

Characterization of a rotary piezoelectric energy harvester based on plucking excitation for knee-joint wearable applications

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Abstract

Wearable medical and electronic devices demand a similarly wearable electrical power supply. Human-based piezoelectric energy harvesters may be the solution, but the mismatch between the typical frequencies of human activities and the optimal operating frequencies of piezoelectric generators calls for the implementation of a frequency up-conversion technique. A rotary piezoelectric energy harvester designed to be attached to the knee-joint is here implemented and characterised. The wearable harvester is based on the plucking method of frequency up-conversion, where a piezoelectric bimorph is deflected by a plectrum and permitted to vibrate unhindered upon release. Experiments were conducted to characterise the energy produced by the rotary piezoelectric energy harvester with different electric loads and different excitation speeds, covering the range between 0.1 and 1 rev/s to simulate human gait speeds. The electrical loads were connected to the generator either directly or through a rectifying bridge, as would be found in most power management circuits. The focus of the paper is to study the capability of energy generation of the harvester for knee-joint wearable applications, and study the effects of the different loads and different excitation speeds. It is found that the energy harvested is around 160 to 490 μJ , and strongly depends on the angular speed, the connected electric loads and also the manufacturing quality of the harvester. Statistical analysis is used to predict the potential energy production of a harvester manufactured to tighter tolerances than the one presented here.

Keywords: Plucked piezoelectric bimorphs, energy harvesting, wideband, wearable energy harvester, piezoelectric generator, pizzicato, frequency up-conversion, knee-joint harvester, human walking.

Introduction

Technological advances in the electronic industry have led to the mass diffusion of compact and portable devices, ranging from gadgets such as mobile phones, music players and navigation assistants, to wearable medical health monitoring devices. Together with miniaturisation has come lower power consumption; the energy requirements of many portable devices is so low, that the idea of scavenging energy from the surrounding environment becomes a viable alternative to replaceable or rechargeable batteries. Significant research efforts have been dedicated to this in recent decades, both within academia [1] and industry [2]. Whilst initial investigations focused on environmental energy scavenging for powering wireless sensor nodes [3], more recent research has also been directed towards human-based energy harvesting (EH), aiming at powering wearable medical or consumer devices. An excellent example of energy harvesting from the mechanical dissipative work taking place during normal gait is an electromagnetic device capable of generating 4.8 ± 0.8 W in the generative-braking mode during human walking [4]. The apparent limitations of the device are its mechanical complexity and the considerable mass of 790 g (1.6 kg including braces). Part of the mass and the mechanical complexity was due to the implementation of gears which increase the rotational speed of the electromagnetic generator to increase its power output and efficiency. As human activities, with the exception of vocalisation, occur at very low frequencies whilst piezoelectric generators are most effective at much higher frequencies, there is a frequency gap that needs to be closed to obtain useful power outputs. A traditional solution in vibration energy harvesting is the implementation of cantilevers with an attached mass, to make a system with low resonant frequencies [5] [6]. Particularly in human-based EH, this has two drawbacks: added weight and the fact that an overall low frequency implies a low energy production. Among the possible methods to solve this problem, some frequency up-conversion techniques have already been identified and investigated in previous works. For example, an impact form of

excitation for EH was presented by Umeda et al. [7] with a piezoelectric monomorph disc struck by a steel ball to induce resonant vibrations in the disc and electric energy generation. The impact involves transfer of momentum; mathematically, the system's initial conditions have non-zero velocity; the principle is similar to hammers striking the wires in a piano. A hand-held prototype harvester based on this principle was realised recently by Renaud et al. [8]: when vigorously shaken from side to side an output power up to 600 μW was produced thanks to a “missile” alternatively striking one or the other of two piezoelectric elements placed at either end of a conduit. Kulah and Najafi [9] introduced a different form of excitation for scavenging energy from low frequency ambient vibrations with a microscale electromagnetic generator where the low-frequency vibration of a suspended magnet excites the high frequency vibration of a number of coil-carrying cantilevers placed around it. The cantilevers are slowly deformed and then suddenly released when the elastic force overcomes the magnetic attraction; mathematically, the system's initial conditions feature a non-zero displacement; the principle is equivalent to the plucking of chords in a harpsichord (or a violin with the *pizzicato* technique). Several concept designs for energy harvesters based on this idea were later presented by Rastegar and Murray [10]. With focus on human based EH, Howells presented the Heel Strike Generator [11], where a system composed of lead screw, gear train and cam produced the controlled sinusoidal deformation of four PZT-5A elements. In this variant of frequency up-conversion, the bimorphs move at a frequency below resonance as they are always guided by the cam.

In a previous paper [12], the present authors have modelled and analysed with finite elements the behaviour and energy generation of piezoelectric bimorphs when excited by plucking. The plucking action was broken down in its fundamental phases and each was studied for energy generation potential. An important result was that the energy produced during the initial deflection is roughly proportional to the speed of deflection. Furthermore, a great proportion of energy is produced in the first few oscillations of the bimorph. This paper is based on the work [12] and is devoted to implementation and characterisation of a rotary piezoelectric energy harvester designed to be attached to the knee-joint for wearable applications. The harvester implemented here is light-weight, mechanically simple and offers good efficiencies even at the low frequencies associated with normal gait. It has a potential of providing as a power source for wearable medical devices and portable electronic gadgets. In this paper, the harvester is presented and characterised with a focus on studying the capability of energy generation of the harvester for knee-joint wearable applications and study the effects of different connected electric loads and different excitations on the energy harvested.

Frequency up-conversion by mechanical plucking

The harvester presented here is based on the frequency up-conversion strategy, with the aim of bridging between the low-frequency inputs from human activities and the high-frequency requirements of piezoelectric devices. Plucking is achieved when a plectrum deflects a piezoelectric bimorph up to a limiting deflection, therefore transferring mechanical energy to it (Figure 1). Once the bimorph is released, it vibrates at its resonance frequency, generating electrical energy via the direct piezoelectric effect. The outcome of plucking is frequency up-conversion, as by one single slow movement of the plectrum a large number of vibrations are produced at high frequency.

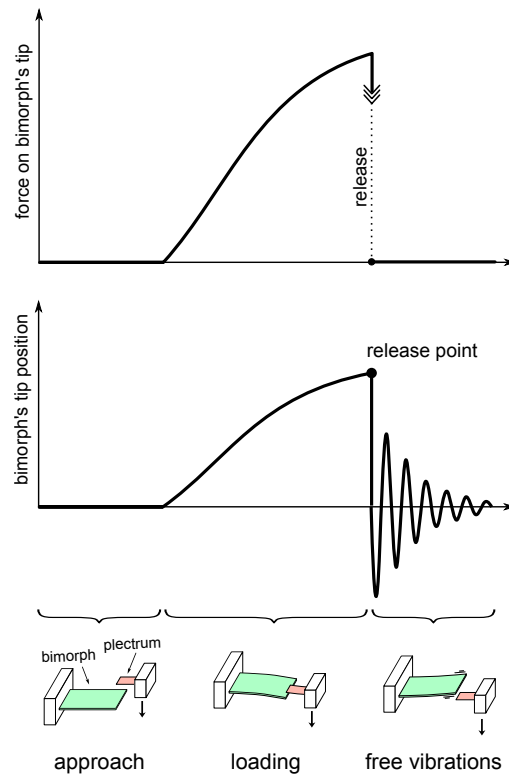


Figure 1: Illustration of the plucking action: during approach, the force on the bimorph is zero; force increases during loading, where mechanical energy is input in the bimorph (and the plectrum); after release, the external force on the bimorph is limited to air damping and to its constraints (mounting) and the device can vibrate unhindered.

Description of the rotary piezoelectric energy harvester for knee-joint wearable applications

A rotary piezoelectric energy harvester based on plucking excitation can take different configurations. A possible embodiment as knee-joint harvester with four bimorphs is sketched in Figure 2 (note that this paper investigates the behaviour of a knee-joint harvester featuring a single bimorph). During normal gait, for example while walking, the knee alternatively flexes and extends once per second, covering a total rotation angle of approximately 70 degrees in each direction. In Figure 2, the outer ring, carrying the plectra, is fixed to the thigh, whilst the inner hub, carrying the bimorphs, rotates with the knee, as it is fixed to the shank. As the person walks and the knee alternatively extends and flexes, each of the multiple plectra on the outer ring plucks the bimorphs. The energy harvester is therefore capable of converting the slow motion of walking into high-frequency vibrations of several piezoelectric bimorphs.

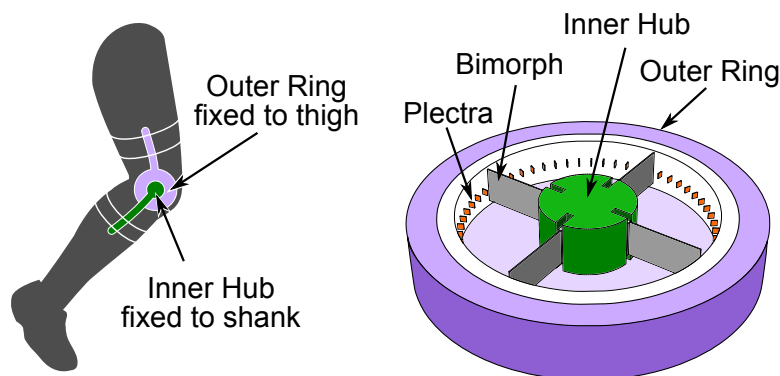


Figure 2: Knee-joint piezoelectric harvester. It is worn on the external side of the knee and fixed by braces. Inside, a hub carries a number of bimorphs which are plucked by the ring-mounted plectra as the joint rotates during walking.

Harvester implementation and experimental set-up

A prototype has been made and characterised with different connected electrical loads and different excitations to study the capability of energy generation of the rotary piezoelectric energy harvesters for knee-joint wearable applications. In the present form as knee-joint harvester, it was designed with a focus on simple one-off construction and flexibility (e.g. the plectra are embedded in a removable PTFE ribbon and the protrusion of the bimorphs can be easily controlled); it occupies a volume of 226 cm^3 and its mass is approximately 235 g. The outer ring and the inner hub of the harvester (Figure 3) were machined out of acetal copolymer. The plectra were cut out of a $125 \text{ }\mu\text{m}$ -thick Kapton[®] polyimide film and embedded in the PTFE ribbon mounted inside the outer ring; the area of the plectra protruding has the approximate shape of a rectangle of dimensions $3 \times 2 \text{ mm}^2$ ($l \times w$). The harvester features a total of 75 plectra spaced $3.5 \pm 0.5 \text{ mm}$ (*mean $\pm$ standard deviation*); due to manufacturing imperfections, one of these plectra is too short to touch the bimorph; also, the first and last plectrum are separated by 8.7 mm, which could fit a further plectrum. Hence, the device tested here has 74 active plectra, but with the same dimensions and spacing it could fit 76 plectra.

The ring was fixed to the rotor of a stepper motor, whilst the hub was held steady by a fixture. The stepper motor was controlled by a microstepper driver (MSD880 from Motion Control Products Ltd.), which received low level control signals from a computer via a D/A card and current amplifiers. This arrangement gives good flexibility, permitting to drive the motor with any velocity waveform compatible with its intrinsic limits of speed and acceleration.

The piezoelectric bimorph used is type T215-H4-303X produced by Piezo Systems Co.; its nominal dimensions are $31.8 \times 12.7 \times 0.38 \text{ mm}^3$, it is made of PZT-5H and poled for series operation. Optical microscopy examination revealed a $130 \text{ }\mu\text{m}$ -thick metal shim sandwiched between two layers of PZT, each of thickness $125 \text{ }\mu\text{m}$. The bimorph was mounted within copper-clad mechanical fixtures doubling up as pick-off electrodes, leaving a free length of about 25.5 mm; the distance between the free end of the bimorph and the axis of the harvester is approximately 42 mm. Electrical loading was applied to the bimorph with a manually-controlled discrete-valued potentiometer (digital potentiometer) having a full scale of $500 \text{ k}\Omega$ and measured linearity better than 1% in the range of interest. The electrical load was either connected directly to the bimorph or via a full bridge rectifier (MULTICOMP – DBLS103G). The voltage across the load was then sampled with a NI-9229 A/D card, whose $1 \text{ M}\Omega$ internal impedance was taken into account to calculate the effective electrical load. The vibration of the bimorph was measured with a Laser Doppler Vibrometer (LDV, Polytec CLV-2534); as it was not possible to shine the laser beam parallel to the direction of vibration, it was placed at a small angle and the resulting systematic error accounted for in the processing of the data.

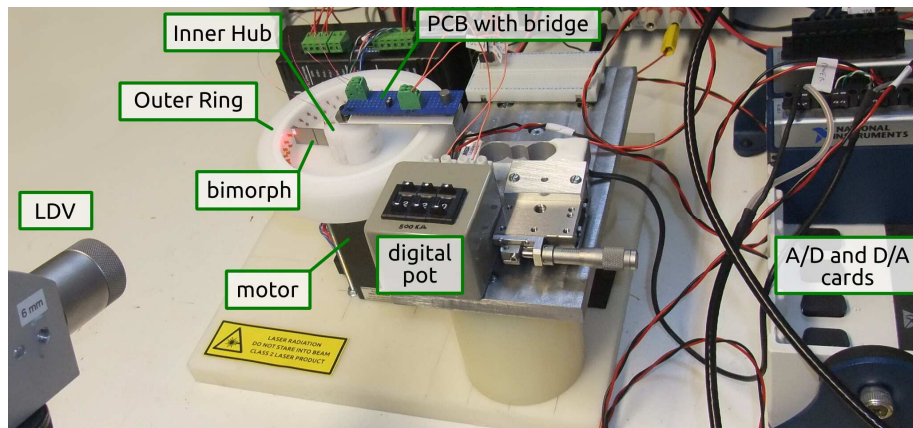


Figure 3: the prototype harvester mounted on the test rig. The rectifying bridge is a surface-mount device soldered to the underside of the printed circuit board (PCB).

Characterisations and discussions

To characterise the capability of harvesting energy by the rotary piezoelectric energy harvester for knee-joint wearable applications, we use the stepper motor mentioned above to reproduce the range of speeds observed in human gait, which are up to about 7 rad/s. The controlled condition of a selection of constant speed between 0.1 and 1 rev/s (periods $T=10\text{s}$ and $T=1\text{s}$) is used because it let us better study the effects of different

excitation speeds on the energy harvested and understand the transient behaviours of the harvester under different excitation speeds and also help to find better design configurations and identify manufacturing requirement of the harvester, for example, with additional speed transmission and uniformity of plectra around the outer ring. In spite of the controlled condition of the revolution speed, it should be pointed out that it is an important task to characterise the rotary piezoelectric energy harvester based on biomechanical data. The authors have studied and characterised the power generation of the harvester based on biomechanical data; due to the main focus of this paper, the results are not reported here but will be published in a subsequent paper in this same journal.

The characterisation of the harvester focussed on two areas. Firstly, the bimorph was connected, either directly or via a rectifying bridge, to a potentiometer set to a selection of values to study the effect of the electrical circuit and identify the optimal electrical load. This is important to the optimal design of a power management circuit. Secondly, the harvester was operated at a selection of rotational speeds, covering the range of speeds observed during normal gait, to investigate the vibrational characteristics of the bimorph at several plucking frequencies and the impact on energy generation.

Effect of the electrical load on energy harvested

Two series of measurements were performed at the speed of 5 s per revolution (Figure 4). In one series, the bimorph was directly connected to a resistance chosen among a selection of values; in the other, a rectifying bridge was placed between bimorph and potentiometer. The main feature of these curves is the presence of a maximum, i.e. a value of resistance for which maximum power is transferred to the load. This happens when the impedance of the electrical load matches the impedance of the bimorph at the dominant operating frequency. The optimal electrical load with rectifying bridge (approximately 100 k Ω) is higher than without bridge (approximately 50 k Ω). This is explained by observing that higher voltages are present on the bimorph's electrodes if a higher resistance is connected; therefore, the fixed forward voltage drop introduced by the diodes making the bridge becomes proportionally less important, i.e. it dissipates a smaller fraction of energy. As a result, when the rectifying bridge is present higher electrical loads become more beneficial and the maximum moves towards higher values of resistance. In Figure 4, the decrease after the maximum is not obvious and it could be argued that with the bridge, for example, the maximum is actually anywhere between about 100 k Ω and 140 k Ω . However, since most user loads have low impedance, among the loads that yield the highest energy the lowest is more representative of real use. Hence we have identified as optimal loads the lowest loads within the respective ranges.

Looking at the relationship between the two curves, the total energy dissipated in the electrical load is higher without the rectifying bridge; the difference between the two plots suggests that 50 to 80 μ J are dissipated in the diodes making the bridge; however, the difference between the two maxima is limited to 56 μ J, so that the losses due to the bridge are partly compensated by increasing the electrical load, although this may not be easily attained by the final user application.

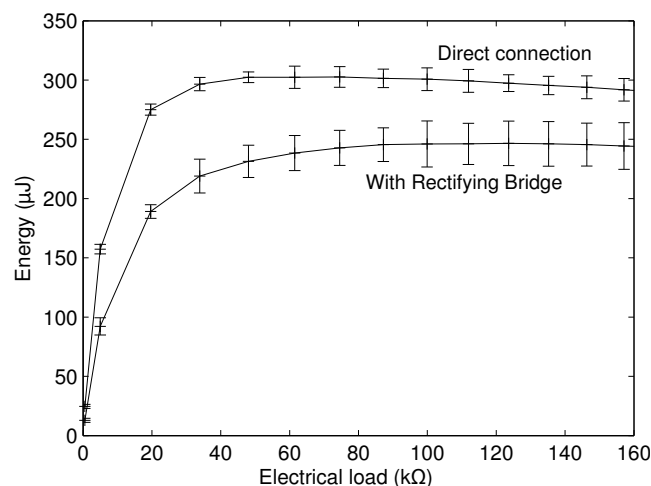


Figure 4. Total energy produced by the bimorph during a full revolution of the outer ring, occurring in 5 s. The plot shows the effect of the resistive load with and without a rectifying bridge. The error bars represent the 90% confidence level as predicted by Student's t-distribution.

Effect of the excitation speed (rotational speed) on energy harvested

Biomechanical data [4] show that during normal gait the angular speed of the knee-joint varies considerably, from 0 up to 6~7 rad/s. It is therefore important, from an application point of view, to characterise the harvester over a similarly wide range of angular speeds.

Two sets of measurements, with direct connection to the electrical load (Figure 5) and with a rectifying bridge interposed (Figure 6), were performed to determine the effect of the rotational speed. The optimal electrical load for each case, as identified in the measurements of the previous section, was connected to the bimorph. Although other measurements, not reported here, show that the optimal load is somewhat higher at lower speeds, all tests were run with the same electrical load, as it would not be feasible, in a real application, to change it during the gait cycle.

The most obvious feature of Figure 5 and Figure 6 is that the energy produced increases with the speed of revolution. This trend is due to a combination of factors including larger total deflection of the bimorph, quicker initial deflection and cleaner release; these are discussed at length later in the paper. The trend seems to be approximately exponential in both cases. This is a result of how the three factors combine: for example, larger deflections are observed only at the highest speed, whilst the quicker initial deflection gives a hyperbolic response, as discussed later. However, whilst the exponential fit is a good one for direct connection, with a bridge interposed the exponential is only marginally better than a linear fit (the fit is the result of standard-deviation-weighted least square fitting and its quality measure is the sum of the weighted residuals). At the moment, there are no apparent reasons to favour one fit versus the other in either electrical configuration, except for the goodness of the statistical fit and the arguments given above.

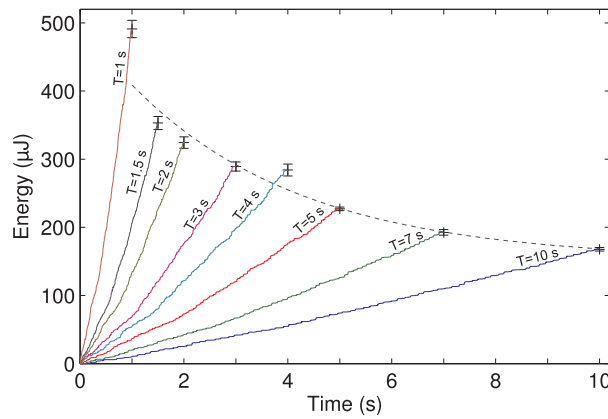


Figure 5. Total energy produced by the bimorph during a full revolution of the outer ring. A 47.6k Ω resistive load was **directly connected to the bimorph**. Data were collected for 3 runs for each speed; only one representative curve is plotted for each speed for the sake of clarity; the error bar at the end shows the average of the total energy produced and the 90% confidence level, calculated with Student's *t*-distribution.

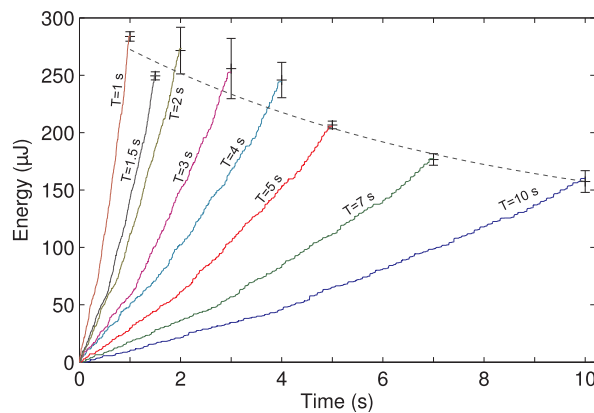


Figure 6. Total energy produced by the bimorph during a full revolution of the outer ring. A **rectifying bridge** was connected between the bimorph and a 99.1 k Ω resistive load. Data were collected for 6 to 8 runs for each speed; only one representative curve is plotted for each speed for the sake of clarity; the error bar at the end shows the average of the total energy produced and the 90% confidence level, calculated with Student's *t*-distribution.

Transient behaviour of the harvester for different excitation speeds

It is worthwhile to analyse in detail the signals produced by the bimorph at different speeds of revolution, as the vibration and the voltage output strongly depend on it (Figure 7 and Figure 8). Both figures were acquired with a rectifying bridge before the electrical load, as this is a common feature of most energy management circuits for piezoelectric harvesters. The displacement traces are obtained from the velocity via time integration; the energy traces are found via time integration of the instantaneous power, calculated as $P(t)=V^2(t)/R$, with $R=99.1\text{k}\Omega$ and V is the (rectified) voltage. When the period is 10 s (Figure 7), the individual plucking actions can be clearly distinguished. As the displacement trace shows, the bimorph is deflected by a plectrum over a time of about 60 ms up to the maximum deflection (just over 0.2 mm in the figure) before being released and permitted to quickly return to the undeflected condition with consequent vibration around the rest position. The voltage signal already rises during the deflection, although it remains below about 2V in the 60 ms of the deflection. Much more interesting voltages are produced as soon as the bimorph is released, with peaks between 7 and 12 V. The energy curve (last sub-plot in Figure 7) has a staircase-like character consisting of 3 major steps, each associated with a plucking action. Whilst there is some energy generation during the initial deflection, the greatest portion of energy is produced during the first few oscillations following release. The criterion for choosing this particular time interval for the figure is that it contains the three main types of peaks observed: the first peak (P1) is the most typical, presenting an unclear release characterised by a few oscillations in the displacement before release and a fragmented step downwards; consequently, the voltage signal is not very large and the energy step is also small. The following peak (P2) has a cleaner release so that the voltage reaches higher values. The last peak (P3) is an almost ideal release, with a sharp rise in displacement until the neat release point; as a consequence, the voltage produced is the highest and so is the energy step; a clean release as in P3 was rarely observed. It is also worth noting that a fixed set of plectra normally produced the cleanest peaks, proving that the quality of the release is mostly determined by the plectra themselves and only to a lesser extent by other factors (such as vibrations), which can cause statistical fluctuations in the release process. The time interval between the peaks is not constant because the physical spacing of the plectra on the outer ring is not perfectly uniform.

At high speed ($T=1$ s), the signals produced from the separate plectra are not easily distinguishable (Figure 8). The decay of the vibrations caused by the first plectrum (P1) can be seen because, due to a defect in the harvester, the following plectrum (P2) is too short to make contact with the bimorph. Thanks to this, the decaying voltage peaks can be observed clearly and the following plectrum (P3) is encountered by a bimorph which is almost at rest. Despite this, we still observe the superposition of the fundamental vibration onto the displacement peak caused by the deflection, although to a lesser extent than in the other peaks. The following 4 plectra (P4→P7) are met at short time intervals, yielding an uninterrupted oscillation of the bimorph, modulated by the contact with the plectra. As a consequence, the voltage signal shows a rapid succession of peaks of different heights, and the energy trace is simply a wavy line rather than a sequence of steps. The outcome of this continuous vibration of the bimorph is an energy production significantly higher than at lower speed, as evidenced in Table 1 and apparent from Figure 5 and Figure 6.

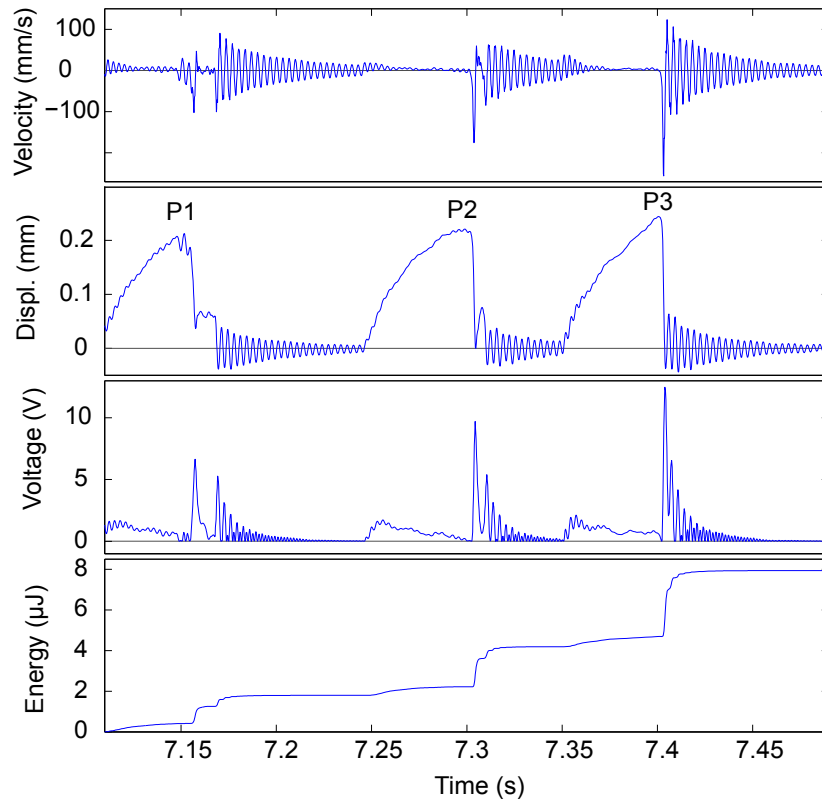


Figure 7. Time domain data for a slow run ($T=10$ s), from top to bottom: velocity, displacement (via integration of velocity and after baseline removal), voltage and energy. The first peak is the most common, showing an unclear release, with the plectrum slowly rubbing the bimorph; the second is cleaner and the third is almost ideal and a rare occurrence.

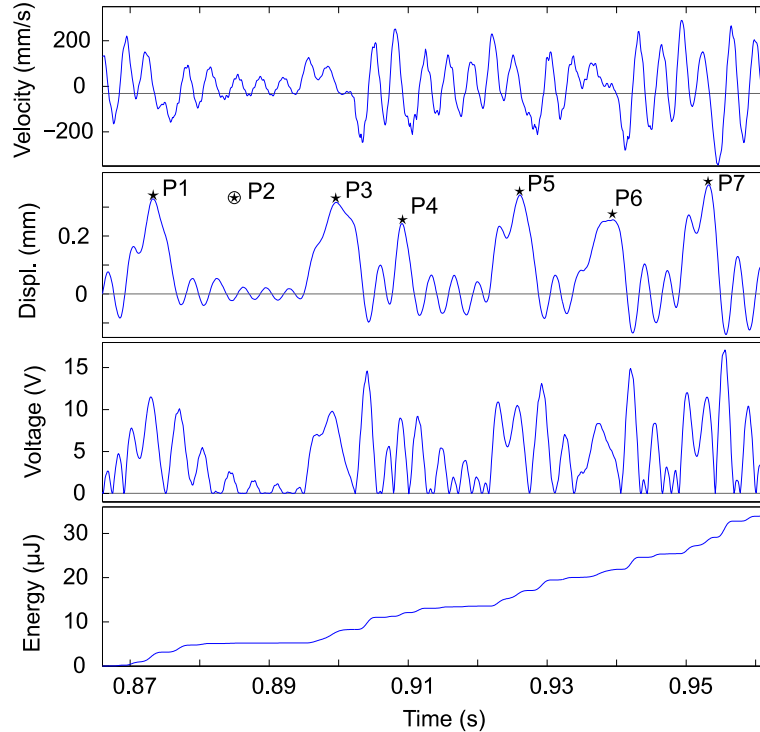


Figure 8. Time domain data for a fast run ($T=1$ s), from top to bottom: velocity, displacement (via integration of velocity and after baseline removal), voltage and energy. After the first plucking (P1), the bimorph has time to ring down as the immediately following plectrum (P2) is too short and does not touch the bimorph; the following plectrum (P3) is met by an almost still bimorph; the last peaks (P3→P7) are almost merged into each other and it can be seen that the bimorph continues to vibrate with considerable amplitude and generate large voltages.

Further discussion

Fast Fourier Transforms (FFTs) of the displacement data in Figure 7 and Figure 8 were calculated for the complete revolution. Clear peaks at about 300 Hz were present in both frequency-domain plots, corresponding to the resonant frequency of the bimorph. The second most important peaks were located between 7 and 8 Hz (slow run, $T=10$ s) and at about 77 Hz (fast run, $T=1$ s). These peaks correspond to the plucking frequency, which is expected to be about 7.6 and 76 Hz, for slow and fast run respectively – there are 74 plectra but they are spaced as 76, and they pluck the bimorph in 10 and 1 s respectively. These results are a clear manifestation of the effectiveness of the frequency up-conversion technique employed, as the vibrational spectrum of the bimorph contains its first resonant frequency in addition to the plucking frequency.

The results presented above show that plectra are affected by manufacturing defects, so that some tend to produce always less energy than others. It is therefore useful to statistically analyse the energy generated by interactions with each plectrum, to estimate the achievable energy, i.e. the energy that could be generated by the harvester if it was produced with the repeatability typical of an industrial manufacturing process, rather than assembled by hand. The basis for this analysis was to measure the bimorph's maximum deflection associated with each plectrum; then, the plectra yielding the highest 90-percentile were selected. In other words, the set included the 7 plectra which produced the largest maximum deflection of the bimorph. To be practically meaningful, one set of plectra was initially selected for $T=10$ s and used for calculation on all speeds; comfortably, the 90-percentile selection process applied to the other speeds usually gave exactly the same set of plectra, with a few instances when the two sets differed by only one plectrum. The average maximum deflection produced by the selected set of plectra is presented in Table 1 for a selection of rotational speeds. As the harvester under study has 74 working plectra, with room for two more, the achievable energy in the table is calculated by assuming 76 active plectra. It is assumed that each of the 76 plectra generates an amount of energy equal to the average energy generated by the 7 plectra in the 90-percentile set. The achievable power in the next column is simply the average power as obtained by dividing the achievable energy by the period of a revolution. The last column represents the ratio of the achievable energy over the measured energy.

Table 1, summarising the total energy measured and achievable for a selection of speeds of revolution, with and without rectifying bridge, confirms previous observations that the energy produced increases with the rotational speed and is also higher, for a given speed, when the rectifying bridge is not present.

Table 1. Summary of the total energy measured and achievable for a selection of speeds of revolution, with and without rectifying bridge. In the former case, the resistive load was set to 99.1 k Ω , in the latter it was 47.6 k Ω .

	Period T (s)	Angular velocity (rad s ⁻¹)	Measured Energy (μ J)	Average deflection ^a (mm)	Achievable Energy ^b (μ J)	Achievable Power (μ W)	Energy Ratio: Achievable/ Measured
with rectifying bridge (R=99.1k Ω)	10	0.628	160	0.322	255	25.5	1.59
	5	1.257	206	0.317	349	70	1.69
	4	1.571	244	0.317	455	114	1.86
	2	3.14	273	0.318	493	247	1.81
	1	6.28	284	0.353	533	533	1.88
without rectifying bridge (R=47.6k Ω)	10	0.628	168	0.315	207	20.7	1.23
	5	1.257	227	0.316	298	59.6	1.31
	4	1.571	283	0.319	462	116	1.63
	2	3.14	325	0.327	508	254	1.56
	1	6.28	490	0.375	830	830	1.69

^a Average maximum deflection produced by contact with the plectra which give the highest 90-percentile in the deflection when $T=10$ s.

^b The achievable energy is calculated assuming 76 plectra each producing the average energy seen in the top 90-percentile for displacement, as detailed in the text.

The average deflection of the selected plectra is essentially constant with speed until the highest speed, where a marked increase is observed. This is probably related to the fact that contact between plectrum and bimorph assumes a more dynamic character at the highest speed (compare Figure 7 with Figure 8), when contact duration is close to half the period of the fundamental mode of the bimorph. On the other hand, the measured energy increases more consistently with speed, indicating that maximum deflection is only one of the factors determining performance and probably not the most important at high speeds.

There are three major reasons why higher energy is produced at faster rotational speeds. The first is the faster initial deflection of the bimorph. As predicted in [12] and evidenced for example in Figure 7, the voltage produced is proportional to the strain rate during bimorph deflection. The effect of this phenomenon on the energy produced is approximately described by:

$$E = \frac{RQ^2}{\Delta t}$$

where Q is the charge generated on the bimorph's electrodes, assumed to be independent of strain rate, R the electrical load and Δt the deflection time [12]. Whilst at $T=10$ s the deflection occurs over about 60 ms (Figure 7), at $T=1$ s it lasts only 5 to 6 ms (Figure 8). The result is that a 10-fold increase in the speed of revolution yields a 10-fold increase in energy generation *in the loading phase* (note that this has no *direct* effect on the energy produced *after* release). The second important factor in the increase of energy output is the cleanliness of release: as observed in Figure 7, an unclear release, where the contact between bimorph and plectrum is lost over a significant time, is highly detrimental to energy production as, instead of being quickly released, the bimorph is almost accompanied to the rest position, with much lower deflection speeds. At higher rotational speeds, however, the contact is lost more quickly and sharply. Finally, a factor contributing only at the highest rotational speed is the increase in the average maximum displacement, as observed in Table 1: at this plucking frequency the plectra typically encounter the bimorph in a manner that favours its continuous vibration, as previously described when presenting Figure 8.

An interesting feature of the last column is that the same trend is found with and without bridge: the ratio of achievable over measured energy increases with speed. This means that at higher speeds a greater proportion of the measured energy is produced by the better performing plectra; in other words: at high speeds the quality of the plectra is more important as poorly performing plectra produce much less energy than the better ones. The fact that these ratios are higher when the bridge is present means that in this case there is a wider gap in energy contribution from the best plectra and the others. This is due to the fact that the bridge introduces a fixed voltage drop, which will be more important for low voltage peaks (poorly performing plectra) than high voltage peaks (better performing plectra). From an application point of view, this means that in a device manufactured with sufficient accuracy, the losses due to the rectifying bridge are less important than in the harvester characterised in this study.

A final consideration on the data in Table 1 is that the maximum deflection values observed are well under 0.4 mm. The bimorph used for the harvester is rated by the manufacturer for a displacement of 0.51 mm. An industrially manufactured harvester would be able to exploit the maximum deflection tolerated by the bimorph; in view of the quadratic dependence between displacement and energy, it is therefore reasonable to assume that the energy production would at least double from this factor alone under most conditions.

Focusing on the measurements with rectifying bridge, the achievable energy ranged between 255 and 533 μ J per revolution, for periods between 10 s and 1 s; a more accurately manufactured harvester would generate twice the energy if the full rated deflection is imposed on the bimorph. Finally, all these data are for a single bimorph, whilst an industrially manufactured harvester could easily host in excess of 16 bimorphs. All together, it is reasonable to expect energy outputs of 8 and 17 mJ per revolution, for periods of 10 s and 1 s respectively. This implies that a rotary energy harvester like the one presented could yield powers up to 17 mW for speeds up to 60 rpm (1 rev/s).

Although a durability study was not within the scope of this paper, it is worth noting that the bimorph used in this study has been subjected to a total of over 16,000 plucking actions, without any notable damage or decrease in energy output. On the other hand, a creep effect seemed to appear from time to time, so that a sequence of tests in the same conditions showed a progressively decreasing energy generation. However, after a few hours, the original conditions seemed to be restored. This could be due to the temperature increase of the whole system, in particular bimorphs and plectra, caused by the heat rising from the stepper

motor underneath, which can reach temperatures of 50 °C. The higher temperature also exacerbates the creep that may affect the polymeric components of the system, in particular the plectra and their mounting.

Conclusions and recommended future work

A prototype has been made and characterised to study the feasibility and energy generation potential of piezoelectric energy harvesters relying on the plucking method of frequency up-conversion.

The investigation of the dependence of energy on electrical load has confirmed that, as for traditional vibrational excitation, also for plucking excitation there exists an optimal impedance, which maximises the power extracted from the piezoelectric bimorph. The optimal value is larger if a rectifying bridge is inserted between bimorph and load, as higher loads mean higher voltages and so proportionally lower loss from the forward voltage drop of the diodes making the bridge.

It was found that the speed at which plectra and bimorph come into contact strongly influences the energy produced. This is because at high speed the initial deflection is faster, yielding higher voltages in that phase; also, the release is quicker and sharper, permitting the exploitation of the entire deflection for energy generation; finally, at the highest speed the duration of the contact becomes comparable with the period of vibration of the bimorph, producing a “dynamic” excitation. With regards to wearable energy harvesting, as the rotation of the knee-joint during gait has highly variable speed, we can expect an instantaneous power output highly dependent on the gait phase. This is the combination of the higher energy production achieved at high speeds and the fact that this energy is produced in a shorter time. As harvested energy is typically not used immediately but stored, this is not expected to be an issue in real applications.

In further studies we have measured the performance of the prototype harvester during actual gait by programming the movement of a simulator with real biomechanical data, showing that the majority of energy is produced in the brief moments when the knee-joint rotates quickly over a wide angle. At present, we envisage the application of harvesters based on the principles and prototype presented here to harvesting energy to power medical diagnostic devices, for example to monitor the operation of a prosthetic limb or to monitor a patient's vital parameters. Whilst this is the focus of our research project, it will be recognised that results presented in this paper can be applied to plucking-based energy harvesters with other configurations, where for example the plectra are mounted on a linear support and a reciprocating motion can be realised between this and the bimorphs.

Several parameters, such as piezoelectric material, geometry of bimorphs and plectra, material for plectra, could be optimised for performance improvements. As the energy production significantly depends on the frequency of plucking, it may also be worth considering a non-uniform spacing between plectra along the outer ring, in an effort to achieve a more constant frequency of plucking over the gait cycle. This adjustment may increase the performance of the knee-joint energy harvester.

The application of advanced power extraction techniques such as SSHI [13] has the potential of increasing the power available at the user load. It is not possible, with the data available now, to predict the potential gain, but research effort should be put into this issue, which is of interest for any plucking-based energy harvester.

The durability of this kind of devices is determined by at least two factors: the maximum stress imposed on the piezoelectric material, which could lead to premature failure, and the possible wear or damage in the region of contact between plectra and bimorph. Both issues may be addressed by introducing a non-contact form of energy transfer between plectra and bimorph, as would be afforded, for example, by magnetic forces.

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