Characterisation of a knee-joint energy harvester powering a wireless communication sensing node

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Abstract

Human-based energy harvesters are attractive as sustainable replacements for batteries to power wearable or implantable devices and body sensor networks. In the work presented here, a knee-joint energy harvester (KEH) was introduced to power a customer-built wireless communication sensing node (WCSN). The KEH used a mechanical plucking technique to provide sufficient frequency up-conversion—from a few Hz to the resonant frequency of the KEH—so as to generate the high power required. It was actuated by a knee-joint simulator, which reproduced the knee-joint motion of human gaits at a walking frequency of 0.9 Hz. The energy generated was first stored in a reservoir capacitor and then released to the WCSN in a burst mode with the help of an energy aware interface. The WCSN was deployed with a three-axis accelerometer, a temperature sensor, and a light detector for data sensing. A Jennic microcontroller was utilised to collect and transmit the measured data to a base station placed at a distance of 4 m. The energy generation by the KEH and the energy distribution in the system was characterised in real time by an in-house-built set-up. The results showed that the KEH generated an average power output of 1.76 mW when powering the WCSN. After charging the reservoir capacitor for 28.4 s, the KEH can power the WCSN for a 46 ms period every 1.25 s. The results also clearly illustrated how the energy generated by the KEH was distributed in the system and highlighted the importance of using a high performance power management approach to improve the performance of the whole system.

Keywords: piezoelectric energy harvester, wearable, wireless sensor node, human motion

(Some figures may appear in colour only in the online journal)

1. Introduction

In the past decades there has been an increasing interest in converting human motion energy to electric energy for supplying electric power for wearable or implantable devices and body sensor networks. This has been driven by the desire to remove the need for battery replacement and so establish a fit-and-forget wearable sensor technology. Together with ever shrinking transistor sizes, the continuous progress made in MEMS and COMS technologies has enabled the mass fabrication of small wearable or implantable sensors with very low power consumption. This has led to the increasing usage of sensors for applications, such as human health and activity monitoring, and human gait analyses. However, these sensors—all of which require power sources—are currently powered by batteries, and these have a limited energy storage capacity and thus a limited lifetime. More importantly, replacement of the batteries can be a problem when the number of the sensors increases, or in the worst case, intrusive surgery is required. As a result, human-based energy harvesting is expected to provide sustainable energy for wearable and implantable sensors so as to increase their lifetime and reduce the burden of replacement of batteries.
To date, a large number of human-based energy harvesters have been proposed and tested that use various mechanisms for their operation, including electromagnetic [e.g., 1, 2], electrostatic [e.g., 3, 4] and piezoelectric [e.g., 5, 6]. Among these, piezoelectric energy harvesters (PEHs) have received most attention because of their simple structures, self-contained power generation capabilities and high energy density [7, 8]. The common design approach for PEHs is to bridge the gap between the resonant frequency of the PEH and the frequency of human motion. This is because PEHs perform with the highest efficiency when operated at their resonant frequencies. However, the frequencies of human motion are much lower than the resonant frequency of the PEHs. This frequency mismatch results in a very low transduction efficiency and so a low generated electric power. To address this issue, a number of frequency-up conversion techniques to provide frequency shifts from a few Hz to the resonant frequency of harvesters have been proposed, based, for example, on impact [9, 10], mechanical plucking [11–13], and magnetic plucking [6]. In the previous work [13], one of the present authors, Zhu, investigated the power generation ability of a piezoelectric bimorph under mechanical plucking by using finite element techniques. Later, the mechanical plucking technique was realised and tested on a rotary energy harvester [14]. The rotary energy harvester was further developed into a knee-joint energy harvester (KEH), which scavenged the mechanical energy of knee-joint motions [15]. Actuated by knee-joint motion at a walking frequency of 0.9 Hz, the KEH produced an average power of 2 mW when the KEH was connected to an optimum resistive load of 20 kΩ. It is easy to see that a harvested power of such magnitude is particularly suitable for powering wireless communication sensors and communication sensor nodes, but unfortunately, compared with the large number of research papers on the design and optimisation of human-based PEHs that have appeared, only a limited number of studies have been carried out on their ability to power wireless communication sensor nodes. In one of these, Shenck and Paradiso [16] used a PEH embedded in a shoe to power an active radio frequency (RF) tag. The RF tag was able to transmit a short range, 12-bit wireless identification code; the energy harvester, adapted from the Thunder transducer design, could power the RF tag for a 0.5 s period every 3 to 5 steps while the wearer was walking. Another, a recent study by Zhao and You [17], reported on a polyvinylidene difluoride (PVDF) based energy harvester embedded in a shoe insole, which was able to power the wireless transmitter once every 6–8 steps when the wearer was walking at 1 Hz. Both studies successfully demonstrated the abilities of the energy harvesters to power wireless sensors. This paper will study the ability of a KEH to power a wireless communication sensing node (WCSN) and also characterise the energy distribution with the aim of understanding how the energy generated by the KEH is distributed in the system. The results will provide guidance to further improve the whole system performance.

2. KEH powered WCSN: system design

Figure 1 shows the block diagram of the KEH powered WCSN. It comprises three modules: the KEH with four PZT bimorphs (B₁ to B₄), a power management module (PMM) with an energy aware interface (EAI), and a WCSN with a base station placed 4 m away.

2.1. Knee-joint energy harvester

As mentioned in the introduction, the KEH, presented in [14, 15], was designed to wear on the external side of the knee, as shown schematically in figure 2(a). The outer ring with plectra embedded is fixed to the thigh, and the inner hub with piezoelectric bimorphs mounted is fixed to the shank. During walking, the thigh and the shank rotate around the knee joint, causing the inner hub and the outer ring to rotate relatively to each other. As a result, the piezoelectric bimorphs are first deflected by the plectra and then released to freely vibrate. By using this plucking mechanism, the low frequency rotation of the knee-joint motion is converted to the resonant vibration (high frequency) of the piezoelectric bimorphs, thus achieving high power generation.

The same prototype of the KEH as was presented in [14, 15], was used in this study—see figure 2(b). Four
PZT-5H bimorphs (T215-H4-303X, dimension 38.1 × 12.7 × 0.38 mm³, Piezo Systems INC, Woburn, US) were mounted in the inner hub with 25.5 mm free length. Seventy-three plectra were embedded in the outer ring. They are made of Kapton® Polyimide film (IM8031, Advent Research Materials Ltd, Oxford, UK). It was found from initial tests that (1) when the overlap between the plectra and the beam was too large, the beam would slide on the surface of the plectra, resulting in a slow release of the beam and consequently a low energy output; (2) when the overlap was too small, the plectra might pass the beam without plucking if the beam was oscillating. The overlap in this study was set to 0.5 mm, which enabled the sliding of the beam on the plectra to be minimised while ensuring that the plectra was always able to pluck the beam. The prototype was mounted on a stepping motor (M60STH88, Motion Control Products Ltd), which served as a knee-joint simulator and reproduced knee-joint motions in this study. The inner hub was held steady by a bracket, whilst the outer ring was rotated by the knee-joint simulator. The main reason to test the KEH on a knee-joint simulator rather than a human subject is the reproducibility of the tests as the motor can accurately reproduce the recorded gait at every run whereas the real gait cycle changes slightly from one step to the next. The KEH occupies a volume of 226 cm³ and has an approximate mass of 235 g.

2.2. Power management module

The ac signals generated by the KEH were rectified by four full-wave rectifiers (DBLS103G, Taiwan Semiconductor, Taiwan). The dc outputs from the rectifiers were connected in series, and then terminated with a 2 mF aluminium electrolytic reservoir capacitor. An EAI, composed of a voltage supervisor (MCP121, Microchip Technology, Inc., Chandler —Arizona, USA) and a switch (a 2N2700 NMOS transistor with a pull resistor) was used to manage the energy flow from the capacitor to the WCSN. Figure 3 illustrates the voltage across the reservoir capacitor under the supervision of the EAI. Initially, the capacitor voltage is zero, the switch is off and the WCSN is at its non-active phase. The voltage then gradually builds up due to the input from the KEH. When the voltage reaches a maximum voltage pre-set by the voltage supervisor, V₁, the switch is turned on and the WCSN is enabled from the non-active phase to an active phase, which means the WCSN is connected to the capacitor and the capacitor is discharged to, that is, powers the WCSN for sensing and transmitting data. A voltage drop in the capacitor will occur due to the energy consumed by the WCSN. As the voltage drops to the detect voltage of the voltage supervisor, V₀ (3.02 V for the MCP121 voltage supervisor), the switch is turned off and the WCSN is disconnected with the capacitor, that is, disconnected with the power source, leading to the WCSN to turn to the non-active phase while the capacitor can charge up again if there is input from the KEH. The system will remain in the non-active phase until the capacitor voltage reaches V₁ again, and then the cycles repeat. V₁ can be chosen based on the energy needed for powering the WCSN. For the implemented case, it was set to be about 3.2 V.

2.3. Wireless communication sensing node

In the custom-built WCSN, three sensors were deployed to collect the required information from the surroundings. These sensors include an ADXL335 three-axis accelerometer (Analog Devices International, Limerick, Ireland, UK), a MCP9700 temperature sensor (Microchip Technology, Inc.,

Figure 2. Pizzicato knee-joint energy harvester (a) schematic: the KEH was designed to wear on the external side of the knee, and to be fixed to the leg by braces (reproduced with permission from [15], copyright 2012 IOP Publishing), (b) prototype mounted on a stepping motor.

Figure 3. An illustration of the voltage across the reservoir capacitor under the supervision of the EAI.
Chandler—Arizona, USA, and a GA1A2S100 light detector (Sharp Electronics, Ltd, London, UK). A microcontroller (JN5148, NXP Semiconductors, Cheshire—Manchester, UK) was utilised to process the data from the sensors and transmit them to a base station. The microcontroller complies with 2.4 GHz IEEE 802.15.4 standard and has added features such as 128 kb random access memory and a 4 Mbit serial flash memory. It set the clock speed of the central processing unit to 32 MHz and transmitted data wirelessly at +2.5 dBm over three different channels using Time Division Multiple Access (TDMA) TDMA protocol. The base station, which has the ability to collect, store, and process data transmitted by the WCSN, was placed 4 m. More details of the WCSN can be found elsewhere [18]. It is worthwhile to mention that the data sensing and transmission of the WCSN was validated through comparing the acceleration measured and transmitted by the WCSN with the data received by the base station.

3. Experimental methods

3.1. Knee-joint motion

The knee-joint motion of a human subject during walking was measured by a marker-based motion capture system, as described in literature [15]. The angle between the thigh and the shank covers up to 57° during one gait cycle, as shown in figure 4, and the cycle takes 1.1 s, corresponding to a walking frequency of 0.9 Hz. The knee-joint simulator was controlled to reproduce this motion repeatedly to simulate continuous walking at 0.9 Hz. It is worthwhile to mention that walking speed can significantly affect the power output from the KEH. The higher the walking speed, the quicker the plucking action and the higher the power output [15]. In this study, only a normal walking frequency of 0.9 Hz was used to characterise the performance of the KEH for an average human walking speed.

3.2. KEH connected to a resistive load

The KEH was first connected to a variable resistor to characterise its power generating ability. A schematic of the experimental setup is shown in figure 5(a). The outputs of the rectifiers were connected in series and their combined output was measured through one channel of a NI 9229 data acquisition card (National Instruments, Newbury, UK). Each PZT bimorph was connected in series with a 100 Ω resistor, and the voltages across these were measured to calculate the current through the corresponding PZT bimorphs.

The voltage across and current through the variable resistor were measured by a system source meter (2612B, Keithley Instruments Inc., Ohio, United States), which has dual channels for either current or voltage measurement.

After the measurements were taken, the energy generation and consumption of the system were calculated. The accumulative energy generated by the KEH at time $\Delta t$, $E_g(t_j)$, is the sum of the energy generated by the four PZT bimorphs ($B_1$ to $B_4$).

$$E_g(t_j) = \sum_{n=1}^{4} E_{Bn}(t_j) = \sum_{n=1}^{4} \sum_{k=1}^{j} P_{Bn}(t_k) \Delta t = \sum_{n=1}^{4} \sum_{k=1}^{j} v_{Bn}(t_k) v_m(t_k) \frac{\Delta t}{100},$$

where $E_{Bn}$ and $P_{Bn}$ are the accumulative energy and the instantaneous power produced by $B_n$, respectively; $v_{Bn}$ and $v_m$ are the voltages across $B_n$ and across the corresponding 100 Ω resistor, respectively; and $\Delta t$ is the sampling period.

Because the four rectifiers are connected in series, a forward voltage of 5.6 V (1.4 V for each) is required to make all the rectifiers conduct current freely. This occurs when the sum of the voltage amplitudes generated by the four PZT
bimorphs is higher than 5.6 V, i.e. $\sum_{n=1}^{4} |v_{bn}(t_k)| > 5.6$. This means that even if some of the PZT bimorphs generate a voltage below 1.4 V for a short moment, as long as the other bimorphs produce a voltage high enough to make $\sum_{n=1}^{4} |v_{bn}(t_k)| > 5.6$, all the rectifiers will conduct current and form a closed circuit. The energy loss in the rectifiers at time $t_j$

$$E_r(t_j) = \sum_{k=1}^{j} P_r(t_k) \Delta t = \sum_{k=1}^{j} 5.6i_r(t_k) \Delta t,$$

(2)

where $i_r$ is the current through the rectifiers, which is the same as the current through the variable resistor, $i_R$.

The energy dissipated in the variable resistor at time $t_j$ is

$$E_R(t_j) = \sum_{k=1}^{j} v_R(t_k)i_R(t_k) \Delta t,$$

(3)

where $v_R$ is the voltage across the variable resistor.

Whenever the average power appears, it is calculated as

$$P_{av} = \frac{E(t_2) - E(t_1)}{t_2 - t_1},$$

(4)

where $E(t_1)$ and $E(t_2)$ are the energies at times $t_1$ and $t_2$, respectively.

3.3. KEH powering a WCSN

When powering the WCSN, the KEH was connected to the WCSN through the PMM in the experimental setup shown in figure 5(b). The components that are identical to those in the dashed box of figure 5(a) are not shown in (b). As before, the knee-joint simulator reproduced the knee-joint motions continuously for 60 s. The PZT bimorph voltages and currents were measured by two NI 9229 cards, as described in section 3.2. The reservoir capacitor voltages and currents

Figure 5. Schematic of the experimental setup (a) with the KEH connected to a variable resistive load, (b) with the KEH connected to the WCSN through the PMM: the components that are identical to those in the dashed box of (a) are not shown in (b).

Figure 6. Average power generated by the KEH as a function of load resistance.

Figure 7. Energy generation by the KEH and energy consumption with a 80 kΩ load resistor.
were measured by a Keithley 2612B system source meter. The voltage across the WCSN and the current from the EAI to the WCSN were measured by another 2612B system source meter. The base station of the WCSN shown in figure 1 was connected to a PC and placed 4 m away from the WCSN. The data received by the base station was monitored by the PC.

Ignoring the current in the EAI, the current through the rectifiers, $i_r$, is

$$i_r(t_j) = i_c(t_j) + i_w(t_j),$$  \hspace{1cm} (5)

where $i_c$ is the current through the reservoir capacitor, and $i_w$ is the current flowing from the EAI to the WCSN. Positive directions of current flow are shown in figure 5(b), with the KEH supplying current $i_r$, the capacitor being charged by current $i_c$, and the WCSN being supplied by current $i_w$.

The energy stored in the capacitor is

$$E_c(t_j) = \sum_{k=1}^{j} P_c(t_k) \Delta t = \sum_{k=1}^{j} v_c(t_k) i_c(t_k) \Delta t,$$  \hspace{1cm} (6)

where $P_c$ is the instantaneous power in the capacitor, and $v_c$ is the voltage across the capacitor measured by the system source meter.

The energy consumed by the WCSN is

$$E_w(t_j) = \sum_{k=1}^{j} P_w(t_k) \Delta t = \sum_{k=1}^{j} v_w(t_k) i_w(t_k) \Delta t,$$  \hspace{1cm} (7)

where $P_w$ is the instantaneous power consumed by the WCSN, and $v_w$ is the voltage across the WCSN measured by the system source meter.
Figure 10. Time dependence of the capacitor and WCSN voltages (a), currents (c), instantaneous powers (e), and accumulative energies (g) with detailed plots of these shown in (b), (d), (f), and (h), respectively.
4. Results and discussions

4.1. Energy generated and energy consumption with KEH connected to a resistive load

The load resistance was varied from 10 to 400 kΩ, and the total energy generated by the KEH in 60 s and the average power in this period were calculated from equations (1) and (4), respectively. A plot of the latter, presented in figure 6, shows that the maximum power (3.5 mW) is observed when the load is 80 kΩ, and this is, therefore, the optimal load resistance.

The performance of the KEH with its optimal 80 kΩ load was characterised, and the results are shown in figure 7. The energy generated by the KEH ($E_g$), lost in the rectifiers ($E_r$) and dissipated in the variable load resistor ($E_R$) as a function of time are compared. It can be noted that $E_g$ is approximately equal to the sum of $E_r$ and $E_R$. Within a 60 s period, the KEH generated energy of 206.5 mJ, 163.1 mJ was dissipated in the resistor, and 41.3 mJ was lost in the rectifiers. The latter two account for 78.9% and 20% of the energy generated, respectively.

4.2. Energy generated and energy consumption with the KEH powering a WCSN

4.2.1. Energy generated by the KEH. With the KEH connected to the WCSN, and the knee-joint simulator reproducing the knee-joint motion continuously for 60 s, the performance of one of the bimorphs in the KEH ($B_3$) was examined in detail during the first cycle of the knee-joint motion, as shown in figure 8. Four bursts of voltage peaks are observed (figure 8(a)). They all occurred at the time when large knee angles were covered in a short time, i.e. the rotation speed was high, and the bimorph was, hence, plucked frequently. Since a bimorph produces most of the energy upon release, the frequent plucking of the bimorph generated high voltage peaks close together. In contrast, when the rotation speed was low or the rotation direction was reversing, the bimorph experienced less effective plucking. Consequently, less voltage peaks were generated. Similar features are also observed in the current (figure 8(b)) and power (figure 8(c)): four bursts of peaks occurred at the time when the knee angle changed rapidly. When the electric power was high, the accumulative energy increased rapidly, as shown in figure 8(d). $B_3$ generated energy of 0.52 mJ in 1.1 s, corresponding to an average power of 0.47 mW.

The accumulative energy generated by the four bimorphs in 60 s is presented in figure 9 and it can be seen that this ranged from 20 to 30 mJ in this period. These fluctuations are attributed to the variations of the plectra they encountered, as the plectra were cut by hand and their tips did not have exactly the same shape. The four bimorphs generated an energy of 105.8 mJ in total, corresponding to an average power of 1.76 mW.

4.2.2. Capability of the energy generated to power the WCSN. Figure 10 shows the time dependence of the capacitor and WCSN voltages (a), currents (c), instantaneous powers (e), and accumulative energies (g) with detailed plots of these shown in (b), (d), (f), and (h), respectively. From figure 10, it can be observed that after charging the reservoir capacitor for 28.4 s, the KEH is able to power the WCSN for a period of 46 ms every 1.25 s. The energies stored in the reservoir capacitor and consumed by the WCSN are discussed below.

The reservoir capacitor voltage increased linearly with time from 0 to 28.4 s when it reached 3.2 V for the first time, as shown in figure 10(a)—this period was the initial charging phase of the capacitor. The capacitor voltage and current were both positive, as expected for the capacitor charging, and therefore so also was the electric power. The energy stored in the capacitor (figure (g)) increased steadily and reached 10.2 mJ at 28.4 s. During this period, the switch in the EAI was off. As a result, the voltage across the WCSN was zero, the WCSN was in the non-active phase, and did not consume energy.

As soon as the voltage across the capacitor reached 3.2 V at 28.4 s, the EAI turned on the switch. The capacitor released its energy to the WCSN. Consequently, a drop of voltage was observed across the capacitor. The current through the capacitor became negative, as expected for discharging of the capacitor; the instantaneous power therefore was also negative leading to a reduction in energy stored in the capacitor. The discharging of the capacitor lasted for 46 ms.

\begin{table}[h]
\centering
\caption{Energy distribution in the system.}
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Energy generated $E_g$} & \textbf{Energy loss in rectifiers} & \textbf{Energy stored in capacitor} & \textbf{Energy consumed by the WCSN} & \textbf{Other losses} \\
\hline
Energy (mJ) & 106.6 & 69.0 & 12.3 & 22.8 & 2.5 \\
Percentage to $E_g$ & 100% & 64.7% & 11.5% & 21.4% & 2.3% \\
\hline
\end{tabular}
\end{table}
until the voltage decreased to 3.08 V. During this period, the capacitor released energy of 0.75 mJ, corresponding to an average discharging power of 16.3 mW.

During the period when the switch was on, a voltage and a current appeared in the WCSN. As a result, the WCSN was switched into its active phase. The WCSN sensed data from the three sensors deployed and then transmitted the data to the base station. The base station successfully received the transmitted data. The WCSN consumed energy of 0.82 mJ in 46 ms, corresponding to an average power of 17.8 mW. This energy is higher than the energy released by the capacitor (0.75 mJ)—the difference in energy, 0.07 mJ, was supplied by the KEH. When the reservoir capacitor was discharging, the current generated by the KEH (after rectification) flowed directly to the WCSN, instead of charging the capacitor.

When the voltage across the capacitor decreased to 3.08 V, the EAI turned off the switch. The reservoir capacitor collected the energy generated by the KEH, and as a result, increases in voltage and energy were observed in the reservoir capacitor. Even though the voltage supply to the WCSN was shut down by the EAI, the voltage across the WCSN did not drop to zero immediately. Instead, it dropped rapidly first and then decreased gradually. The gradual decrease of the voltage is because there was a small decoupling capacitor (100 nF) shunting the WCSN. After the switch was off, the decoupling capacitor discharged the energy that it stored when the switch was on. Consequently, the voltage across the WCSN decreased slowly. Because the discharging power from the decoupling capacitor was too low to maintain the active phase of the WCSN, the WCSN was still switched to the non-active phase. During this period, no current flowed to the WCSN from either the reservoir capacitor or the KEH. Even though the energy stored in the decoupling capacitor was released to the WCSN, this part of the energy was already included in the energy consumed by the WCSN in the last active phase. Therefore, the energy consumed by the WCSN in the non-active phase was zero.

The voltage across the reservoir capacitor took 1.25 s to increase from 3.08 V to 3.2 V. Immediately following that, the EAI turned on the switch, and the cycles repeated. Successful data transmission was observed during each active phase of the WCSN. In 60 s, after accumulating energy for 28.4 s, the WCSN finished 27 transmissions successfully, and consumed energy of 22.8 mJ.

4.2.3. Energy distribution in the system. Figure 11 shows how the energy generated by the KEH is distributed in the system. The energy distribution includes the energy lost in the rectifiers, stored in the reservoir capacitor and consumed by the WCSN. The energy loss in the rectifiers was calculated using equation (2). The energy distribution agrees well with the energy generated, with a small difference increasing with time and reaching 2.5 mJ at 60 s. This small difference is attributed to measurement error and some unaccounted for loss in the system, such as the energy consumed by the EAI and the current leakage in the reservoir capacitor.

Of the energy generated by the KEH, 64.7% was lost in the rectifiers; 11.5% was stored in the capacitor; and 21.4% was consumed by the WCSN (table 1). This highlights the importance of reducing the energy loss in the rectifiers. The rectifiers in this system used silicon diodes. Replacing the silicon diodes with Schottky diodes is expected to reduce the energy losses, since the forward voltage of a Schottky diode is between 0.15 and 0.45 V compared with 0.6–0.7 V for a silicon diode [19].

| Load     | Energy generated (mJ) | Average power generated (mW) | Energy loss in rectifiers (mJ) | Average power loss in rectifiers (mW) |
|----------|-----------------------|------------------------------|-------------------------------|--------------------------------------|
| Resistor | 206.5                 | 3.43                         | 41.3                          | 0.7                                   |
| WCSN     | 106.6                 | 1.78                         | 69.0                          | 1.2                                   |

Table 2. Comparison of the performances of the KEH with two different loads: (i) 80 kΩ resistor, (ii) WCSN.
Table 2 compares the performances of the KEH with two different loads: (i) the 80 kΩ load resistor, (ii) the WCSN. The KEH generated an average power of 1.78 mW with the WCSN, compared with 3.43 mW with the 80 kΩ resistor. The nearly 50% degradation of the power generation with the WCSN is attributed to the mismatched impedance between the KEH and the successive loads (the PMM and the WCSN). The mismatched impedance resulted in a low power transfer efficiency. For the present design of PMM, the rectified output was directly connected to the reservoir capacitor without considering impedance matching. It is expected that, by the use of a maximum power point tracking circuit in the PMM, the power generation of the KEH when loaded by the WCSN can be improved significantly.

Interestingly, the rectifiers consumed more energy with the WCSN than with the 80 kΩ resistor, even though the KEH generated less energy with the WCSN. This is because when the KEH was connected to the reservoir capacitor (and the WCSN), a higher current flowed through the rectifiers, compared with when the KEH was connected to the 80 kΩ resistor, as shown in figure 12. This originates from the voltage across the capacitor being much lower, below 3.2 V, than the voltage, up to 80 V, across the 80 kΩ resistor, as shown in figure 13. Therefore, when the KEH was connected to the capacitor, the energy generated was derived from a low voltage and high current. In contrast, when the KEH was connected to the 80 kΩ resistor, it was from a high voltage and low current.

### 5. Conclusion

The capability of a KEH to power a custom-built WCSN was studied in this paper. The energy generated by the KEH and the energy distribution of the system was characterised with the KEH connected firstly to a load resistor, and then to the WCSN. With an optimal load resistance of 80 kΩ, the KEH generated an average power of 3.5 mW when actuated by knee-joint motions at 0.9 Hz. With the same actuating conditions, the KEH loaded by the WCSN generated an average power of 1.76 mW, which is sufficient to power the WCSN for a 46 ms period every 1.25 s after an initial charging time of 28.4 s. The KEH could, therefore, be used to power wireless sensors that are not required to sense and transmit data at high sampling frequencies. A wearable KEH with the PMM and the WCSN integrated onto the inner hub is under development, and once available, similar tests will be carried out. The maximum interactive force between the bimorph and the electra was estimated to be around 0.3–0.4 N, while the efficiency of the KEH, which is the electric energy generated over the input mechanical energy, was estimated to be up to 12%–16%. Although, the cost of the KEH is around 150 US$ for the current research stage, it is expected to reduce significantly by high volume production. The rectifiers were found to consume up to 64.7% of the energy generated, and the mismatched impedance between the KEH and the succeeding load resulted in nearly 50% degradation in power generation. In light of these results, future work should give priority to the development of high performance power management circuits with lower losses and capabilities of impedance matching.

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### References

[1] Donelan J, Li Q, Naing V, Hoffer J, Weber D and Kuo A 2008 Biomechanical energy harvesting: generating electricity during walking with minimal user effort Science 319 807–10
[2] Rome L C, Flynn L, Goldman E M and Yoo T D 2005 Generating electricity while walking with loads Science 309 1725–8
[3] Eun Y et al 2014 A flexible hybrid strain energy harvester using piezoelectric and electrostatic conversion Smart Mater. Struct. 23 045040
[4] Naruse Y, Matsubara N, Mabuchi K, Izumi M and Suzuki S 2009 Electrostatic micro power generation from low-frequency vibration such as human motion J. Micromech. Microeng. 19 094002
[5] Kymissis J, Kendall C, Paradiso J and Gershenfeld N 1998 Parasitic power harvesting in shoes 1998 Digest of Papers, 2nd Int. Symp. on Wearable Computers pp 132–9
[6] Pillatsch P, Yeatman E M and Holmes A S 2014 A piezoelectric frequency up-converting energy harvester with rotating proof mass for human body applications Sensors Actuators A 206 178–85
[7] Cook-Chennault K, Thambi N and Sastry A 2008 Powering MEMS portable devices—a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems Smart Mater. Struct. 17 043001
[8] Shu Y and Lien I 2006 Analysis of power output for piezoelectric energy harvesting systems Smart Mater. Struct. 15 1499
[9] Renaud M, Fiorini P, van Schaik R and Van Hoof C 2009 Harvesting energy from the motion of human limbs: the design and analysis of an impact-based piezoelectric generator Smart Mater. Struct. 18 035001
[10] Umeda M, Nakamura K and Ueha S 1996 Analysis of the transformation of mechanical impact energy to electric energy using piezoelectric vibrator Japan. J. Appl. Phys. 35 3267–73
[11] Murray R and Rastegar J 2009 Novel two-stage piezoelectric-based ocean wave energy harvesters for moored or unmoored buoys SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring pp 72880E–12
[12] Rastegar J and Murray R 2009 Novel two-stage piezoelectric-based electrical energy generators for low and variable speed rotary machinery *SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring* pp 72880B–8

[13] Pozzi M and Zhu M 2011 Plucked piezoelectric bimorphs for knee-joint energy harvesting: modelling and experimental validation *Smart Mater. Struct.* 20 055007

[14] Pozzi M and Zhu M 2012 Characterization of a rotary piezoelectric energy harvester based on plucking excitation for knee-joint wearable applications *Smart Mater. Struct.* 21 055004

[15] Pozzi M, Aung M S, Zhu M, Jones R K and Goulermas J Y 2012 The pizzicato knee-joint energy harvester: characterization with biomechanical data and the effect of backpack load *Smart Mater. Struct.* 21 075023

[16] Shenck N S and Paradiso J A 2001 Energy scavenging with shoe-mounted piezoelectrics *IEEE Micro* 21 30–42

[17] Zhao J J and You Z Jul 2014 A shoe-embedded piezoelectric energy harvester for wearable sensors *Sensors* 14 12497–510

[18] Marsic V A 2012 Wireless sensor communication system with low power consumption for energy harvesting technology *Msc by Research* School of Applied Sciences, Cranfield University

[19] Van den Heever T and Perold W 2013 Comparing three different energy harvesting circuits for a ZnO nanowire based nanogenerator *Smart Mater. Struct.* 22 105029