



# Article An Energy Logger for Kinetic-Powered Wrist-Wearable Systems

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**Abstract:** Kinetic energy harvesting is a promising technology towards the development of alternative battery-charging schemes or even self-powered wearable devices that obtain their power supply from human motion. Although there are many developments with schemes that leverage piezoelectric materials and human motion to power devices especially from footsteps, some other body locations like the wrist still need assessment with piezoelectric generators to evaluate their potential of limitations. In this work, we present the results of logging the energy transference from a wrist-worn piezoelectric harvester to a battery in a wearable device. This system is the continuation of our previous work where we implemented the harvester with a resistive load previously tuned to obtain maximum power and assessed the energy harvested during physical activities. Now, we replace the linear load with a charge controller and a Li-ion battery in the same wearable set-up. These new conditions are not optimal for the piezoelectric generator but present a more realistic environment for the kinetic harvester and allows a more precise study of the feasibility of a self-powered system. Tests show that five minutes of activities that involve arm motion can provide between 1.75 mJ and 2.98 mJ of energy, which can represent between 3.6 seconds and 6.2 seconds of additional battery duration. Hence, these results provide an insight of the limitations and challenges remaining in the piezoelectric-based kinetic harvesting field for wearable devices.

Keywords: kinetic energy harvesting; piezoelectric generator; wearable devices

# 1. Introduction

The growing demand for e-health and smart fashion has positioned wearable devices as a promising market for the near future with an expectation of \$24bn by 2024 [1,2]. However, wearable technologies face limited functionality due to battery lifetime and the need of battery recharging or replacing [3]. In response to this issue, energy harvesting schemes can be employed as alternative solutions by converting light, heat, and/or motion into electricity [4,5]. Moreover, the field of kinetic harvesting has shown relevant developments for the piezoelectric, electromagnetic, electrostatic, and triboelectric technologies [6–9].

Piezoelectric harvesters (PEH) have been considered a potential alternative to develop self-powered systems and wearable battery chargers [10–14]. For wearable systems, there are several works that leverage footsteps to scavenge energy using PEHs in shoe soles [15–18]. As works like [3,19,20] suggest, there are other locations for on-body kinetic harvesting such as the hip and the wrist, where PEHs can supply wearable systems. However, the characteristics of the excitation induced in these other body locations differ highly from the foot strike used in shoe-mounted systems. Therefore, the power obtained varies depending on the location and the application.

Thus, it is necessary to assess PEHs on the body locations with the potential for wearable applications, under application-related environments to estimate the amount of energy that can be

practically harvested. Although there are some works in literature that present measurements with PEHs in body parts like the head [21], hip [19], elbow [22], knee [23], and wrist [20]; all of them and other similar systems only tested the harvesters with a resistive load or with no load. Since the performance of a PEH is highly dependent on impedance matching [24], tests with the optimal resistive load can reflect promising power measurements, but they also limit the applicability of such harvested power. A change in the load also represents a shift in the power measuring method. Fixed resistive loads permit the use of a simple equation to calculate the DC harvested power. On the other hand, nonlinear loads require non-trivial approaches that involve a separate tracking of current and voltage. Despite the development of some alternatives to the impedance matching issue such as shown in [25], the assessment of these systems in a wearable environment is pending.

To provide insights of the performance of PEHs as battery chargers in a wrist-worn environment, we present the results of logging the energy transferred from our wearable PEH-based harvester described in [26] to a battery in a wrist-worn device. Our previous work in [26] explains the development and testing of a wrist-worn PEH with a resistive load which maximizes the harvested power. The selected PEH is a custom off-the-shelf (COTS) device which allows reproducibility of our experiments and gives an insight of the suitability of materials available in the market for this kind of application. This system is assessed with different arm motions and physical activities. Then, the harvested energy is used to estimate the amount of time that a wrist-worn target system would work with such energy. The issue with those calculations is to assume that the harvester would perform with the same efficiency if the resistive load is replaced with the target system. Now, instead of that assumption, we implement the harvesting system as a battery charger in a wrist-worn device. Such device works as a BLE (Bluetooth Low Energy)-enabled harvested power tracker in this case, but its applications can extend from heart rate tracker to other health care applications [27].

The challenges of our solution are related to voltage and current measurement at the input of the battery-charge controller and to provide a tracking method that enables other applications for collected data. Since PEHs are high impedance sources [28], they are expected to provide high voltages and small currents. As [29] states, PEHs typically display voltages in the order of tens of volts, while currents are in the order of microamperes. Consequently, power measurement with PEHs cannot employ methods like electromagnetic induction [30] due to the very small currents. In our proposed solution, we study the input characteristics of the charge controller and used them to estimate the voltage and current that would flow from the harvesting circuit (Section 3.3).

On the other hand, the reporting via BLE links allows our system to store amounts of data in a mobile device that would not be possible for the wearable device. Consequently, the availability of user-custom energy transference data can be extended for fitness or healthcare applications like in [15,31].

The contributions of this paper are summarized as follows:

- An approach to measure the harvested power from the PEH using the conditions of input voltage and current imposed by the charge controller. The absence of a fixed linear load motivates this method where we address the challenge of measuring currents on the order of microamperes by studying the behavior of the PEH with a nonlinear load.
- A wrist-worn PEH-based battery charger for wearable applications. This prototype is tested with daily activities to assess its harvesting capabilities under human motion excitation and with a nonlinear load such as a battery charging controller.
- A BLE-enabled harvesting tracker that allows the integration of mobile computing, and consequently, the extension of applications for the kinetic harvester.

The rest is of the paper is organized with the following structure. Section 2 describes the related work. Section 3 contains the transition from our previous work as a baseline for the current development and a description of each component of the system. Sections 4 and 5 show the tests and conclusions, respectively.

## 2. Related Work

Several developments in literature show tests of PEHs in different body locations. Since the harvesting technology that leverages footsteps is very mature, only works for other parts of the body are considered. Additionally, it is of special interest to examine works with COTS generators because they keep focus on the system performance as well as we do in this article.

Authors of [32] introduce a novel curved piezoelectric structure and test it at a shoe and a wristwatch. Tests presented in [32] include a battery management circuit, and its voltage output shows the capabilities of the system to reach a charging voltage after 15 seconds of tapping on the structure. However, the fact of using a custom-made generator implies high costs and difficulties for reproducibility. A similar case is presented in [33] with a piezoelectric shell structure to scavenge energy from arm bending and stretching motions. Additionally, results in [33] are presented only in open circuit condition. Another structure for finger-motion kinetic harvesting is reported in [34], but this structure is tested only with resistive loads to characterize the voltage output. The same situation with harvesters for knees and head but with limited testing can be found in [35,36] and [21], respectively. Instead, this work presents reproducible experiments due to the employment of COTS devices, and the results are not attached to only one kind of activities as in [32,33].

Other works do not propose structures, but, instead, they show applications or studies using COTS PEHs. For example, Ref. [19] explores the average power generation using a COTS PEH module with a fixed resistive load and placing it in different parts of the body during walking, running, and cycling. The authors also show the hypothetic additional time that a battery would last with the average power of each activity, while the battery powers an activity tracker. On the other hand, the systems presented in [20,37] employ commercially available PEHs to exploit the arm movements with wrist-worn harvesters and show their results by using a fixed resistive load without going further on the application of their devices. In the case of our study, we change the fixed resistive load for battery charger to show the performance on a more realistic scenario. Considering an application, the work in [14] proposes a self-powered PEH-based activity tracker. Such system uses the charge in a capacitor to power a BLE beacon sender and then leverages the power of the transmitted signal to identify the activity being performed by the user. The harvester for this case is a hand-held box with a COTS PEH which has a fixed resistive load for harvesting power estimation; however, this hand-held device differs from the wearable set-up that we are proposing in this article, which changes the nature of induced vibrations on the PEH.

While systems with custom-made PEHs show promising harvesting results, the reproducibility of such systems is constrained by the technologies used in each case. In fact, the harvesting capabilities of COTS PEHs in a wearable environment are presented only with resistive loads, setting a challenge for other situations where the PEHs supply nonlinear loads. Hence, as can be noticed in cited literature, our proposed scenario where a COTS PEH is employed as a battery charger and its performance is assessed in terms of transferred energy is still pending. In addition, the details of the performance of the PEH with a nonlinear load, which are used here to estimate transferred power to the battery, constitute an approach that has not been presented in previous works.

## 3. System Components

## 3.1. Overview

The proposed design comprises two main features: kinetic harvesting from a piezoelectric generator, and power transference tracking. For the harvesting task, the PEH shall be followed by an AC/DC converter that permits the flow of the harvested current to a battery through a controller. For the tracking process, a device must measure the voltage and the current considering the very small currents and the low power available; then, the information must be constantly saved for the computation of the total transferred energy. Thus, Figure 1a displays the diagram for the present work divided into four groups, and Figure 1b shows the block diagram of our previous work in [26]. Group

1 comprises the PEH, which is the kinetic energy scavenger. Then, the AC/DC conversion takes place within the components of Group 2. Group 3 contains a reverse-protection diode, a current-measuring series resistor, and a charge controller for a Li-ion battery. Group 4 is comprised of a series of diodes that creates a voltage reference between the harvested voltage and an ADC input pin in a BLE-enabled ultra-low power (ULP) micro-controller unit (MCU) (RFD77101, as in [26]). The power monitoring system uses the MCU to read the rectified voltage from the PEH alongside with the current, and reports them to a mobile application through BLE. Following the reports, the mobile application computes the instantaneous power, and allows the estimation of the harvested energy specifying how much is transferred to the MCU battery during any time interval selected by the user. It should be noticed that, in [26], the main goal is to measure instantaneous power drawn by the resistive load, while the objective in the current development is to measure energy transferred to the battery charge controller. Hence, Figure 1b contains a diagram that illustrates how the PEH waveform is transformed to DC with a full-bridge rectifier with a resistor; then, the voltage is monitored with a BLE link in an Android mobile application.



(a)



Figure 1. (a) block diagram of this work; (b) block diagram of the previous work.

## 3.2. Piezoelectric Generator

The PEH employed in this work is a COTS device, following the tendencies from [19,20,38,39]. In this case, we select the PPA-1022 fabricated by Midé [40] for having the smallest footprint, and hence being most compatible with wearable technologies. Since the frequency response of human activities take place below 10 Hz [41], the resonance frequency of the PPA-1022 must be adjusted to maximize the harvesting process. Thus, the resonance frequency of the PPA-1022 is trimmed to 10 Hz using a tip mass formed by two neodymium magnets corresponding to a 20-gram moving mass. Due to the magnetic force, the magnets stay attached to the PPA-1022 as shown in Figure 2. The device configuration is designed to keep clamped 21 mm of the cantilever leaving 32 mm free for deflections. All these conditions ensure a low resonance frequency, as explained in [40].



Figure 2. Wrist-worn PEH-based (Piezoelectric harvesters) kinetic harvester.

## 3.3. Haevesting Circuit

As shown in Figure 1a, following the PEH, the electronic circuitry allows for processing the AC output from the PEH to the DC input in a Li-ion battery through a charge controller and the respective charge current monitoring. Thus, the first stage requires the electronics to perform the AC/DC conversion. A compact SMD DF02S diode bridge with a 10  $\mu$ F capacitor transforms the PEH output into DC voltage. The DF02S bridge rectifier offers a 1.1 V voltage drop with a 5  $\mu$ A of maximum reverse current. Although other works suggest the use of Schottky rectifiers, such diodes display higher reverse currents compared to conventional rectifiers, which in a PEH-based system represents poor rectification and high losses, since the PEH emulates a very-low current source [28].

The MCU used in this work is embedded in the RFD77101 module, which is part of the Lilypad Simblee board. The Lilypad board is specially designed for wearable applications, and also contains a BLE radio and an ARM Cortex-M0 processor [42]. The overall current consumption, considering internal components, is below 10  $\mu$ A in steady state. In addition, this board incorporates a JST (Japan Solderless Terminal) connector for the Li-ion battery and a MCP73831 charge controller to prevent overcharge and overdischarge of the battery that supplies the board [43].

For this work, a 3.7 V/110 mAh single-cell Li-ion battery provides the energy for the Lilypad Simblee. The MCP73831 permits a voltage supply range from 3.75 V to 6 V [43]. Therefore, any element that intends to transfer energy to the battery must have a supply voltage of at least 3.75 V. When the charge controller is off, the internal connections of the Lilypad board can lead the battery to supply elements connected in the voltage input pin of the MCP73831 controller. In consequence, the reverse-protection diode is added to prevent the battery to charge the capacitor in the harvesting circuit as shown in Group 3 of Figure 1b. The resistor in a series with this diode stands for current measure purposes. By experimentation, we realize that the instantaneous current flowing from the AC/DC converter reaches at most 15–20  $\mu$ A. Consequently, a 10 k $\Omega$  resistor in series with the charge controller helps to track the current through the voltage between its terminals, and such voltage drop falls below a maximum of 0.2 V.

### 3.4. Energy Harvesting Tracker

To perform a proper tracking of the current flowing to the charge controller, the MCU needs measurements of the voltage in the capacitor, which is the diode-side terminal of the resistor plus the diode voltage drop, and the controller-side of the resistor. The capacitor voltage rises to 4.3 V when the charging current is 20  $\mu$ A. On the other hand, the controller-side terminal of the resistor does not change from 3.75 V, which is the minimum supply voltage for the controller. This phenomenon is due to the very-low supply current. Hence, the system must interpret the 0.55 V difference to a 20  $\mu$ A charging current in this case. Since the voltage on the controller does not change under the low-current conditions of this harvesting system, the tracking of the capacitor voltage is enough to estimate the charging current. In addition, the mentioned current conditions induce a low voltage drop on the

reverse-protection diode of 0.35 V. Then, the 0.55 V voltage difference in this case corresponds to a 0.35 V drop in the diode and 0.2 V in the resistor.

However, the MCU faces an issue in the voltage measuring process related to its analog-to-digital converter (ADC). The Lilypad Simblee provides a 3.3 V regulation for the MCU supply using a MIC5219 regulator [42]. In consequence, the ADC cannot interpret voltages above that supply. As a solution, the authors propose the use of a series of diodes that forces a voltage drop between the capacitor and the ADC to map the 4.3 V to 3.3 V. Thus, the capacitor must provide the energy for the battery and the voltage input for the ADC. Nevertheless, this ADC has an input resistance of 19 M $\Omega$ , which represents a neglectable current loss compared to the controller. Since the current flowing to the ADC stands below 1  $\mu$ A, the voltage drop on each diode is 0.25 V approximately. Consequently, four series diodes accomplish the desired task of dropping 4.3 V to 3.3 V with neglectable losses. The MCU samples the mapped capacitor voltage periodically every 99 ms. Then, it computes the real capacitor voltage assuming a total drop of 1 V in the diodes. After this, assuming 0.35 V fall on the reverse–protection diode, the voltage through the resistor is calculated and sent via BLE in a broadcasting event. Finally, the MCU enters in a ULP sleep state during 99 ms to save energy.

Once the Lilypad Simblee sends the current data via BLE, a custom-made mobile application for Android devices connects automatically to the Lilypad Simblee, receives data, shows the current as it comes, and stores it for graphical analysis and energy estimation. Figure 3 shows the two main views of this mobile application.



Figure 3. Views of the mobile application, (a) live; (b) historical.

Figure 3a displays the *Live* tab. It contains an on/off switch that allows the automatic reception from the wearable device. When the switch is activated, it requests the user to enable the Bluetooth connections. Internally, the app tries to catch the broadcasting signal of the pre-defined MAC address of the Lilypad Simblee. This configuration permits automatic connection and reception. According to the BLE protocol, data must be organized in different sets of features named *services*, which can contain different features or *characteristics* [44]. Each *characteristic* is related to data within the *service*. Every time the app detects a change on the value of a custom pre-defined *characteristic* for the voltage value, it triggers a function which immediately gets the voltage on the 10 k $\Omega$  resistor and computes the charging current. After this, the current value is stored in a local SQLite database and displayed in a label next to the switch, as seen in Figure 3a.

The other main view is the *Historical* tab shown in Figure 3b. This tab exhibits a form which asks the user for a time window. After the selection of initial and final time stamps, the user presses the *Search* button and the app queries the local database for the data within the selected time window. Once the data are selected, the app plots a graph of the current against time. Additionally, the current

values are used to compute the instantaneous power on the input of the charge controller, assuming a 3.75 V input voltage.

According to the measuring system, when the capacitor does not have enough voltage to transfer energy, the voltage difference is negative from the system perspective. Although there is not current flowing from the battery to the capacitor, the app computes a negative current. However, these negative values are internally related to non-charging states, and, therefore, ignored in the power computation. Thus, taking all the instantaneous power values corresponding to positive current, the transferred energy from the kinetic harvester to the controller is calculated with the help of a Riemann sum as presented in Equation (1),

$$E = \sum_{i=2}^{n} P_i \times \Delta t, \tag{1}$$

where  $\Delta t$  is the length of the time window between the current sample and the previous sample,  $P_i$  is the instantaneous power of the *ith*-component in the resulting dataset, *n* is the number of data found, and *E* is transferred energy to the controller during the consulted time window. Nevertheless, the real amount of energy transferred to the battery depends on the controller efficiency under these conditions.

### 4. Tests and Results

Once the harvesting tracker properly reports through the app, the system is tested to validate its capabilities. Following the statements from [5,19] about the location of on-body kinetic harvesters, the system could be placed whether in the wrist or the hip. For this work, the tests are performed with the system configured as a kinetic harvesting bracelet. The device mounted in a wrist is depicted in Figure 2.

Ten subjects (six men and four women) are asked to perform four different activities for five minutes each. All subjects carried out the activity set only one time to avoid the influence of fatigue on the results. Since the goal is to characterize the battery recharging from arm movements, the activities are selected considering the amount of arm involvement in the selected movements. Activities from the study in [26] like walking and punching a boxing bag are discarded due to the poor generation results. Hence, the activity set comprises clapping, jogging, dribbling a basketball, and jumping jacks. The jogging activity is performed around a college basketball court with speeds ranging from 3 km/h to 6 km/h; clapping is maintained between one clap and two claps per second; for the basketball dribbling, the subjects are asked to keep a pace of at least one dribble every two seconds, with the ball reaching the height of the hip of the subject in every bounce and without body displacement; the jumping jacks are done at rates between 20 jumps and 40 jumps per minute. At the beginning of each session, authors corroborate with the subjects that they do not feel any major discomfort that conditions their performance. Then, the subjects execute each activity and they are asked to rest during at least three minutes. After every session, authors consult the corresponding time window in the application and tabulate the estimation of transferred energy from the kinetic harvester to the charge controller. Table 1 resumes the results obtained during experimentation.

Considering that the system battery charge capacity is 110 mAh, with a 3.7 V nominal voltage, the total energy available in this fully charged element is 1465.2 J, using the conversion factor of 3.6 from mWh to J. Since the results in Table 1 are in  $\mu$ J, calculating the percentage of battery saved does not show significant values. Instead, authors propose a different approach.

According to its datasheet, the RFD77101 consumes 600 nA in ULP sleep state and 8 mA while transmitting at 0 dB [42]. Adding the quiescent currents of the MCP73831 and the MIC5219 regulator, the Lilypad Simblee requires a total of 50  $\mu$ A during ULP sleep. Therefore, for the configuration of the kinetic harvesting tracker, the board needs 18.3  $\mu$ J for the 99 ms of ULP sleep and 29.6  $\mu$ J for the transmission events, which includes waking up, ADC reading, and processing of the MCU. Hence, we define a *working cycle* as the process where the tracker sleeps and wakes up to measure and transmit. For those whose length is 100 ms, it can be stated that each cycle requires 47.9  $\mu$ J of energy.

Subject	Transferred Energy after Activities (mJ)				
	Jogging	Clapping	Dribbling	Jumping	
1	2.80	2.98	2.18	2.18	
2	2.36	2.75	1.94	1.88	
3	1.75	2.24	1.92	1.80	
4	2.16	2.29	2.07	1.97	
5	1.95	2.82	1.86	1.89	
6	2.07	2.59	1.94	1.77	
7	1.96	2.67	1.95	1.93	
8	2.25	2.46	1.79	2.21	
9	2.14	2.00	1.76	1.75	
10	1.83	2.63	2.00	1.84	

Table 1. Transferred during each activity session.

Consequently, the impact of the kinetic harvester on the battery can be quantified in terms of additional working cycles. Thus, dividing the transferred energy by the cycle energy can provide accurate information about the capabilities of the kinetic harvesting process using piezoelectric generators (PEGs). Table 2 shows the results in terms of additional working cycles. Additionally, Table 2 contains three new rows for a better understanding of the results. The average values evince the tendencies to obtain more harvested energy by jogging and clapping than dribbling a basketball and jumping jacks. These results are due to the consistent pace required by those activities. Nevertheless, clapping implies a faster movement than jogging, which leads to a rapid charging of the capacitor and more power transferred to the charge controller.

Subject	Additional Working Cycles after Activities				
	Jogging	Clapping	Dribbling	Jumping	
1	58.5	62.4	45.6	45.6	
2	49.4	57.5	40.6	39.4	
3	36.6	46.9	40.2	37.7	
4	45.2	47.9	43.2	41.2	
5	40.8	59.0	38.8	39.5	
6	43.3	54.2	40.6	37.1	
7	41.0	55.9	40.8	40.4	
8	47.0	51.5	37.5	46.1	
9	44.8	41.8	36.8	36.6	
10	38.2	55.0	41.8	38.5	
Minimum	36.6	41.8	36.8	36.6	
Average	44.5	53.2	40.6	40.2	
Maximum	58.5	62.4	45.6	46.1	

Table 2. Working cycles obtained during activities.

In addition, it must be noted that the difference between minimum and maximum values in jogging and clapping are greater than the corresponding difference in dribbling and jumping. Although the latter reports smaller tendencies compared to the other two activities, they exhibit values that are very similar across subjects. This phenomenon is caused by the nature of these movements. Dribbling a basketball, even for people who are not experienced with such skill, forces similar deflections on the PEG among different subjects. Jumping jacks provoke such effect as well.

In contrast, some subjects clapped harder than others, inducing larger deflections on the PEG. In addition, the jogging style varied among subjects, and this determines the involvement of arm movements and consequently the amount of vibration induced in the kinetic generator. Finally, it must be noted that the harvested energy can supply at least 36 additional working cycles, which can also be interpreted as 3.6 seconds of additional battery operation. This approach for the measurement of the impact of the energy harvesting system leads to a comprehensive view of the capabilities from

actual kinetic harvesters and the need to continue reducing the power requirements in wearable devices. We can affirm that this PEG cannot provide enough energy to keep the selected MCU working continuously. However, the growing tendencies of recent electronic developments towards reduction of power consumption [45] could help to extend the use of the harvested energy in a scenario similar to that presented here.

# 5. Conclusions

In this paper, we present the assessment of a wrist-worn piezoelectric-based kinetic battery charger. We propose the use of a custom-off-the-shelf piezoelectric generator as a source, mounting it in a wearable device that tracks the power transferred from the generator to a battery. Experiments are carried with ten subjects who performed four activities (jogging, clapping, dribbling, and jumping) for five minutes each. Results show that the transferred energy after each activity session provides between 3.6 seconds and 6.2 seconds of additional battery lifetime, given the consumption of the wearable device powered by the battery. Given the recent tendencies of minimizing the power consumption of wearables and biomedical devices, it is feasible to have a higher impact on new developments with the reported energy harvesting values ranging from 1.75 mJ to 2.98 mJ. The insights on the performance of the wrist-worn piezoelectric kinetic harvester presented here can be used to determine the suitability of using off-the-shelf devices to supply self-powered systems in a wearable environment.

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