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Prospects of Regenerating Energy from Human Kinematics

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Abstract

Practice of Energy harvesting is very old, which has been based on established principles and theories, which is utilized in various machines and devices. for powering sensor networks and mobile electronics. Systems can scavenge power from human activity or derive limited energy from ambient heat, light, radio, or vibrations. Ongoing power management developments enable battery-powered electronics to live longer. Such advances include dynamic optimization of voltage and clock rate, hybrid analog-digital designs, and clever wake-up procedures that keep the electronics mostly inactive. Applying suck techniques to larger machines such as treadmill and bicycle, by using various dynamometers in a gym facility or at home can also produce renewable energy in large amount. Humans release a lot of energy from their everyday activities, such as simple breathing and walking. Energy harvesting's true legacy dates to the water wheel and windmill, and credible approaches that scavenge energy from waste heat or vibration have been around for many decades. Nonetheless, the field has encountered renewed interest as low-power electronics, wireless standards, and miniaturization conspire to populate the world with sensor networks and mobile devices. This article presents a whirlwind survey of energy harvesting using various conversion technologies, spanning historic and current developments in the world today.

1. Introduction

The world's energy consumption is at an all time high with the demand continuously increasing. This situation brings up several challenges that need to be addressed:

1) Depletion due to finite availability of non-renewable energy sources, e.g. fossil fuels
2) Environmental pollution, e.g. with coal use in power plants
3) Increasing population, especially in developing countries which lack resources for clean energy
4) Global warming with the related climate changes and adverse implications
5) Powering new technological applications, e.g. ultraportable electronics, wireless sensor nodes, etc.

These challenges have been reason for much controversy in the developed world; however, recent investigations have also shown a much more basic challenge of availability in the less developed parts of the world. Data from the World Bank obtained as recently as 2012 estimated that about 25% of the India’s population (greater than 0.3 billion people) has no access to electricity[1]. Larger numbers include those that have very limited access to electricity. Further, most countries with the lowest values for percent of population with electricity also have low values of urban population percentage.

A short comparison of the two most populous countries with known booming economies also suggests an interesting relation between these two parameters. Establishing a direct relationship would require a further, more comprehensive investigation but it can be imagined that when the population is more diffused, less people are likely to have access to electric power. Difficulties such as the costly and time-consuming development of long range power transmission to scattered remote areas can inhibit those regions from having electricity. This lack of power in remote regions can hinder a country’s ability to undergo overall economic development. Hence, it

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is learned that electricity is still needed on the basis of availability to a significantly large amount of the world's population [2]. Further, means of delivering or producing electricity in a way that is feasible and practical in remote regions, especially those of less developed countries, are worth investigating.

In terms of meeting the energy demand, data shows the high dependence the world has overall on fossil fuels. Fossil fuels are known to be non-renewable, having formed over millions of years of decomposition of prehistoric biological forms such as plant matter and the dinosaurs. The rate at which modern society is consuming these resources is far quicker, however, risking the depletion of this resource. Furthermore, the manner in which the resource is consumed is known to produce pollutants (e.g. Carbon Monoxide (CO)) and green house gases (e.g. Carbon Dioxide (CO2)) in our environment[3]. Carbon Dioxide emissions have been steadily growing through the combustion of fossil fuels as needed in transportation, power generation and otherwise. One of the main reasons why this is a critical problem is that the world heavily depends on these fossil fuels currently to feed its energy demands.

2. A Brief History of Human Power Generation

Human power has been instrumental in helping solve problems since ancient times. For example, all tools have historically been human powered. It is believed that the first human powered device to generate rotary motion was the potter's wheel, around 3,500 B.C. Later, devices such as Archimedes‟ screw allowed efficient transfer of water from one level to another. The Chinese, after 200 C.E., were found to use hand cranks to aid in textile manufacturing, metallurgy and agriculture. After the mid-15th century, the technique of incorporating flywheels to produce smooth motion proliferated, allowing devices such as the spinning wheel to gain popularity in Europe. Cranks and pedal power became one of the most efficient means of coupling human power to applications. In the 19th century, the bicycle's use of pedals allowed an efficient means of self-transportation[4]. In parallel with the invention of the electric dynamo in the 19th century, it is speculated that pedal power was used to generate electric power as early as then. However, with the burgeoning of the industrial revolution in the 19th century and forward, human society found other ways of powering their engineered applications. Particularly, the availability of cheap and plentiful electricity, powerful motors and disposable batteries can be attributed to the decrease in popularity of using human strength. Also, the ethical implications of having humans produce energy as punishment, as seen in some prison mills, further diminished the popularity of human sourced power [5]. It would take until the latter half of the 20th century for science to seriously reinvestigate this resource.

3. Modern Applications

Today, human power has made sort of a comeback with many applications where it can be of use and the reason to investigate is alternative energy. A novel feeling of empowerment is recognized when people are able to do things for which they had to rely on machines previously. So much so, that the idea of powering solely from human energy exists as a technical challenge. For example, the American Society of Mechanical Engineers (ASME) holds the Human Powered Vehicle Challenge (HPVC) competition annually for encouraging higher education students to construct and compete with single-driver prototypes power by the driver alone[6]. Further, the Royal Aeronautical Society has various challenges for the Kremer's prizes in human powered flight[7] .Human power has also been found to be uniquely good at providing energy generation in isolated situations. For example, the development of hand-operated axial flux generators which can be useful for dismounted soldiers, search and rescue operation in case of natural disasters, relief workers in remote regions and field scientists[8]. The study demonstrates how 60W can be maintained from the generator for different applications while maintaining a lightweight design for portability. Further provides a good example of applying human power in remote areas of developing countries. In 1991, many rural parts of India lacked any access to electricity. Further, fossil fuel or solar/wind energy generation required skill in operation and maintenance along with monetary resources that were unavailable. Human energy was determined to be simple, dependable, required low capital, and reliable source to 100W power. This localized generation of electricity has also made human power an excellent method for micro-power generation. Theoretical analyses have been done to show that brisk walking motion can produce up to 5-8W, adequate for basic wearable computing [9]. Recent research shows the performance of three methods to perform this extraction. In, a summary of current progress in piezoelectric generator technology shows power generation capabilities of up to 8400μW [10]. Further, small-scale electromagnetic generators are a little harder to manufacture but can produce power in the order of mW .Shows the development of an electrostatic generator which uses micro ball movement induced by low frequency human motion to generate at least 40μW. Such output power may seem relatively negligible but it has potential in

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partially or completely removing the need for batteries, making portable designs lighter, smaller and longer lasting. This is especially promising for applications such as implantable and wearable 12 electronics, ambient intelligence, condition monitoring devices, and wireless sensor networks. These micro-electricity generators also feature the unique aspect of passive electricity generation. That is, the generation requires no deliberate human effort. This is recognized as an advantage in terms of psychological human factors, prompting the study of power generation through child's play in. This system used a pneumatically actuated generator for safety and cost considerations and was able to produce about 5W. Further, investigates energy generation from a dance club by developing floor tiles that feature small-scale electromagnetic generators, allowing a single person to produce around 5-8W for extended periods of time. The study went further to measure power output when multiple humans are involved, as expected in a dance club environment. On average between 20-30W with some peak values within 60-100W were produced in this scenario. Hence, it is demonstrated how energy can be extracted from actions that are a regular part of human life, not requiring deliberate effort. Moreover, there is potential in benefiting from the social nature of humans to multiply the energy generated. The energy challenge as discussed earlier has generated interest in human provided power as it is a renewable, carbon-free source. Pedal power generation has even been established as a business with the presence of companies such as MNS Power (Mesa, AZ) which sells DIY plans and equipment with which anyone can build a human powered generator. Also, Re Rev (St. Petersburg, FL) has retrofitted at least 30 fitness facilities already to use existing ellipticalsin generating electricity. Generating power via pedaling on a stationary bike has also been investigated to find an output of 43-244W[11], depending on the load resistance. Hence, it is seen that human power generation has multiple applications in modern society. It can be useful when users are isolated as possible with natural disaster, military deployment or being in a remote area. It also provides for an intuitive, easy to implement and relatively low cost design which is particularly useful in rural areas of developing nations where skill in operating equipment and investment capital is limited. Acquisition of energy via non-deliberate human effort is also possible which could be useful for various novel portable electronics applications. Furthermore, it can allow for power generation to be done socially, removing the feeling of deliberate effort while increasing the power output significantly. The thought of using human energy as an alternative and renewable energy source is gaining popularity to the level that businesses have formed around converting exercise equipment such as stationary bikes and ellipticals to electricity generators

4. The Potential of Human Power

When the energy intake of humans is considered, a large potential seems apparent. Considering the standard 2000kcal of daily consumption (97W of power in, on average), humans take in about 8.368MJ or 2324Wh of energy every single day[12]. This is approximately the same amount of energy stored in the typical car battery (2400Wh). However, the expenditure of energy for common tasks is relatively high aswell.

Table: 1. Estimated amount of energy expenditure for common tasks.

Activity	Power Consumed (W)
Sleeping	81
Sitting	116
Swimming	582
Sprinting	1630

Table: 2. Values for maximum power that can be captured as a result of human activity.

Activity	Maximum Human Power (W)
Pushing Button	0.64
Squeezing Handle	12
Rotating Crank	28
Riding Bike	>100

Hence, the available energy that can be captured over a short period of time isin reality quite limited. The obvious impracticality of this shows why the scope thus far in humanpower generationhas been limited to lower power applications such as consumer electronics.

1 gram of fat contains 9 kcals or roughly 37,656J. To obtain a rough estimate of the energy an average male would expend going from being obese (Body Mass Index (BMI) = 35) to normal (BMI = 22), the following analysis is conducted:

Table: 3. Values of parameters for two test subjects

Parameter	Value when Obese (BMI=35)	Value when normal (BMI=22)
Average Height	70 inches	70 inches
Weight	110 Kg	70 kg
Body Fat % estimate (by weight)	34.80%	15.56%
Mass of Fat	38350 g	10799 g

$$(38350g - 10799g)(37656J) = 1037.46MJ$$

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Thus an estimated 27.551 kg of fat needs to burned to achieve a normal BMI from obesity, releasing an approximate gross total of 1037.46 MJ or 288.183 KWh of energy. Considering a maximum efficiency of generating systems to be around 25%, 72.05kWh could be generated if the released energy is captured [13]. While this is a rough estimate, it shows the magnitude of energy that can potentially be produced from human power through exercise over time. Also, this is the expenditure from one typical obese individual. The potential is even greater when the magnitude at which obesity and overweight affects the human population is brought into scope. As health consciousness becomes more prevalent, the energy released from fat burning exercise does not have to be completely neglected.

5. Generating Electricity During Walking

A biomechanical energy harvester had been developed that generates electricity during human walking with little extra effort. Unlike conventional human-powered generators that use positive muscle work, this technology assists muscles in performing negative work, analogous to regenerative braking in hybrid cars, where energy normally dissipated during braking drives a generator instead [14]. The energy harvester mounts at the knee and selectively engages power generation at the end of the swing phase, thus assisting deceleration of the joint. Test subjects walking with one device on each leg produced an average of 5 watts of electricity, which is about 10 times that of shoe-mounted devices. The cost of harvesting—the additional metabolic power required to produce 1 watt of electricity—is less than one-eighth of that for conventional human power generation [15]. Producing substantial electricity with little extra effort makes this method well-suited for charging powered prosthetic limbs and other portable medical devices.

It was proposed that a key feature of how humans walk may provide another means of economical energy harvesting. Muscles cyclically perform positive and negative mechanical work within each stride [16]. Mechanical work is required to redirect the body's centre of mass between steps and simply to move the legs back and forth. Even though the average mechanical work performed on the body over an entire stride is zero, walking exacts a metabolic cost because both positive and negative muscle work require metabolic energy. Coupling a generator to leg motion would generate electricity throughout each cycle, increasing the load on the muscles during acceleration but assisting them during deceleration. Although generating electricity during the acceleration phase would exact a substantial metabolic cost, doing so during the deceleration phase would not, resulting in a lower cost of harvesting than for conventional generation. An even lower cost of harvesting could be achieved by selectively engaging the generator only during deceleration

6. Pedal Power Generation

Bicycle is the main mode of transportation for many Indian villagers. Most of these villages are un-electrified. Power generated by pedaling can be converted from mechanical to electrical energy by using either dynamo or alternator. Small powered lighting devices can be charged using dynamo and can be used in the night by students for study purposes. This principle can be extended to power mobiles, iPods, laptops etc [17]. Power can be also generated from the rotation of the wheels of alternator vehicles like bikes and cars, where there is a possibility of generating more power [18]. The generated power can be either used in the same vehicle or can be stored in a battery for powering some other devices. Riding bicycle helps in maintaining a good physic and along with it power can be also generated.

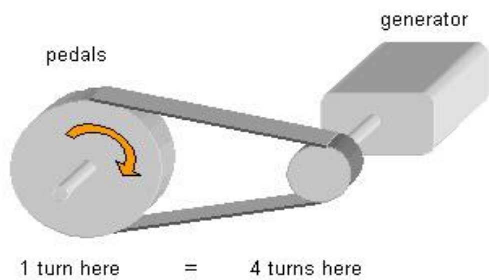

Fig: 1. Belt drive transmitting torque from pedal to generator. Photo courtesy

In this, a dynamo is attached to the bicycle's tire for power generation. When the rider pedals, the motion of the tire in contact with the dynamo results in the rotational motion of the roller (of the dynamo). This motion causes the dynamo to produce electrical energy (AC). The dynamo output is given to the rectifier circuit, filter and then to voltage regulator and hence the DC regulated output is used for charging NiMH batteries

The entire setup can be fixed on the bicycle and the batteries can be charged while the user rides the bicycle for any day-to-day activity. For example, most people in villages use cycle for short distance travel of one to few kilometers for their daily work or children travel to schools in cycles. The circuit is designed in such a way that it can be fixed and charged even while the user rides it on the road. By this way, the energy spent in riding the bicycle can be used for

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charging the batteries. Alternatively, a user can ride the bicycle in stationary

7. Heavy Breathing: Power from Respiration

An average person of 70 kg has an approximate air intake rate of 32 liters per minute[19]. However, available breath pressure is only 3% above atmospheric pressure[20]. Studies indicate that the power consumed in breathing normally is between 0.1 and 40 Watts [21]. Increasing the effort required for intake of breath may have adverse physiological effects [22] so only exhalation will be considered for generation of energy. Thus, the maximum available power is

$$W = P\Delta V$$
$$= 0.03 \times \left(\frac{1.013 \times 10^5\, kg}{m.\sec^2}\right) \times \left(\frac{32l}{60sec}\right) \times \left(\frac{1\, m^3}{1000\, l}\right)$$
$$= 1.6208W$$

During sleep, the breathing rate, and therefore the available power, may drop in half, while 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[23]. 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% [24], and any attempt to tap this energy source would provide additional load on the user. Thus, the benefit of the estimated 0.40 W of recoverable power has to be weighed against the other.

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 cm change in chest circumference when breathing normally and up to a 5 cm change when breathing deeply[25]. 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

$$P = (100N) \times (0.05m) \times \left(\frac{10\ breaths}{60\ s}\right) = 0.833W$$

A ratchet and flywheel or a stretchable dielectric elastomer generator 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. While such a chest band may at first seem inappropriate, some popular breath and heart rate monitors sold as exercise equipment use similar chest bands for their sensors. Interestingly, the idea of using a chest band for recovering power from the user is quite old. Another similar mechanism for winding watches in the historical record from the 1600's[26]. Researchers have explored tapping the energy of breathing for powering implantable electronics; in vivo animal tests of a piezoelectric foil laminate that's bonded to a pair of ribs that stretch the foil during breathing have generated 17 W in a dog, and with improvements claim to be able to attain 1 mW[27].

8. Piezoelectric shoe inserts and elastomer heels

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 [28].

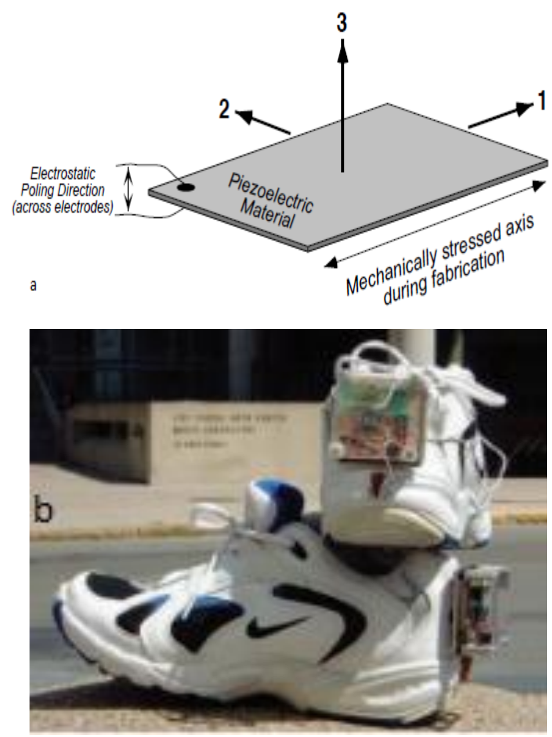
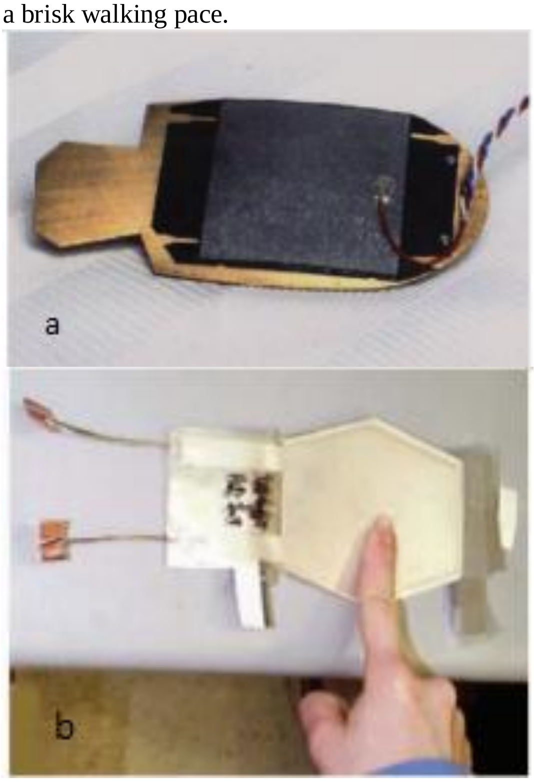


Fig: 2. Definition of axes for piezoelectric materials on left. Note that the electrodes are mounted across the 3 axis.Photos courtesy SRI, International

Consider using polyvinylidene fluoride PVDF shoe inserts for recovering some of the power in the process of walking.There are many advantages to this tactic. With only 1.1 mm thick material in the natural flexing of the shoe when walking provides the necessary deflection for generating power from the piezoelectric pile[29]. PVDF is easy to cut into an appropriate shape and is very durable. In fact, PVDF might be used as a direct replacement for normal shoe shoes without moving parts or seriously redesigning the shoe. A small women's shoe has a footprint of approximately 116 cm. Knowing that the maximum effective force applied at the end of a user's step increases the apparent mass by up to 30%, the user needs only 52 kg of mass to deflect the PVDF plate a full 5 cm[30]. Thus, scaling the previous 1.5W at 0.6 deflections per second to 2 steps per second, these numbers indicate that

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

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



stiffeners. Thus, the inserts could be easily put into

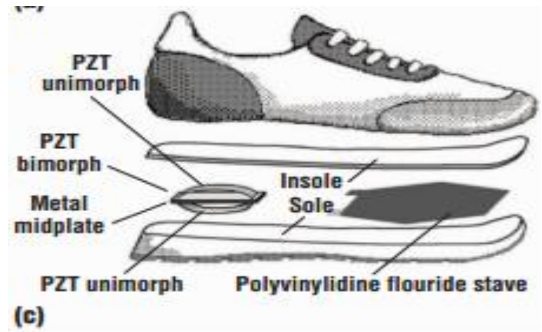


Fig: 3. Prototype PVDF bimorph generator for a shoe insole. Power is generated through the mechanical bending of the sole. Photos courtesy SRI, International

In 2000, Trevor Baylis and collaborators at the Electric Shoe Company in the UK claimed to have generated 100-150mW of power from heel inserts embedded with a piezoelectric crystal[22]; Baylisdemonstrated the system by using it to partially charge a cellular phone battery after a five-day trek through the Namibian Desert.

Fig: 4. An electrostatic generator based on compression of a charged dielectric elastomer during heel strike. Prototype implementation in a boot (left) and close-up of the generator (right), showing bellows on bottom and retaining frame on top. Photos courtesy SRI, International

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