that, some improvements must be done, by increasing the thickness of the piezoelectric polymer film, by placing four or six generators in each sole and by using films with increased properties with respect to piezoelectricity and elasticity.

V. CONCLUSIONS

From the several methods available in order to integrate energy generating elements harvesting human energy, piezoelectric materials associated with electrostatic generators seem to be one of the most promising elements. In particular, electroactive polymers are especially interesting due to their low cost, flexibility and easy integration into elements such as clothes and shoes. In this paper electroactive polymers based in β-PVDF have been used in order to fabricate an energy harvesting system fully integrated into the sole of a shoe. Conventional methods were used in order to fabricate the sole, with no modification of the industrial production process. Through the simple configuration and electronics, energy harvesting is possible. In order to get energy values suitable for the functioning of electronic appliances, improvements in the material in order to improve electromechanical conversion, the readout electronics, in order to optimize the energy transfer and precise determination of the geometry and number of the piezoelectric generators should be performed.

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