Human-powered wearable computing

by T. Starner

Batteries add size, weight, and inconvenience to present-day mobile computers. This paper explores the possibility of harnessing the energy expended during the user's everyday actions to generate power for his or her computer, thus eliminating the impediment of batteries. An analysis of power generation through leg motion is presented in depth, and a survey of other methods such as generation by breath or blood pressure, body heat, and finger and limb motion is also presented.

Wearable computing is an effort to make computers truly part of our everyday lives by embedding them into our clothing (e.g., shoes) or by creating form factors that can be used like clothing (e.g., sunglasses).[1] This level of access to computation will revolutionize how computers are used. Although the computational hardware has been reduced in size to accommodate this vision, power systems are still bulky and inconvenient. Even today's laptops and PDAs (personal digital assistants) are often limited by battery capacity, output current, and the necessity of having an electrical outlet within easy access for recharging. However, if energy can be generated by the user's actions, these problems will be alleviated.

At this point, a review of vocabulary and units is in order. Energy is defined as the capacity to do work. For this paper, the joule (J) will be used as the standard unit of energy. A joule ($kg \cdot m^2/sec^2$, i.e., kilogram multiplied by meters squared divided by seconds squared) is the product of a force of one newton acting through a distance of one meter. For reference, Table 1 compares some common sources of energy. The calorie, which is 4.19 joules, is also often used as a unit of energy. However, in dietary circles, a Calorie refers to a kilocalorie or 1000 calories. Therefore, an average adult diet of 2500 Calories translates to 10.5 megajoules (MJ).

Power, often confused with energy, is the time rate of doing work. Power can be measured in watts ($W = kg \cdot m^2/sec^3$), or joules per second. Table 1 also shows power requirements for some common computing devices. The reader should be aware that in some literature, units of power are combined with units of time to indicate energy. For example, watt seconds, watt hours, and kilowatt hours are often used instead of joule, kilojoule, and megajoule.

As shown by human-powered flight efforts,[2] the human body is a tremendous storehouse of energy. For example, the energy obtained from a jelly doughnut is

$$(330\,000 \text{ calories})\left(\frac{4.19\text{ J}}{\text{calorie}}\right)\left(\frac{1\text{MJ}}{1\times 10^{6}\text{ J}}\right) = 1.38\text{ MJ}$$

This energy may be stored in fat at approximately

$$\left(\frac{9000 \text{ calories}}{1\text{g}_{\text{fat}}}\right)\left(\frac{4.19\text{ J}}{\text{calorie}}\right) = 38\,000\text{ J per gram of fat}$$

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Table 1 Comparisons of common energy sources and common power requirements

Energy Sources		Common Power Requirements	
AA alkaline battery	10^4 J	Desktop (without monitor) computer	10^2 W
Camcorder battery	10^5 J	Notebook computer	10 W
Liter of gasoline	10^7 J	Embedded CPU board	1 W
A calorie	4.19 J	Low-power microcontroller chip	10^{-3} W
(Dietary) Calorie	4,190 J	Average human power use over 24 hours	121 W
Average human diet	1.05×10^7 J	Average human diet	1.05×10^7 W

Thus, an average person of 68 kg (150 lbs) with 15 percent body fat stores energy approximately equivalent to

$$0.15(68\,\mathrm{kg})\left(\frac{1000\,\mathrm{g}}{1\mathrm{kg}}\right)\left(\frac{38\,000\,\mathrm{J}}{1\mathrm{g}_{\mathrm{fat}}}\right) = 390\,\mathrm{MJ}$$

$$= 283 \text{ jelly doughnuts}$$

The body also consumes energy at a surprising rate, generally using between 70000 and 1400000 calories per hour, depending on the activity (see Table 2). In fact, trained athletes can expend close to 9.5 million calories per hour for short bursts.[3] In contrast, the energy rate, or power, expended while sleeping is

$$\left(\frac{70\,000\text{ calories}}{1\mathrm{hr}}\right)\left(\frac{4.19\,\mathrm{J}}{\text{calorie}}\right)\left(\frac{1\mathrm{hr}}{3600\,\mathrm{sec}}\right) = 81\mathrm{W}$$

Thus, the jelly doughnut introduced earlier would be "slept off" in 4.7 hours. If only a small fraction of such power could be harnessed conveniently and unobtrusively, batteries *per se* could be eliminated. However, difficulties arise from the acquisition, regulation, and distribution of the power.

Recent technology makes these tasks easier. Computers are now small enough to disappear into the user's clothing or body. With such small devices, the main power consumers, namely the CPU and storage, could be located near the implemented power source. Interface devices, such as keyboards, displays, and speakers, have limitations as to their placement on the body. However, these devices may communicate wirelessly via a "body network" as described by Zimmerman.[4] They may generate their own power, share in a power distribution system with the main generator (wired or wireless), or use extremely long-lasting batteries. Thus, depending on the user interface desired, wires may not be needed for power or data transfer among the components of a wearable computer.

In the following sections, power generation from breathing, body heat, blood transport, arm motion, typing, and walking are discussed. Although some of these ideas are fanciful, each has its own peculiar benefits and may be applied to other domains such as medical systems, general consumer electronics, and user interface sensors. More attention is given to typing and walking since these processes seem more practical sources of power for general wearable computing.

Body heat

Since the human body eliminates energy as heat, it follows naturally to try to harness this energy. However, Carnot efficiency puts an upper limit on how well this waste heat can be recovered. Assuming normal body temperature and a relatively low room temperature (20° C), the Carnot efficiency is

$$\frac{T_{\mathrm{body}} - T_{\mathrm{ambient}}}{T_{\mathrm{body}}} = \frac{(310\mathrm{K} - 293\mathrm{K})}{310\mathrm{K}} = 5.5\%$$

In a warmer environment (27° C) the Carnot efficiency drops to

$$\frac{T_{\mathrm{body}} - T_{\mathrm{ambient}}}{T_{\mathrm{body}}} = \frac{(310\mathrm{K} - 300\mathrm{K})}{310\mathrm{K}} = 3.2\%$$

Table 2 indicates that for sitting, a total of 116 W of power is available. Using a Carnot engine to model the recoverable energy yields 3.7–6.4 W of power. In

Table 2 Human energy expenditures for selected activities (derived from Reference 3)

Activity	Kilocal/hr	Watts
Sleeping	70	81
Lying quietly	80	93
Sitting	100	116
Standing at ease	110	128
Conversation	110	128
Eating a meal	110	128
Strolling	140	163
Driving a car	140	163
Playing violin or piano	140	163
Housekeeping	150	175
Carpentry	230	268
Hiking, 4 mph	350	407
Swimming	500	582
Mountain climbing	600	698
Long-distance running	900	1048
Sprinting	1400	1630

more extreme temperature differences, higher efficiencies may be achieved, but robbing the user of heat in adverse environmental temperatures is not practical.

However, even under the best of conditions (basal, non-sweating), evaporative heat loss accounts for 25 percent of the total heat dissipation. This "insensible perspiration" consists of water diffusing through the skin, sweat glands keeping the skin of the palms and soles pliable, and the expulsion of water-saturated air from the lungs.[5] Thus, the maximum power available, without trying to reclaim heat expended by the latent heat of vaporization, drops to 2.8–4.8 W.

The above efficiencies assume that all of the heat radiated by the body is captured and perfectly transformed into power. However, such a system would encapsulate the user in something similar to a wet suit. The reduced temperature at the location of the heat exchanger would cause the body to restrict blood flow to that area.[5] When the skin surface encounters cold air, a rapid constriction of the blood vessels in the skin allows the skin temperature to approach the temperature of the interface so that heat exchange is reduced. This self-regulation causes the location of the heat pump to become the coolest part of the body, further diminishing the returns of the Carnot engine unless a wet suit is employed as part of the design.

Although a full wet suit or even a torso body suit is unsuitable for many applications, the neck offers a good location for a tight seal, access to major centers of blood flow, and easy removal by the user. The neck is approximately 1/15 of the surface area of the "core" region (those parts that the body tries to keep warm at all times). As a rough estimate, assuming even heat dissipation over the body, a maximum of 0.20–0.32 W could be recovered conveniently by such a neck brace. The head may also be a convenient heat source for some applications where protective hoods are already in place. The surface area of the head is approximately three times that of the neck and could provide 0.60–0.96 W of power given optimal conversion. Even so, the practicality, comfort, and efficacy of such a system are relatively limited.

Breath

An average person of 68 kg has an approximate air intake rate of 30 liters per minute.[3] However, available breath pressure is only 2 percent above atmospheric pressure.[6,7] Increasing the effort required for intake of breath may have adverse physiological effects,[7] so only exhalation will be considered for generation of energy. Thus, the available power is

$$\begin{aligned} W &= p\Delta V \\ &= 0.02\left(\frac{1.013\times10^5\,\mathrm{kg}}{\mathrm{m}\cdot\mathrm{sec}^2}\right)\left(\frac{30\,\mathrm{l}}{1\,\mathrm{min}}\right)\left(\frac{1\,\mathrm{min}}{60\,\mathrm{sec}}\right)\left(\frac{1\,\mathrm{m}^3}{1000\,\mathrm{l}}\right) \\ &= 1.0\,\mathrm{W} \end{aligned}$$

During sleep the breathing rate, and therefore the available power, may drop in half, whereas increased activity increases the breathing rate. Forcing an elevated breath pressure with an aircraft-style pressure mask can increase the available power by a factor of 2.5, but it causes significant stress on the user.[5]

Harnessing the energy from breathing involves breath masks that encumber the user. For some professionals such as military aircraft pilots, astronauts, or handlers of hazardous materials, such masks are already in place. However, the efficiency of a turbine and generator combination is only about 40 percent,[8] and any attempt to tap this energy source would put an additional load on the user. Thus, the benefit of the estimated 0.40 W of recoverable power has to be weighed against the other, more convenient methods discussed in the following sections.

Another way to generate power from breathing is to fasten a tight band around the chest of the user. From empirical measurements, there is a 2.5 centimeter (cm) change in chest circumference when breathing normally and up to a 5 cm change when breathing deeply. A large amount of force can be maintained over this interval. Assuming a respiration rate of 10 breaths per minute and an ambitious 100 N force applied over the maximal 0.05 m distance, the total power that can be generated is

$$(100\text{N})(0.05\text{m})\left(\frac{10\text{ breaths}}{1\text{min}}\right)\left(\frac{1\text{min}}{60\text{sec}}\right) = 0.83\text{W}$$

A ratchet and flywheel attached to an elastic band around the chest might be used to recover this energy. However, friction due to the small size of the parts may cause some energy loss. With careful design, a significant fraction of this power might be recovered, but the resulting 0.42 W is a relatively small amount of power for the inconvenience.

Blood pressure

Although powering electronics with blood pressure may seem impractical, the numbers are actually quite surprising. Assuming an average blood pressure of 100 mm of Hg (mercury) (normal desired blood pressure is 120/80 above atmospheric pressure), a resting heart rate of 60 beats per minute, and a heart stroke volume of 70 milliliters (ml) passing through the aorta per beat,[9] then the power generated is

$$(100\text{mm Hg})\left(\frac{1.013\times10^{5}\text{kg/m}\cdot\text{sec}^{2}}{760\text{ mm Hg}}\right)\left(\frac{60\text{ beats}}{1\text{min}}\right)$$
$$\left(\frac{1\text{min}}{60\text{ sec}}\right)\left(\frac{0.07\text{l}}{\text{beat}}\right)\left(\frac{1\text{m}^{3}}{1000\text{l}}\right) = 0.93\text{W}$$

Although this energy rate can easily double when running, harnessing this power is difficult. Adding a turbine to the system would increase the load on the heart, perhaps dangerously so. However, even if 2 percent of this power is harnessed, low-power microprocessors and sensors could run. Thus, self-powering medical sensors and prostheses could be created.

Upper limb motion

A comparison of the activities listed in Table 2 indicates that violin playing and housekeeping use up to 30 kcal/hr, or

$$\frac{30\text{ kcal}}{1\text{hr}}\left(\frac{4.19\text{ J}}{1\text{calorie}}\right)\left(\frac{1\text{hr}}{3600\text{sec}}\right) = 35\text{W}$$

of power more than standing. Most of this power is generated by moving the upper limbs. Empirical studies done by Braune and Fischer[10] at the turn of the century show that for a particular 58.7 kg man, the lower arm plus hand masses 1.4 kg, the upper arm 1.8 kg, and the whole arm 3.2 kg. The distance through which the center of mass of the lower arm moves for a full bicep curl is 0.335 m, and raising the arm fully over the head moves the center of mass of the whole arm 0.725 m. Empirically, bicep curls can be performed at a maximum rate of 2 curls/sec, and lifting the arms above the head can be performed at 1.3 lifts/sec. Thus, the maximum power generated by bicep curls is

$$(1.8\text{ kg})\left(\frac{9.8\text{m}}{\text{sec}^{2}}\right)(0.335\text{m})\left(\frac{2\text{curls}}{\text{sec}}\right)(2\text{arms}) = 24\text{W}$$

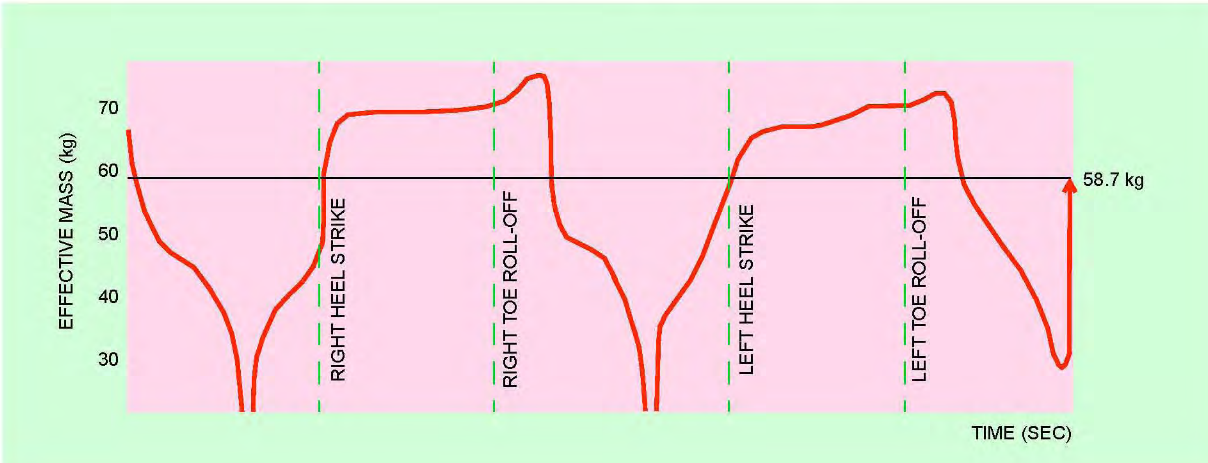
and the maximum power generated by arm lifts is

$$(3.2\text{kg})\left(\frac{9.8\text{m}}{\text{sec}^{2}}\right)(0.725\text{m})\left(\frac{1.3\text{lifts}}{\text{sec}}\right)(2\text{arms}) = 60\text{W}$$

Obviously, housekeeping and violin playing do not involve as much strenuous activity as these experiments. However, these calculations do show that there is plenty of energy to be recovered from an active user. The task at hand, then, is to recover energy without burdening the user. A much more reasonable number, even for a user in an enthusiastic gestural conversation, is attained by dividing the bicep curl power by a factor of eight. Thus, the user might make

Power generation by body heat, breath, or motion can potentially power a computer.

Figure 1 Empirical data taken of effective force perpendicular to the ground on the foot while walking for a 58.7 kg man (from Reference 10); this data curve should scale roughly based on weight



one arm gesture every two seconds. This, then, generates a total of 3 W of power. By doubling the normal load on the user's arms and mounting a pulley system on the belt, 1.5 W might be recovered (assuming 50 percent efficiency from loss due to friction and the small parts involved), but the system would be extremely inconvenient.

A less encumbering system might involve mounted pulley systems in the elbows of a jacket. The take-up reel of the pulley system could be spring-loaded so as to counterbalance the weight of the user's arm. Thus, the system would generate power from the change in potential energy of the arm on the downstroke and not require additional energy by the user on the upstroke. The energy generation system, the CPU, and the interface devices could be incorporated into the jacket. Thus, the user would simply don the jacket to use his or her computer. However, any pulley or piston generation system would involve many inconvenient moving parts and the addition of significant mass to the user.

A more innovative solution would be to use piezoelectric materials at the joints that would generate charge from the movement of the user. Thus, no moving parts *per se* would be involved, and the jacket would not be significantly heavier than a normal jacket. However, as will be seen in the following sections, materials with the appropriate flexibility have only 11 percent efficiency, making the recoverable power 0.33 W.

Walking

Using the legs is one of the most energy-consuming activities the human body performs. In fact, a 68 kg man walking at 3.5 mph, or 2 steps per second, uses 280 kcal/hr or 324 W of power.[3] Comparing this to a standing or strolling rate implies that up to half this power is being used for moving the legs. While walking, the traveler puts up to 30 percent more force on the balls of his feet than that provided by body weight (Figure 1). However, calculating the power that can be generated by simply using the fall of the heel through 5 cm (the approximate vertical distance that a heel travels in the human gait[10]) reveals that

$$(68\,\mathrm{kg})\left(\frac{9.8\,\mathrm{m}}{\mathrm{sec}^2}\right)(0.05\,\mathrm{m})\left(\frac{2\,\mathrm{steps}}{\mathrm{sec}}\right) = 67\,\mathrm{W}$$

of power is available. This result is promising given the relatively large amount of available power compared to the previous analyses. Even though walking is not continuous like breathing, some of the power could be stored, providing a constant power supply even when the user is not walking. The next three subsections outline the feasibility of harnessing this power via piezoelectric and rotary generators, and the fourth subsection presents calculations on harnessing wind resistance.

Piezoelectric materials. Piezoelectric materials create electrical charge when mechanically stressed. Among the natural materials with this property are quartz, human skin, and human bone, though the latter two have very low coupling efficiencies. Table 3 shows properties of common industrial piezoelectric materials: polyvinylidene fluoride (PVDF) and lead zirconate titanate (PZT). For convenience, references for data sheets and several advanced treatments of piezoelectricity are included at the end of the paper.[11,12,14–16]

The coupling constant shown in Table 3 is the efficiency with which a material converts mechanical energy to electrical energy. The subscripts on some of the constants indicate the direction or mode of the mechanical and electrical interactions (see Figure 2). "31 mode" indicates that strain is caused to axis 1 by electrical charge applied to axis 3. Conversely, strain on axis 1 will produce an electrical charge along axis 3. Bending elements, made by an expanding upper layer and a compressing bottom layer separated by a shim, are made to exploit this mode in industry. In practice, such bending elements have an effective coupling constant of 75 percent of the theoretical due to storage of mechanical energy in the mount and metal shim center layer.

The most efficient energy conversion, as indicated by the coupling constants in Table 3, comes from compressing PZT (d_{33}). Even so, the amount of effective power that could be transferred in this way is minimal since compression follows the formula

$$\Delta H = \frac{FH}{AY}$$

where F is force, H is the unloaded height, A is the area over which the force is applied, and Y is the elastic modulus. The elastic modulus for PZT is 4.9×10^{10} N/m^2. Thus, it would take an incredible force to compress the material a small amount. Since energy is defined as force through distance, the effective energy generated through human-powered compression of PZT would be vanishingly small, even with perfect conversion.

In contrast, bending a piece of piezoelectric material to take advantage of its 31 mode is much easier. Because it is brittle, PZT does not have much range of motion in this direction. Maximum surface strain for this material is 5×10^{-4}. Surface strain can be defined as

Figure 2 **Definition of axes for piezoelectric materials—note that electrodes are mounted on axis 3[13]**

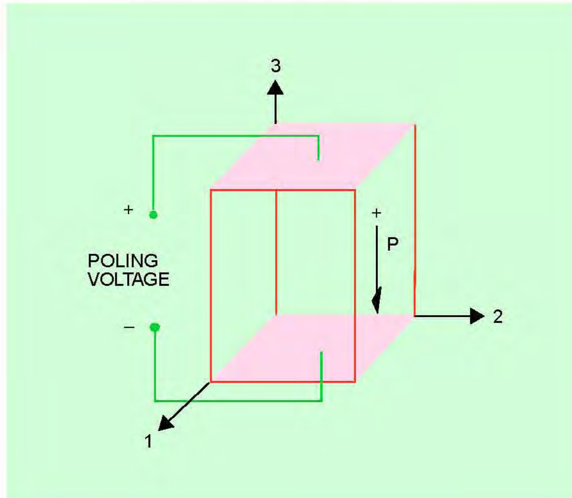


Table 3 **Piezoelectric characteristics of PVDF and PZT (adapted from References 11, 12, and 13)**

Property	Units	PVDF	PZT
Density	g/cm^3	1.78	7.6
Relative permitivity	$\varepsilon/\varepsilon_0$	12	1700
Elastic modulus	10^{10}N/m	0.3	4.9
Piezoelectric constant	10^{-12}C/N	d_{31}=20 d_{33}=30	d_{31}=180 d_{33}=360
Coupling constant	CV/Nm	0.11	k_{31}=0.35 k_{33}=0.69

$$S = \frac{xt}{L_c^2}$$

where x is the deflection, t is the thickness of the beam, and L_c is the cantilever length. Thus, the maximum deflection or bending for a beam (20 cm) of a piezoceramic thin sheet (0.002 cm) before failure is

$$x = \frac{(S)(L_c^2)}{t} = \frac{(5 \times 10^{-4})(0.2\text{m})^2}{0.00002\text{m}} = 1\text{cm}$$

Thus, PZT is unsuitable for jacket design or applications where flexibility is necessary.

PVDF, in contrast, is very flexible. In addition, it is easy to handle and shape, exhibits good stability over time, and does not depolarize when subjected to very high alternating fields. The cost, however, is that the coupling constant for PVDF is significantly lower than that for PZT. Also, shaping PVDF can reduce the effective coupling of mechanical and electrical energies due to edge effects. Furthermore, the efficiency of the material degrades depending on the operating climate and the number of plies used. Fortunately, from an industry representative,[17] we know a 116 cm^2 40-ply triangular plate with a center metal shim deflected 5 cm by 68 kg three times every 5 seconds results in the generation of 1.5 W of power. This result is a perfect starting point for the calculations in the next subsection.

Piezoelectric shoe inserts. Consider the use of PVDF shoe inserts for recovering some of the power in the process of walking. There are many advantages to this tactic. First, a 40-ply pile would be only (28 micrometers)(40) = 1.1 mm thick (without electrodes). In addition, the natural flexing of the shoe when walking provides the necessary deflection for generating power from the piezoelectric pile (see Figure 3). PVDF is easy to cut into an appropriate shape and is very durable.[11,12] In fact, PVDF might be used as a direct replacement for normal shoe stiffeners. Thus, the inserts could be easily put into shoes without moving parts or seriously redesigning the shoe.

A small woman's shoe has a footprint of approximately 116 cm^2. Knowing that the maximum effective force applied at the end of a user's step increases the apparent mass by 30 percent, the user needs only 52 kg (115 lbs) of mass to deflect the PVDF plate a full 5 cm. Although the numbers given in the last section were for a 15.2 cm by 15.2 cm triangular 40-ply pile, the value can be used to approximate the amount of power an appropriately shaped piezoelectric insert could produce. Thus, scaling the previous 1.5 W at 0.6 deflections per second to two steps per second,

$$(1.5\text{ W})\left(\frac{2\text{ steps/sec}}{0.6\text{ steps/sec}}\right) = 5\text{ W}$$

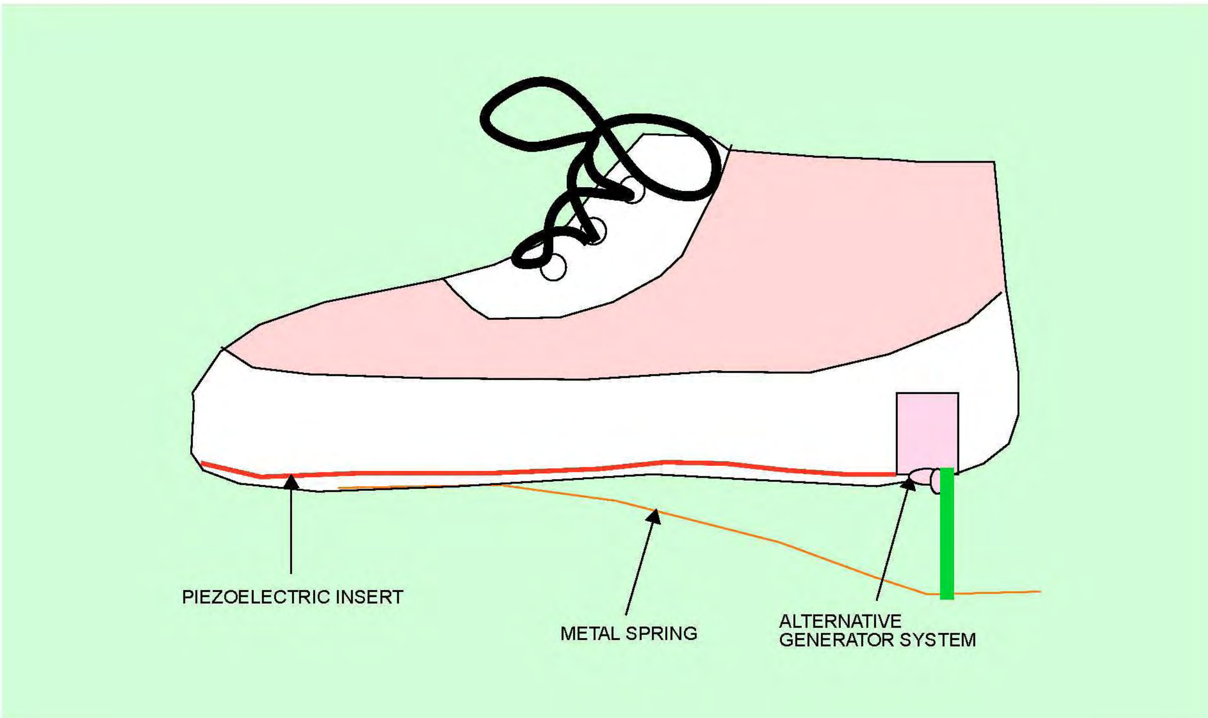
of electrical power could be generated by a 52 kg user at a brisk walking pace.

Rotary generator conversion. Through the use of a cam and piston or ratchet and flywheel mechanism, the motion of the heel might be converted to electrical energy through more traditional rotary generators. The efficiency for industrial electrical generators can be very good. However, the added mechanical friction of the stroke-to-rotary converter reduces this efficiency. A normal car engine, which contains all of these mechanisms and suffers from inefficient fuel combustion, attains 25 percent efficiency. Thus, for the purposes of this section, a 50 percent conversion efficiency will be assumed for this method, which suggests that, conservatively, 17–34 W might be recovered from a "mechanical" generator.

How can this energy be recovered without creating a disagreeable load on the user? A possibility is to improve the energy return efficiency of the shoe and tap some of this recovered energy to generate power. Specifically, a spring system, mounted in the heel, would be compressed as a matter of course in the human gait. The energy stored in this compressed spring can then be returned later in the gait to the user. Normally this energy is lost to friction, noise, vibration, and the inelasticity of the runner's muscles and tendons (humans, unlike kangaroos, become less efficient the faster they run[3]). Spring systems have approximately 95 percent energy return efficiency, whereas typical running shoes range from 40 percent to 60 percent efficiency.[18,19] Volumetric oxygen studies have shown a 2–3 percent improvement in running economy using such spring systems over typical running shoes.[19] Similarly suggestive are the "tuned" running track experiments of McMahon.[20] The stiffness of the surface of the indoor track was adjusted to decrease foot contact time and increase step length. The result was a 2–3 percent decrease in running times and seven new world records in the first two seasons of the track. Additionally, a reduction in injuries and an increase in comfort was observed. Thus, if a similar spring mechanism could be designed for the gait of normal walking, and a ratchet and flywheel system is coupled to the upstroke of the spring, it may be possible to generate energy while giving the user an improved sense of comfort (Figure 3). In fact, active control of the loading of the generation system may be used to adapt energy recovery based on the type of gait at any given time.

Since a simple mechanical spring would not provide constant force over the fall of the heel but rather a linear increase (for the ideal spring), only about half of the calculated energy would be stored on the down-

Figure 3 Simple diagram showing two shoe generation systems: (1) piezoelectric film insert or (2) metal spring with coupled generator system



step. An open question is what fraction of the return energy of the spring can be sapped on the upstep while still providing the user with the sense of an improved "spring-in-the-step" gait. Initial mock-ups have not addressed this issue directly, but a modern running shoe returns approximately 50 percent of the 10 J it receives during each compression cycle[18] (such "air cushion" designs were considered a revolutionary step forward over the hard leather standard several decades ago). Given a similar energy return over the longer distance of the spring system, the energy storage of the spring, and the conversion efficiency of the generator, 12.5 percent of the initial 67 W is harnessed for a total of 8.4 W of available power.

Air resistance. A final potential method of generating power is to harness air drag while the user is walking. At a run of 6 miles per hour (mph), only 3 percent of the expended energy (10^3 W) is performed against air resistance.[3] Although 30 W of power is a significant amount, little of this energy could be harnessed without severely encumbering the user. At more reasonable walking speeds, the available power declines sharply. Thus, it seems pointless to pursue a hard-to-recover energy source that can only yield 3 percent of the user's total energy when leg motion may consume over 50 percent of the total energy during the same activity.

Finger motion

Keyboards will continue to be a major interface for computers into the next decade.[1] As such, typing may provide a useful source of energy. On a one-handed chording keyboard (HandyKey's Twiddler), it is necessary to apply 130 grams of pressure in order to depress a key the required 1 mm for it to register. Thus,

$$\left(\frac{0.13\,\text{kg}}{\text{keystroke}}\right)\left(\frac{9.8\,\text{m}}{\text{sec}^2}\right)(0.001\,\text{m}) = 1.3\,\text{mJ per keystroke}$$

is necessary to type. Assuming a moderately skilled typist (40 words per minute, or wpm), and taking into account multiple keystroke combinations, an average of

$$\left(\frac{1.3\,\mathrm{mJ}}{\mathrm{keystroke}}\right)\left(\frac{5.3\,\mathrm{keystrokes}}{\mathrm{sec}}\right) = 6.9\,\mathrm{mW}$$

of power is generated. A fast QWERTY typist (90 wpm) depresses 7.5 keys per second. A typical keyboard requires 40–50 grams of pressure to depress a key the 0.5 cm necessary to register a keystroke (measured on a DEC PC 433 DX LP). Thus, a QWERTY typist may generate

$$\left(\frac{0.05\,\mathrm{kg}}{\mathrm{keystroke}}\right)\left(\frac{9.8\,\mathrm{m}}{\mathrm{sec}^2}\right)(0.005\,\mathrm{m})\left(\frac{7.5\,\mathrm{keystrokes}}{\mathrm{sec}}\right)$$
$$= 19\,\mathrm{mW}$$

of power. Unfortunately, neither method provides enough continuous power to sustain a portable computer, especially since the user would not be continuously typing on the keyboard. However, there may be enough energy in each keystroke for each key to "announce" its character to a nearby receiver.[21] For example, the keyboard may have a permanent magnet in its base. Each key would then have an embedded coil that would generate a current when the key was moved. Another possibility is to use PVDF, which bends at each keystroke, to generate energy (again, 11 percent efficiency). Thus, a wearable, wireless keyboard may be possible.

Notebook computer power

Current notebook computers offer a unique method for generating energy—simply opening the computer may supply power. However, this one action needs to provide power for the entire session; otherwise, users would be forced to flap their computers open and closed. From some simple empirical tests, the maximum force that a user may reasonably expect to exert when opening a notebook computer is

$$(20\,\mathrm{lbs})\left(\frac{1\,\mathrm{kg}}{2.2\,\mathrm{lbs}}\right)\left(\frac{9.8\,\mathrm{m}}{\mathrm{sec}^2}\right) = 89.1\,\mathrm{N}$$

Assuming a maximum of 0.5 m of swing when opening the computer,

$$(89.1\,\mathrm{N})(0.5\,\mathrm{m})\left(\frac{1}{600\,\mathrm{sec}}\right) = 74\,\mathrm{mW}$$

of power would be available for a 10-minute session. For an hour's use, the available power drops to 12 mW. For most current applications, these power rates are inadequate.

Storage considerations

Figure 4 shows a summary of the body-driven generation methods discussed so far. Every power generation system proposed, with the possible exception of heat conversion, would require some power storage device for periods between power generation cycles. Thus, some attention is necessary regarding the efficiency of storage.

Electrical storage may be preferable because of its prevalence and miniaturization. First, however, the power must be converted to a usable form. For the piezoelectric method, a step-down transformer and regulator would be needed. Current strategies for converting the high voltages generated by piezoelectric materials to computer voltage levels can attain over 90 percent efficiency.[22] Care is needed to match the high impedance of the piezo generator properly, and, due to the low currents involved, the actual efficiency may be lower. For the other generation methods, power regulators would be needed as well, and aggressive strategies can attain 93 percent efficiency.

The most direct solution to the problem of electrical storage is to charge capacitors that can be drained for power during periods of no power generation. However, simply charging the capacitor results in the loss of half the available power.[23] Unfortunately, a purely capacitive solution to the problem is also restricted by size. Currently, small (less than 16 cm^3) 5 V supercapacitors are rated for approximately 3 farads. Thus, only

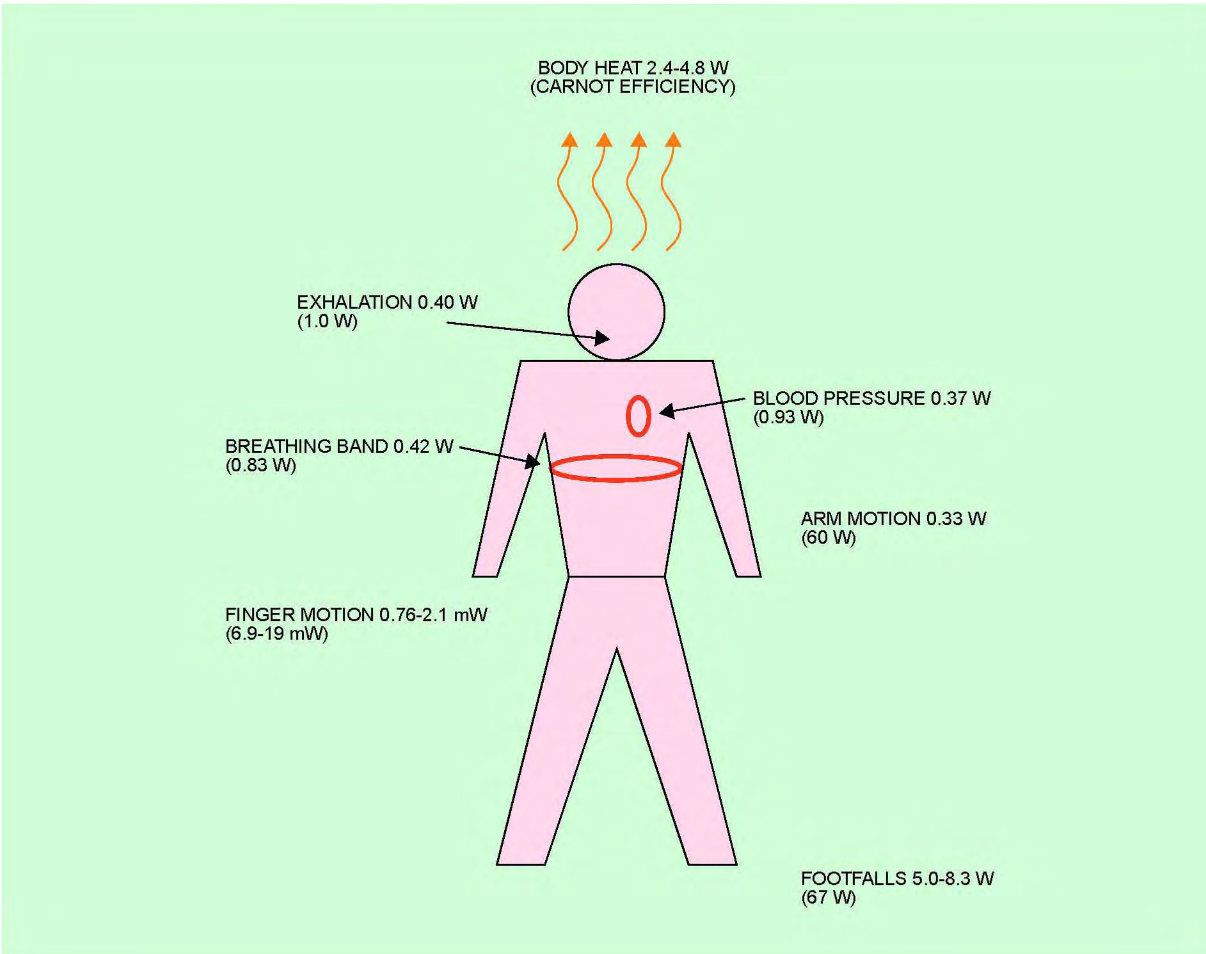
$$E = (0.5)CV^2 = (0.5)(3\mathrm{F})(5\mathrm{V})^2 = 37.5\mathrm{J}$$

of energy can be stored. Correspondingly, for non-generative cycles of a minute,

$$\frac{38\mathrm{J}}{60\,\mathrm{sec}} = 0.62\,\mathrm{W}$$

can be provided from a fully charged capacitor. This amount is acceptable as an energy reservoir for

Figure 4 Power from body-driven sources; total power for each action is included in parentheses



breathing, blood pressure, and body heat. Capacitive storage is not suitable for upper limb motion, walking, or typing, except for domains in which the particular body action is continuously performed, since power supplied from the capacitor over an hour drops to 0.01 W. In order to provide even 1 W of power over this time interval, 100 such capacitors would be necessary. In such cases, rechargeable batteries may be employed. Table 4 compares the energy densities, both by weight and volume, of currently available batteries. The on-time values are of particular interest since they show the maximum amount of time a 5 W computer could be run from a battery contained in the heel of a shoe (assuming 100 cm^3 of volume). Note that the mass of the zinc-air battery would be around 0.12 kg if it could be manufactured in this form factor.

Mechanical energy storage may be more attractive for some of the generation mechanisms described above. For example, with walking as a source of power generation, flywheels, pneumatic pumps, and clock springs may prove more fruitful in storing power. However, the possibilities are numerous, and coverage of the field is beyond the scope of this paper.

Power requirements for computing

A recent trend in computing is for more capability to be packed into smaller spaces with less power consumption. At first this trend was pushed by laptop computers. With the advent of pen computing and PDAs, components have become even smaller and

Table 4 Comparison of rechargeable battery technologies†

Property	Lead Acid Gel	Nickel Cadmium	Nickel-Metal Hydride	Lithium-Ion	Zinc-Air
MJ/kg	0.115	0.134	0.171	0.292	0.490
J/cm^3	426	354	498	406	571
On-time (hr)	2.37	1.97	2.77	2.26	3.17

† Derived from data released by CPSI.[24] On-time refers to the running time of a 100 cm^3 battery with a 5-W drain.

more manageable. Now it is possible to make a computer that can be worn and run constantly.[1]

For example, the author's wearable computer requires 5 W of power to run all components continuously (head-mounted display, hard disk, 25 MHz 80386 CPU, 8M RAM, serial/parallel/PCMCIA ports, etc.) A standard off-the-shelf 1 kg gel cell battery can power this unit for six hours. However, such a battery has a volume of 450 cm^3. Better battery technology is available, and the author's computer does not use power management.

A viable wearable computer that could be made with a PIC 16C71 processor from Microchip Technology Inc. This chip requires only 18 mW at 4 MHz and 0.1 mW at 32 kHz.[25] With flash memory instead of rotary disk storage, some driver circuitry, and a Private Eye** head-mounted display from Reflection Technology Inc., a functional wearable computer (without communications) could be made with a power consumption of 0.5 W. Thus, significant computing power can be obtained even on a relatively strict power budget.

Conclusion

Although computing, display, communications, and storage technology may become efficient enough to require unobtrusive power supplies, the desire for the fastest CPU speeds and highest bandwidth possible will offset the trend. In addition, dependence on power cells requires the user to "plug in" occasionally. This is impossible in some military and professional contexts. If body motion is used, it may be significantly more convenient to shift weight from one foot to another, for example, than to search for an electrical outlet.

Each of the generation methods has its own strengths and weaknesses, depending on the application. However, power generation through walking seems best suited for general-purpose computing. The user can easily generate power when needed, and, in many cases, the user's everyday walking may be sufficient. A surprising amount of power (5–8 W) may be recovered while walking at a brisk pace, possibly without stressing the user. If less power is needed, piezoelectric inserts may be used, reducing the mechanical complexity of the generation system. However, issues of energy storage and human factors still have to be resolved. Thus, the natural next step is to prototype a generator.

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Cited references

1. T. Starner, S. Mann, B. Rhodes, J. Healey, J. Levine, and A. Pentland, *Wearable Computing and Augmented Reality,* to appear in 1997 Presence issue on Augmented Reality, MIT Press, Cambridge, MA; also Vision and Modeling Technical Report #355, MIT Media Laboratory, Cambridge, MA (1995).
2. R. Sullivan and T. Clancy, *Experimental Measurement of the Power Required to Fly the Daedalus Human Powered Aircraft,*

American Institute of Aeronautics and Astronautics, Washington, DC (1989), p. 3385.
3. D. Morton, *Human Locomotion and Body Form*, The Williams & Wilkins Co., Baltimore (1952).
4. T. Zimmerman, *Personal Area Networks (PAN): Near-Field Intra-Body Communication*, master's degree thesis, MIT Media Laboratory, Cambridge, MA (September 1995).
5. *A Textbook of Aviation Physiology*, J. Gillies, Editor, Pergamon Press, Oxford (1965).
6. Correspondence with Donna Wren, M.D. (May 1995).
7. Correspondence with Paul Picot, Robarts Research Institute, London, Ontario, Canada (May 1995).
8. D. Halliday, R. Resnick, and K. Krane, *Physics, 4th edition*, Vol. 1 & 2 extended, John Wiley & Sons Inc., New York (1992).
9. *Heart Disease: A Textbook of Cardiovascular Medicine*, E. Braunwald, Editor, W. B. Saunders Company, Philadelphia (1980).
10. W. Braune and O. Fischer, *The Human Gait* (originally published 1895–1904), Springer-Verlag, Berlin (1987).
11. Piezo Film Vibration Sensors: New Techniques for Modal Analysis and Data Sheet, AMP Inc., Valley Forge, PA.
12. J. Fraden, *AIP Handbook of Modern Sensors*, American Institute of Physics, New York (1993).
13. Piezoelectric Motor/Actuator Kit Manual, Introduction to Piezoelectricity, Piezo Systems, Inc., Cambridge, MA. Reprinted with permission.
14. W. Cady, *Piezoelectricity*, Dover Publishers, Inc., New York (1964).
15. R. Holland and E. EerNisse, *Design of Resonant Piezoelectric Devices*, Research Monograph No. 56, MIT Press, Cambridge, MA (1969).
16. N. Rogacheva, *The Theory of Piezoelectric Shells and Plates*, CRC Press, Boca Raton, FL (1994).
17. Correspondence with Don Halvorsen, AMP Inc. (May 1995).
18. *Endurance Training Journal*, Running Training Section, http://s2.com/etj/index.html.
19. Correspondence with H. Herr (April 1996).
20. T. McMahon, *Muscles, Reflexes, and Locomotion*, Princeton University Press, Princeton, NJ (1984), pp. 219–229.
21. Idea suggested by Michael Hawley, MIT Media Laboratory (March 1995).
22. Correspondence with Russell Hoffman, Fore Systems Inc. (May 1995).
23. N. Gershenfeld, *The Physics of Information Technology* (preliminary draft), Cambridge, MA (May 1995).
24. Data sheet comparing battery performance for the Mobile Assistant™, Computer Products and Services, Inc., Fairfax, VA (1995).
25. Preliminary data sheet on PIC 16C71, Microchip Technology Inc. (1992).

General references

G. Cavagna, H. Thys, and A. Zamboni, "The Sources of External Work in Level Walking and Running," *Journal of Physiology* **262**, 639–657 (1976).

G. Cavagna, N. Heglund, and C. Taylor, "Mechanical Work in Terrestrial Locomotion: Two Basic Mechanisms for Minimizing Energy Expenditure," *American Journal of Physiology* **233**, No. 5, R243–R261 (1977).

Control of Posture and Locomotion, R. Stein, K. Pearson, R. Smith, and J. Redford, Editors, Plenum Press, New York (1973).

T. McMahon, "Spring-Like Properties of Muscles and Reflexes in Running," *Multiple Muscle Systems: Biomechanics and Movement Organization*, J. Winters and S. Woo, Editors, Springer-Verlag, Berlin (1990).

Mechanics and Energetics of Animal Locomotion, R. Alexander and G. Goldspink, Editors, Chapman and Hall Ltd., London (1977).

R. Shephard, *Human Physiological Work Capacity*, Cambridge University Press, Cambridge, U.K. (1978).

J. Williams, H. Metcalfe, F. Trinklein, and R. Lefler, *Modern Physics*, Holt, Rinehart, and Winston Inc., New York (1968).

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