Evaluation of Motions and Actuation Methods for Biomechanical Energy Harvesting

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***Abstract*— This paper addresses energy harvesting from biomechanical motions. Such a technique is useful for powering small portable devices, such as wireless phones, music players, and digital assistants. For very low power devices, biomechanical energy may be enough to provide baseload power. In others, such as cell phones (which typically requires up to 3 W), biomechanical energy would recharge batteries for extended use between line charges, or allow for peak just-in-time power. In this paper, we consider several biomechanical motions for power generation. We evaluate actuation methods, including magnetic, piezoelectric, electrostatic, and electrical polymers for various motions in terms of energy, power, mass, and cost. We also discuss the practical issues associated with each, especially in terms of the power electronics required to connect the biomechanical sources to useful loads.**

***Index Terms*—Biomechanics, Electroactive Polymers, Electrostatic, Energy conversion, Magnetic, Piezoelectric.**

I. INTRODUCTION

IN recent years, technology for portable electronics devices has been developing rapidly. People are seeking to make electronic devices smaller and longer lasting, which put the power problem more and more important. The current approach for powering portable devices is battery, which has weight, and troublesome recharging by limited life time.

Biomechanical energy has been paid much attention as either a possible replacement or a backup for the batteries. Various motions during walking and other activities have been considered as the sources for energy [1-4]. Estimations of work during these activities have been mostly based on the assumption that the work performed during these motions is due to an exchange of potential energy. However, we speculate that estimations based on the exchange of potential energy approach are limited, which results in an overestimation of the true value of energy needed to perform a given motion.

Our research has led to a more accurate estimation for human energetic motions. We considered several motions during walking, at the joints (ankle, knee, hip, shoulder, and elbow), heel strike, and whole body center mass motion. When analyzing the joints we used inverse dynamics method [5], and compared our experimental values to those measured in [6]. To calculate the energy values produced during heel strike we used linear displacement method combined with results from [7]. Center of mass energy values were determined using a model for mass point on a rigid and massless leg [8]. The procedures used for our estimation and the results are discussed later.

Meanwhile, efforts have been made to build heel strike energy conversion devices [2-4, 9-11]. While building those devices, we are generally facing two considerations: first, the harvesting device has to be able to fit on human body without significantly adding physical demand to nor altering the biomechanics of the human generator; second, we are seeking maximum efficiency. Several authors have claimed to analyze the relative merits of different techniques [1-4,9], but have greatly simplified calculations and neglected to differentiate between energy storage and energy conversion. In our paper, we will address the calculation of power conversion limitations of various techniques in detail to give a general evaluation of human power conversion methods.

II. ENERGETIC MOTIONS

Based on the notion that the work performed during human energetic motions is due to an exchange of potential energy, several authors [2] have considered heel strike as an ideal candidate motion for energy harvesting, and early estimates of this motion placed heel strike power approximately 67W for an average male walking in natural speed [1].

However, we speculate that estimations based on the exchange of potential energy approach are limited. Considering heel strike motion, the reason for our speculation is as follow. First, heel strike motion is not a real free fall motion; second, actual energy that is available for power generation comes from the compression of elastic material (shoe heel) against the ground. Further, estimation of the rest of the body joints do not allow an exchange of energy from potential to kinetic energy during a motion. In the following, we will show detailed estimation for join, heel strike and center mass motion.

A. Methodology

1) Joint

Our calculation of the net mechanical work at the joint is based on the definition of work as a product of torque and angular displacement. That is

$$W=\int_0^\theta T d\theta=\int_0^t T\omega dt \qquad (1)$$

where T is the torque, θ is the angle of rotation, ω is the angular velocity and t is time.

To determine the values for joint and torques we used inverse dynamics, in this method the joints torque values are obtained from measured motion and ground reaction forces.

This analysis is based on a Newton-Euler mechanics where a model for the human body is constructed using rigid segments [5].

The measured motion and ground reaction forces were obtained using an experiment in which three males (body mass, height) walked at natural speed with right foot contact with a force plate (AMTI BP600900). A six-camera 100 Hz Vicon system captured the subject motion.

Further, it is important to consider the fraction of negative work out of the total work performed during motion. Reference [5] defined positive work as the work performed when the muscle moment acts in the same direction as the angular velocity of the joint (i.e., the muscles adding energy to the motion), and negative work as the work done when the muscle moment acts in the direction opposite to the angular velocity of the joint (i.e., the joint muscles are absorbing energy from the motion and converting it to heat).

Therefore, it might be useful if an electric generator can absorb some of that negative work, rather than the muscle, and by that reducing the load on the human. This is contrary to the need for putting 'extra' muscle energy when the generator is using motion where the muscles perform positive work (e.g. moving the arm up with the generator resisting the motion).

2) Heel Strike

To calculate the work produced during heel strike we used the definition of work as the force acting through a linear displacement, with the displacement being in the same direction as the force. That is,

$$W = \int_{s_0}^{s_f} F_s(s)ds \qquad (2)$$

where W is work, $F_s(s)$ is a component of force function along the direction of movement, ds is the differential displacement vector, s_0 is the initial location, and s_f is the final location.

In reference [7], the energy lost in a running shoe was calculated, and related to force acting through a linear displacement. Using a viscoelastic model for a midsole, [7] obtains values that range from 1.72 J to 10.32 J during heel strike when running at 4.5m/s. Our own estimation is based on the external forces developed during walking as measured with a force plate.

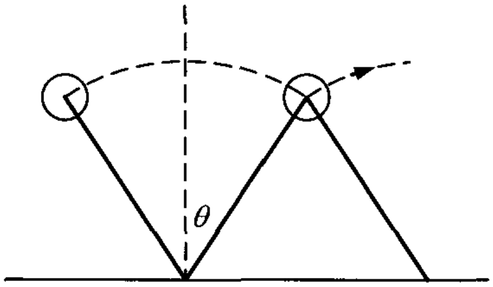

Fig. 1. The body center of mass motion modeled as an inverted pendulum

3) Center Mass Motion

During walking the center of mass for the entire body undergoes a motion similar to a sine wave with amplitude of about 2.5 cm [5]. This means that any object carried by a human need to follow similar trajectory. To allow this, there needs to be exchange of energy between the human and the object. This phenomenon can be seen, for example, when carrying a backpack where the straps are pulled against our shoulders. It might be possible to utilize this relative motion to generate some energy. Reference [8] used the motion of the human center of mass to develop an approximation of the total mechanical energy needed for running and walking. This model consists of a mass point moving on a rigid leg. While a foot is on the ground, the hip (where the center of mass is) travels along an arc of a circle centered at the foot (Fig. 1). This model was used in our estimation.

B. Results and Conclusion

1) Joints

Results of the inverse dynamics calculation provided us with the typical profiles of angle, torque, and mechanical power of a knee joint during a full stride (Fig. 2). The mechanical work performed during a gait cycle in each joint was calculated using numerical integration of the power as in (1). Results of this calculation, as well as results of the calculation of the fraction of negative work performed at the joints during gait cycle, are presented in Table 1.

2) Heel Strike

Based on the measurements, the maximal ground reaction during the heel contact is approximately 1.2 times the body weight (Fig. 3). We assumed displacement of 4 mm in the shoe sole, a mass of 80kg, and that work is performed only during compression. Based on these assumptions, the estimated value for the work performed on the shoe sole during heel strike is 2 J/step. Since 50-80% of the energy is stored as elastic energy in the shoe [7]. The energy that is available for use would be in the range of 0.4-1.0 J/step. Thus for a gait cycle of 1 Hz at walking (two steps per second), maximal power will be 2 W.

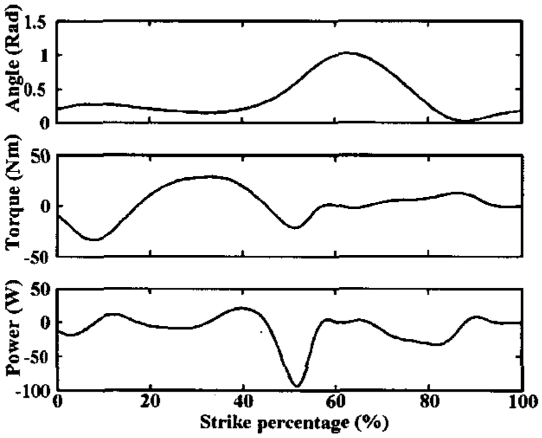

Fig. 2. Typical profiles of angle, torque and mechanical power during a full stride (from heel-strike to heel strike) in the knee joint (where angle zero refers to straight leg.)

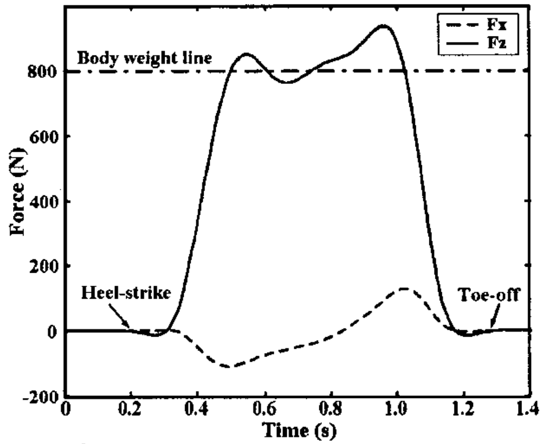

Fig. 3. Ground reaction forces as measured during the right foot contact with the ground from heel strike to toe-off (Fx is the friction force, and Fz is the load force, which is normal to the ground).

3) Center of Mass

Our estimation of the energy required for 20Kg load that follows the center of mass trajectory assumed: an average walking speed of 1 m/s, leg length of 0.98 m, and one leg range of motion of $\theta = 30°$. This results in a value of 0.5 J/step.

The results of our analysis are summarized in Table 1.

Our results suggest that while heel strike is certainly a good candidate, mainly due to the fact that device for harvesting energy could be incorporated easily into the shoe. Previous estimation of ~67W for the available energy from this motion is far too optimistic. Furthermore, the most powerful motions are actually ankle, hip, and knee movement. Also of interest in energetic motions is the fraction of the movement that is negative work by the human. Our calculations show that knee bending involves substantial negative work. The electric generator, as attached to the knee, can absorb some of that negative work, and by that reduce the load on the muscles, rather than the human putting 'extra' energy into the generator. Therefore, power capability combined with human effort must simultaneously be considered to evaluate the total power electric generated versus the human ergonomic impact.

III. ACTUATION TECHNIQUES

Once the motions are identified with their requisite power capability versus fatigue, it remains to efficiently convert that power to electricity, and then to useful voltage and current levels. Since this is a relatively new problem for electromechanics, we must consider various, perhaps unusual, techniques. Most of our calculations are based on the heel strike energy conversion.

A. Piezoelectric Actuation

Piezoelectric materials generate a voltage when compressed or bent [12]. It is a natural material for biomechanical energy conversion, particularly heel-strike, due to linear motion and the independence of voltage generated with speed. We will address the detailed calculation of the power available from piezoelectric energy conversion based on the heel strike.

1) Compression Mode

First, consider the compression mode generation. Define a piezoelectric cell with width W, length L, and thickness t. Typically, t is much smaller than L and W. The piezoelectric constant in the 'thickness' direction is d_{33}. If we apply a force, F, in the thickness direction, the voltage, V, across the thickness direction is

$$V = \frac{d_{33} F t}{\varepsilon L W} \tag{3}$$

Therefore, the electrical energy is

$$W = \frac{1}{2} C V^2 = \frac{1}{2} d_{33}^2 F^2 \frac{t}{\varepsilon L W} \tag{4}$$

Constants d_{33} and ε are fixed by the material. Thus a good figure of merit for materials is

$$FOM = d_{33}^2 / \varepsilon \tag{5}$$

Maximizing (4) gives the most energetic material. Inspecting a table of common materials shows that PVDF and PZT are good candidates. PVDF has $d_{33} = -33$ pC/N and

TABLE I
ENERGETIC MOTIONS FOR BIOMECHANICAL ELECTRIC POWER

Joint/Motion	Work [J/step]	Power [W]	Max moment [Nm]	Negative work [%]
Heel Strike	1 (1-5)	2 (2-20)		
Ankle	34.9 (33.4)	69.8 (66.8)	~140	42 (28.3)
Knee	24.7 (18.2)	49.5 (36.4)	~40	85.2 (92)
Hip	19.6 (18.96)	39.2 (38)	~40	11.5(19)
Elbow	1.07	2.1	1-2	37
Shoulder	1.1	2.2	1-2	61
Center of Mass	0.5	1		

$\varepsilon = 12\varepsilon_0$, while PZT has $d_{33} = 370\,\text{pC/N}$ and $\varepsilon = 1700\varepsilon_0$. They yield a similar *FOM*; the difference comes out in the voltage they produce for a given force. PVDF is slightly more energetic, but will produce much higher voltage (perhaps undesirable high).

Thus, we can maximize (4) by manipulating the area and thickness. Inspection shows that maximizing thickness and minimizing area yield the best possibility. However, this comes with compliance. The thickness for heel strike is limited by the thickness of the heel that is acceptable. The area will be limited in minimum by either the breakdown electric field or the maximum stress of the material prior to plastic deformation. At a maximum, the area must fit on a heel. A more subtle constraint is the voltage produced under force. Too much or too little causes practical problems with connecting the generator to the load.

First, we maximize the thickness (e.g. 2.5 cm). If the breakdown field is E_b, we can get an area (LW) of

$$A_b = LW = d_{33}F/(\varepsilon E_b) \tag{6}$$

Next, if the maximum pressure is $P_{\max}$, resulting in a voltage of

$$V_p = \frac{d_{33}P_{\max}t}{\varepsilon} \tag{7}$$

However, we may have a realistic voltage to work with, say $V_{\max}$. Thus, the area associated with the realistic voltage is

$$A_r = \frac{d_{33}Ft}{\varepsilon V_{\max}} \tag{8}$$

Yet, we have a maximum area of the shoe to consider, $A_{\max}$, which will yield a minimum voltage

$$V_{\min} = \frac{d_{33}Ft}{\varepsilon A_{\max}} \tag{9}$$

Therefore, we must choose the area such that the area itself and the voltage that results meet these constraints.

Consider a plausible example for heel strike (PVDF), wherein the thickness is $t = 2.5\,\text{cm}$, the breakdown field is $E_b = 10^8$ V/m, the maximum pressure is $P_{\max} = 14\,\text{MPa}$, and maximum voltage is $V_{\max} = 10\,\text{V}$ (obviously one can play with this number a bit, but suppose the device is no more electrically dangerous than a 9 V battery in normal circumstances). Assume a mass of 90 kg, which is somewhat high for an average man, and take the heel to be about 120 cm^2.

These parameters yield $V_b = 2.54\,\text{MV}$, $A_b = 0.004\,\text{in}^2$, $A_{\min} = 0.1\,\text{in}^2$, $V_p = 110\,\text{kV}$, $A_r = 1000\,\text{in}^2$, and $V_{\min} = 544\,\text{V}$. We see that the constraints cannot be satisfied. The breakdown field isn't a problem, but if basing the area on maximum stress, we need 110 kV. Even when spreading out the area to fill out the shoe, a high voltage of 544 V is still needed.

Now, assume a 90 kg person walking at 2 step/s with 120 cm^2 heel area, from the calculation, the PVDF generates 16 μW at 544 V. The PZT yields a much lower voltage, 45 V, to work with, but still only 14 μW. Their power levels are really not useful in modern technologies.

A possible approach might be to layer the piezoelectric materials in multiple layers, thus we can lower the output voltage of each layer. For PVDF, a 60-layer device will give each layer only 9 V to 10 V. We can also reduce the thickness by a factor of 60 to make it work, but that leaves us only 130 nJ per layer.

Thus, we conclude that compression mode piezoelectric generator is not a useful application for heel strike energy conversion.

2) Bending Mode

Suppose instead we bend the piezoelectric device. This takes advantage of the 31 mode instead. It is a more complicated device, but also provides much more energy.

a) Cantilever Mounted

First, under the assumption that the strain is distributed evenly along the bender, let's consider a cantilever mounted bender with width W, length L, thick t, charge coefficient d_{31}, voltage coefficient g_{31}, Young's modulus Y, and maximum surface strain S_{max}. By applying a force, F, at the free end, the voltage across the thickness direction is

$$V = \frac{3FLg_{31}}{2Wt} \tag{10}$$

Thus, the total available energy per bending is

$$E = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon LW}{t}\frac{9F^2L^2{g_{31}}^2}{4W^2t^2} \tag{11}$$

where $F = K_{stiff}\Delta x$, where Δx is the free end deflection and K_{stiff} is the equivalent stiffness of the bender as

$$K_{stiff} = \frac{3YI}{L^3} = \frac{3t^3WY}{12L^3} \tag{12}$$

Plugging (12) into (13), the energy in terms of bender's physical dimensions is

$$E = \frac{9}{8}\frac{\varepsilon L^3}{Wt^3}\frac{9T^6W^2Y^2}{144L^6}\Delta x^2{g_{31}}^2 \tag{13}$$

With $S = \dfrac{t\Delta x}{L^2}$, we can constrain the maximum energy value with S_{max} as

$$E_{\max} = \frac{9}{128}\varepsilon WtLS_{\max}{}^2 Y^2 g_{31}{}^2 \qquad (14)$$

In the expression, WtL is the bender total volume, which is constrained by the maximum device size the heel can tolerate. $\varepsilon Y^2 g_{31}{}^2$ is a constant determined by the material properties. Assume a maximum volume from $W = 10\,\text{cm}$, $L = 18\,\text{cm}$, $t = 0.13\,\text{mm}$ (although t can be chosen to for more power, it will limit Δx and therefore S_{max}), we can get 0.4 mW power with PZT or 36 mW power with PVDF from a cantilever mounted bender.

However, in the actual heel strike, the strain is concentrated at the bending point of the foot rather than distributed evenly. Thus, it is almost impossible to get actual power from the bender. Therefore, we can exclude the cantilever mounted bender from a useful method for heel strike energy conversion.

b) Simple Beam Mounted Bender

Now consider a simple bean mounted bender with width W, length L, thick t, charge coefficient d_{31}, voltage coefficient g_{31}, Young's modulus Y, and maximum surface strain S_{max}.

From [13], the voltage across the thickness direction under a thickness direction force F at the middle of the bender is

$$V = \frac{1}{4}\frac{3FLg_{31}}{2Wt} \qquad (15)$$

Going through a similar procedure as above, the available energy is

$$E = \frac{9}{8}\frac{\varepsilon E^2 t^3 g_{31}{}^2 W}{L^3}\Delta x^2 \qquad (16)$$

with $S = \frac{4t\Delta x}{L^2}$, we can get the expression constrained with S_{max}

$$E = \frac{9}{128}\varepsilon WtLS^2 Y^2 g_{31}{}^2 \qquad (17)$$

However, for a simple beam mounted bender, if the bender is originally flattened, it is difficult to make a deflection when it is attached to the heel. A better way to do it is to use the pre-loaded bender, which is a simple mounted device with deflection at original shape. When a force is applied to such pre-loaded devices at the opposite direction of its original deflection, the bender will be flattened. The strain change will induce a voltage across the two side of the bender. Theoretically, the absolute strain will be the same as flat bender; therefore, the induced voltage should be the same. However, the experiment data has shown that the pre-loaded bender has much better piezo properties than a flat bender: higher d_{31} coefficients [14]. Research is being conducted to obtain more accurate estimation of the effective d_{31} coefficients. In our calculation, we used a value of 2.3 times original d_{31} coefficient.

In [1], researchers fulfilled a heel strike energy conversion device with a PZT based preloaded bender (so-called "Thunder device", from Face International Corporation. For comparison, we made our power calculation based on various Thunder benders.

Reference [15] has showed that a comfortable displacement under the human heel is 1.27 cm. Thus, to obtain maximum power, we can stack two Thunders to form a clamshell stack. And stack more such clamshells to get a total deflection around 1.27 cm.

By using (14) and accounting the effective d_{31} coefficient, we calculated the available power from the current available thunder benders from FACE with 1 strikes/s walking velocity as shown in Table 2.

TABLE 2
PRE-LOADED BENDING GENERATOR

	TH-6R	TH-7R	TH-8R
Stack No.	2	1	3
Cost (USD)	380	196	552
Voltage (V)	670	560	230
Power (mW)	133	111	8

Even under the best circumstances, only mJ of energy can be stored in a heel-sized material. By using only one TH-6R clamshell stack, MIT media lab has come up with the experiment data of 306 volt and 30 mJ per step, which shows that we are actually over-estimating the available energy. Compared with the millivolt level power, the voltages involved are obviously high. Further, more layers creates a bad wiring problem and adds cost. Meanwhile, the coupling coefficient (fraction of mechanical to electrical energy converted on a movement) is at best 0.7, which must be dealt with twice both on compression and release. So, better than 50% efficiency is hard to achieve. The fundamental problem is that the same device is being used for *storage* **and** *conversion*. While seemingly elegant, the piezoelectric material does neither particularly well.

B. Electrostatic

Compression or rotation could be done with electrostatic machines. These machines are like the piezoelectrics except without the electroactive material. To generate power, an applied voltage is required, so standalone operation is impossible. Electrostatic machines only outperform magnetic with very small dimensions (microns) involved [16]. Therefore, we feel electrostatic machines are unlikely to be useful for this problem, though we cannot rule out future studies.

C. Electroactive Polymers (EAP)

EAPs are very similar to piezoelectrics in that mechanical stress produces a (high) voltage stored capacitively [1]. However, EAPs can provide more strains and are much more versatile and designed more for actuation than piezoelectrics, which are primarily for sensing. However, EAPs have low efficiency compared to magnetic machines running at sufficient speed. Similar to electrostatic generators, they need an applied voltage to provide charges on the electrodes. Further, for the dielectric elastomer generator, a relatively high voltage (1-6 kV) is needed for operation, which requires high-voltage-low-current switches, more complicated power electronics circuit, and consequently adds cost for the generator. On the other hand, the excellent strain properties of EAPs allow much more energy to be stored in a compression, which can be released for power generation. In [4], a heel-strike generator was built with dielectric elastomer (one of the electronic EAPs and was reported to generate 0.28 J energy, which is much high than that of the piezoelectric generators. Compared with magnetic materials, EAPs are much lighter and easier to tailor. Although EAPs are still in a research phase, we can conclude that they are eminently suitable for unusual motions and are a good alternative for biomechanical application [16].

D. Magnetic Actuation

Magnetic machines dominate in normal electromechanics due to the low cost, high efficiency, and proven designs. Weight and volume are of utmost importance to consider when choosing a topology for the machine. For any device with parts in relative motion, a gap for fluid (usually air) is required. In [17], it was shown that except for machines with very small air gaps (microns), magnetic-based topologies have much higher energy density than electrostatic. However, these machines are generally most efficient at higher speeds and in rotary implementations. For example, machine modeled as a voltage-behind-resistance (like a PM generator at low speed) has efficiency

$$\eta = \frac{1}{2} + \frac{1}{2}\sqrt{1-\frac{4RP}{\omega\lambda}} \qquad (18)$$

where P is the output power, R is the series resistance, and λ is the peak magnet flux linkage of the PM.

This is clearly bad for low speed implementation. Some motions are rotary, though not fully 360 degrees, and the speed of motions is relatively slow. Other motions, such as heel strike, are distinctly linear requiring a linear machine or some mechanical converter to use a rotary machine (which is of course undesirable).

Though this seems unpromising for magnetic machines, the rotation can be made much faster using flywheel arrangements in rotary motions or a mechanical spring (or better yet an elastic material in a shoe) in linear motions (heel strike) that can give high bursts of speed by releasing energy stored. The machine speed is not limited by the ~1 Hz walking as some have proposed [1]. Better than 90% efficiency is routinely obtained in good machines with sufficiently high speed. In [2,3,5], the authors focus on piezoelectrics, but implement a crude magnetic machine that far outperforms their relatively well-designed piezoelectric machine. A truer drawback to magnetic methods is that the material is relatively heavy compared to other methods.

It is clear that existing magnetic-based generator designs do not closely match the requirements of biomechanical energy conversion. Therefore, radical redesign of magnetic-based devices will be a thrust of their application task.

Somewhat similar conclusions were reached in a 1997 workshop [18], wherein high priority was given to magnetic systems. The discussion recorded in [18] was mostly speculative, however. In [19], human-power and other systems are contrasted, but without extensive data. Magnetic devices are discussed, however, as a less likely method of preferred actuation. However, if an appropriate system can be constructed to increase machine speed while power is delivered, we believe magnetic systems are probably the best alternative for the time being.

IV. EXPERIMENTS TO DATE

Our group is developing several energy harvesting machines based on our research findings. At present we have constructed a PM magnetic machine with linear motion (looks like a big voice coil). The machine incorporates a spring that stores mechanical energy efficiently. When released, the spring rapidly forces the generator speed, generating useful voltage. This would potentially be useful for heel strike, though this particular machine (shown in Fig. 4) was built for demonstration and design calibration. A voltage transient on spring release is shown in Fig. 5, which reveals a reasonable (3.5 V) peak to work with. When compressed a mere 1 cm (a proven comfortable condition for heel strike [15]) by an 800 N (~ 80kg) person, the spring stores about 4 J, so that approximately 4 W is going into the generator if compressed at 1 Hz. Notice that the transient occurs in < 40 ms, meaning the effective speed (and therefore efficiency) during the transient is much higher than simply moving the translator in and out at 1 Hz. Testing on this machine continues.

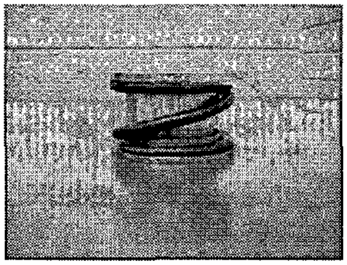

Fig. 4. PM linear generator for demonstrating decoupled storage and conversion of magnetic machines.

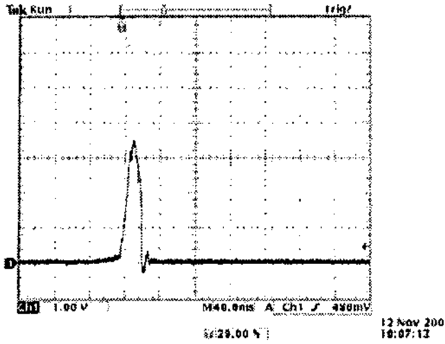

Fig. 5. Voltage transient of release of linear PM machine.

V. CONCLUSION

Piezoelectrics only have limited applications for loads with very low energy consumption. The magnetic machine and EAP are the best candidates for biomechanical energy harvesting generators, with magnetics being preferred for rotary motions and required mechanical energy storage (for speed bursts). EAPs are good for bending and linear motions, but EAPs' suitable for this application are not commercially available. The machines must be matched with energetic motions that are both powerful and ergonomic. A good candidate is the knee motion linked to a rotary magnetic machine with high pole count and a flywheel-ratchet assembly that keeps speed high. The EAP would match well to heel-strike and bending of the ankle, which both involve minimal or no rotation and need for light weight.

Electronically, the magnetic machine is far easier to work with. The voltage produced is easily scalable to make the power electronics design easy. EAPs have high voltage (kV) at low current (<mA), making them unlike commercially available silicon devices, for which there is no other market. In either case the electricity produced is of variable amplitude and frequency, making power conversion tricky, which is in future work.

VI. ACKNOWLEDGMENT

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