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Entry

Human Power Production and Energy Harvesting

Antonio Cicchella [1,2]

[1] International College of Football, Tongji University Siping Campus, Shanghai 200092, China; antonio.cicchella@unibo.it
[2] Department for Quality-of-Life Studies, University of Bologna, 40126 Bologna, Italy

Definition: This entry presents a holistic examination of the problem of harvesting energy from the human body. With the advent of the industrial revolution, in modern times, there is less and less need for physical human work; at the same time, motion is essential for health. Thus, sports and physical leisure activities have seen a dramatic increase in popularity. Until several decades ago, energy consumption was not an issue, at least in developed countries, but in recent years, it has become more and more evident that energy resources are finite and that there are limits to how much anthropic pressure the environment can sustain; one evident outcome is global warming. The repurposing of human energy also has psychological benefits, making people socially responsible and transforming otherwise wasted potential into a rewarding activity. Thus, on a small scale, over time, it has become evident that re-using and saving energy are vital. Humans can produce a large amount of energy through physical work, but over the past few decades, technologies have been developed to store and reuse energy that would otherwise be wasted. Some interesting applications and a critical review of the problem, which is linked to human metabolism and sport, are presented.

Keywords: human energy harvesting; human power production; environment; energy balance

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1. Introduction

Human metabolism is strictly connected to the environment, and, on a large scale, to sustainability, pollution, and climate change. In fact, it is a well-established fact that "anthropic pressure" is the main determinant of environmental pollution, including the exploitation of resources, such as water and food. It is well known that ground consumption is also linked to human metabolism. The need to reduce carbon emissions worldwide is one of the biggest challenges science faces today and in the foreseeable future. In this definition, it refers to the amount of energy that humans use from the planet's resources, which is the social sense of human consumption. The "green transition" and related increased public awareness about environmental problems motivated the search for alternative sources of energy. Historically, human beings have been studied as machines for energy production and consumption [1] and for their impact on the environment [2]. Energy harvesting from the human body is a rapidly developing field of research. Interest in harvesting energy from the human body is not new, and it is practically incorporated in some everyday use devices, such as automatic watches, which use energy from movement to charge. In this case, the oscillation of the arm (pendulum) during walking feeds the watch mechanism, which is used to store energy. Large movements with much greater applied force can generate higher energy, which can then be used to sustain the functioning of various devices (e.g., cell phones) and, in some cases, partially or totally, can even sustain the energy requirements of a gym or sports facility, particularly if harvested at the same time from many individuals [3]. The mechanical efficiency of the human body is in the range of 15–30%, which means that 70% of the energy provided by food is dissipated into heat [4].

The human body contains a great amount of energy. In fact, the average adult's body fat deposits store as much energy as a one-ton battery [5], and it has been calculated that the monthly energy capacity of a person taking 7500 steps/day is equivalent to a 0.40 mAh battery rated at 1.2 V [6]. An average person could generate power comparable to a 1 m^2 solar panel on a sunny day and 10 m^2 of solar panels on an overcast day [7]. Robert Obrest, an athlete competing as a strongman, eats 15,000 to 20,000 calories per day, storing the capacity to produce a large amount of energy [8].

The heat from the body can be a source of continuous energy given that the core body temperature is maintained at 37 °C by the metabolic processes. It has been calculated that the whole human body can dissipate 60–180 W depending on the type of activity performed [9]. Thermoelectric devices have been proposed to harvest this energy, and it has been calculated that if this device has a conversion efficiency of ∼1%, the resulting power produced would be in the range of ~0.6–1.8 W, which is sufficient to supply energy to many wearable sensors [7]. This energy is generated from energy-dense sources (fat). Motion energy is particularly interesting as a source of energy because it has a power density as high as 200 $\mu W/cm^2$ and is available on demand [6], depending on fatigue. The average energy expenditure for one-person (energy used by the body) is 1.07 × 107 J per day [9], equivalent to 800 AA (2500 mAh) batteries, which would weigh about 20 kg. This amount of energy can be produced from 0.2 kg of body fat [10].

2. Energy Production in Sport

Table 1, from various sources, presents a synthesis of human power production.

Table 1. Energy production in different activities (values for males). Sources: Refs. [11–18].

Energy Source	Production Rate and Peaks (W)
Olympic 50 m sprinter	2000
Sprinting	3440
Professional cyclist (1 h)	400
Peak	1100
Weightlifting	6629
Vertical jump with run-up	5600
Sprinters 100 m	2392
Laborer (over 8 h)	75
Agriculture (peak/min)	420
One footstep	2–5

Top-level track cyclists can sustain 600–700 W for 1 min, the amount of energy necessary to toast a piece of bread. They can peak for a few seconds at 2500 W [11] during a sprint, while during a competition lasting at least one hour, a professional cyclist can sustain 400 W while an amateur cyclist can sustain around 200 W. Naturally, the power that can be produced by the upper limbs is much lower and is equal to 30 W for arm cranking for 30 min in top athletes [9]. Powerlifters can achieve from 2140 W in the 56 kg class [12] to 6629 W in a 110 kg lifter [13] in fractions of a second for a jerk drive.

In 100 m sprint running, values of 2392 ± 271 and 1494 ± 186 W and 30.3 ± 2.5 and 24.5 ± 4.2 $W{\cdot}kg^{-1}$ (males and females) were recorded after one second [14]. Vertical jumping with a run-up reached around 5600 W [15]. Arm power averaged over ten maximal strokes in 24 elite Spanish rowers (body mass 84 ± 5 Kg) was 630 ± 45 W, or 7.5 $W{\cdot}kg^{-1}$ [16]. The propulsive phase of cross-country skiing is well above 1000 W (>15 $W{\cdot}Kg^{-1}$) [17] and the instantaneous power is as high as or higher (i.e., 1350 W) than a 1500 m sprint race using the alternating style [17]. Regarding human labor (not sport), a study by Poulianiti [18] reported a peak power/minute of activity ranging from 122 w/min (textiles workers) to 420 W/min (agricultural workers).

The basic energy consumption of the body was calculated in 4 kJ/kg body weight/daily hours. To calculate an individual's basic energy consumption, the following formula has been proposed [19]:

$$\text{Total energy consumption} = \text{body weight (Kg)} \times 4\ \text{KJ} \times 24\ \text{h/day}/4.18\ \text{kJ} \qquad (1)$$

Energy for human activity comes from food; the energy cycle is summarized in Figure 1:

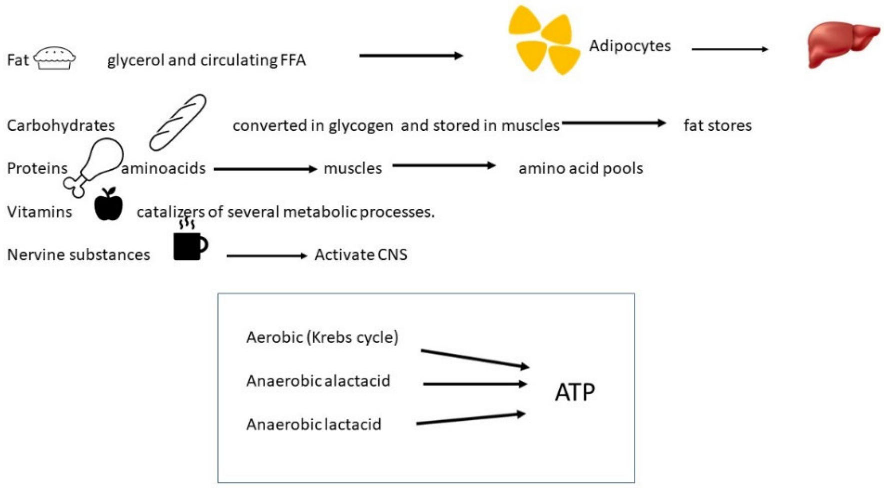

Figure 1. Cycle of metabolic human energy production.

The molecule of adenosine triphosphate (ATP), which is the basic tile of energy in humans, comes from nutrients. ATP is used in every metabolic process, and it ultimately enables life. The more visible utilization of ATP is the motion of limbs, which allows for interaction with the environment and all human activities, entering a loop cycle of energy consumption and production outside of the individual human bodies, which is produced starting from food or storage in the human body. There are three different ways to produce ATP: anaerobic, anaerobic glycolytic, and aerobic. The first two ways rely mainly on glucose, which is ultimately in the form of glycogen, stored in the muscles and liver, while the aerobic way mainly relies on fat (circulating in the blood or stored) by means of mitochondrial respiration [10].

The fast anaerobic production of ATP is needed when a given movement is at its maximum power and ATP storage can last from 6 to 10 s. This way of energy production does not require nutrients to enter any biochemical cycle, because the supply is very fast and relies on the available creatine phosphate (CP) in the muscles. The second energy pathway is the anaerobic glycolytic path, which can last (at the maximum possible power output) for around 1 min, or about a 400 m run. Glycolysis produces two ATP molecules by shunting pyruvate away from mitochondria and through a lactate dehydrogenase reaction. During the aerobic chain, citric acid or the Krebs cycle produce 36 ATP molecules, for a total of 38 molecules of ATP created, with 2 ATP molecules formed outside the mitochondria [10].

From a certain perspective, energy production can be viewed as a process where consumption proceeds from an individual dimension necessary for living to a social fact when the energy is absorbed from, and released into, the environment to produce a work task or sports activity. Sport poses a series of problems concerning energy reuse. In fact, people practicing sports need to feed themselves more than non-sports-oriented people. The overconsumption necessary for sport is absorbed from the environment in different forms, but mainly through the breeding of livestock (meat) and growth of carbohydrates (crops, which imply soil consumption, fertilizer, and so on). Exercise also generates additional heat in the environment because of the energy needs of sports facilities. Increasing awareness of the energy production–consumption balance, carbon neutrality and climate change has pushed the revival of the ecological idea of the re-utilization of human energy. From here, the idea of recycling human motion to produce energy by means of immediate energy reuse, and when possible, storage, has gained traction even in the mainstream. Excluding ancient times, when human and animal energy was the basis for all human activity, such as transportation, building, etc., with the advent of the industrial revolution, the need for human physical work has progressively decreased. Even small activities, such as sewing, have been outsourced to machines, which, in turn, are built by other machines, today controlled by a computer code written by a programmer, which in turn, is being partially substituted by artificial intelligence. But to what extent and for how long can the human body stay without moving and consuming energy? With the advent of the industrial revolution, factories started to provide physical activity for the workers to make them move after work; this was the reason behind the birth of many football clubs still in existence today (e.g., Manchester United). Several companies also provide workers with free gym memberships to allow them to burn unused energy. Thus, the energy conundrum is a typical issue of modern times. On the one hand, there is now an increased incentive to save energy and reuse it to preserve the environment; on the other hand, there is a need to move and dissipate energy to be healthy, not to mention the psychological benefits that are linked to the rewarding feedback loop coming from the social utility of producing energy and to transforming otherwise wasted energy into a benefit for the local community. This reward mechanism together with environmental awareness is a strong motivator for human energy harvesting.

3. Energy Harvesting

Recently, some researchers investigated the possibility of harvesting the energy produced by the human body to feed small wearable or portable devices (such as smartphones) or produce energy for facilities such as gyms. Wearable sensors and probes embedded in clothes for health monitoring, such as EEGs, can be fed by thermo-electric generators (TEG), which use body heat (evaporation, convection, and radiation) to produce energy [20]. In modern warfare, each soldier carries a 7 kg battery for 72 h operation of GPS devices, telecommunication equipment, and other equipment. If a share of this energy could be sourced from harvesting body motion, it could significantly reduce the human energy expenditure required to carry such a weight [21].

Treadmills and bikes able to harvest human energy [22] are commercially available, albeit currently only economically sustainable by the end users in the presence of public incentives. Moreover, in the long run, the use of these devices has been demonstrated not to be economically viable because of the high cost of the devices [23]. The same is true for devices available in public spaces, which are able to produce energy from walking or jumping. Regardless of this limitation, in special conditions such as rural villages in low-income countries, the harvesting of energy in children's playgrounds has been successful [23]. These technologies enabled villages in Ghana to produce a small amount of energy, which was then used to provide public lighting, all the while engaging youth in social playing.

The jaw joint has been proposed as a source of energy through mastication [24], which may be able to feed an earring device for people with hearing impairments. Knee joints are still the main energy producer through motion in the human body [25]. With the advent of powered exoskeletons, energy harvesting in knee joints can power orthosis and help disabled people walk [25]. For this purpose, piezoelectric converters have been proposed as harvesters of energy from knee joint movements during walking and stair climbing [25]. Energy from walking and running [26] can be harvested from the shoe's sole by embedding various kinds of transducers into it (piezoelectric, strain, pressure, capacitive, triboelectric) [27–29]. The harvested energy can also be immediately used, for example, to support forces for contralateral ankle joint movements in case of orthosis [25]. A light harvester embedded in a pair of shoes was proven to be successful in providing electrical power up to 7.71 mW during walking at a speed of 8 km/h and up to 5.28 mW when going upstairs [26]. In order to harvest energy from motion, other technologies have been proposed, ranging from small harvesters, such as sliding backpacks to recharge smartphones [30], to large harvesters, such as oscillating bridges or instrumented walkways, which are able to store energy from vibration [6,28–30]. Walking has particularly attracted the interest of researchers in the field. It has been shown that elastic-oscillating devices generate electrical power without an increase in the metabolic power required to walk.

This is a better performance than when walking with a rigidly fixed carried weight. Such a device was able to generate up to 0.22 ± 0.03 W of electricity when walking with 9 kg of carried weight [31].

Additionally, the amount of energy harvested can be used as an indicator of energy expenditure and is thus useful for physiological studies as well as for obtaining information about a population's mobility behavior [32].

The employment of human energy in the eco-design of houses and buildings is also of great interest for its social impact [33,34]. Using home appliances and domestic work to produce and recycle energy has been gaining ground in recent years. For example, pedal-powered home water pumps are becoming more popular, allowing individuals and some small companies to be independent of electric companies; for instance, the quilt finishing business has used treadle sewing machines to power houses [33]. Pedal-powered amplifiers have been used by musicians, freeing themselves from engines and extension cords [33]. Some research has shown that smart meters or in-home displays of power usage are useful to stimulate energy saving [34]. This visual feedback can have a significant role in raising awareness about energy consumption. It has shown that visual feedback about the electric consumption placed in a house reduced energy consumption to the order of 10% and reduced the demand at peak times [34]. If the British population spent half of their sedentary time generating power to run a TV using a pedal-powered bike, this would lead to savings of about GBP 49 million of electricity each year [34]. To pursue the "green transition", further effort is necessary in the research and development of storage methods on a small (e.g., batteries and capacitors) and large (e.g., pumped hydro, compressed air storage, and electrolytic hydrogen) scale [34]. Energy from sports stadiums can also be harvested. The vibrations generated from crowd noise can produce energy, but, for now, on a very small scale. Crowd noise at Wembley Stadium (100,000 people producing 120 dB of noise) in London showed that in order to generate 175 W of energy to cook an egg, up to 142 dB of consistent sound would be required. At 80 dB per person standing 1 m away, 1.6 million people (standing 1 foot away from the egg) would be needed to successfully boil the egg. Thus, the only way to produce a consistent amount of energy in a stadium is the energy produced by the kinetic energy of the crowds, harvested by means of piezo-electric transducers. A study performed in 2012 showed floor tiles with piezoelectric transducers produce an average of 7 W for each footfall kicked by a 70 kg walking person [35], which is sufficient to power LED lighting and small electronics. An interesting example of energy harvesting is also the club chain "Club Watt" in Rotterdam, the Netherlands. The chain is powering their nightclubs using piezoelectric transducers underneath the dance floor. The kinetic energy produced by a mass of dancers generates an enormous amount of electrical energy, which can be employed by the club to supply energy to the lights and amplified music. The aims of this project were not only to implement sustainability into the structure of the organization but also to communicate the message of sustainability to the audience [36]. Some technology is currently available on the market to harvest energy from walking, running, and jumping on public paths, based on piezo-resistive devices [37]. The development and better efficiency of piezo-resistive devices is a key factor in the development of technology for energy harvesting, as well as for energy storage methods [38]. Methods also exist to harvest energy from animals, e.g., from the movements of cows [39], at least to "feed" electronic collars for position tracking, but this topic goes beyond the aims of this entry, and the technology in this field is still in its infancy.

4. Conclusions

The need to reduce pollution and carbon dioxide emissions worldwide can be achieved only with the summation of many sources of energy, producing low power in comparison to traditional energy sources. In specific situations, such as in sports, there is a voluntary production of energy that is usually lost. Implementing a large-scale shift in the design of sports facilities and sports gear can help the harvesting of some of this dissipated energy, by using several different available technologies. Sport is in some ways an energy dissipator itself, necessitating an increase in food consumption. Developing energy harvesters can thus be beneficial not only from a health perspective but also for the environment, and it can help with the sustainability of power usage. The harvesting of energy goes well beyond the field of sports. It has been demonstrated that many domestic activities are potential energy producers/savers. The simple idea of making energy consumption/production visible can increase awareness about energy usage. The design of intelligent buildings and facilities (sports facilities) able to harvest energy (e.g., the heat produced by the public attending a sports event) could significantly reduce energy demand and dissipation, acting as a powerful factor in improving the environment. The energy production–consumption cycle is a conundrum of modern times: on the one hand, there is a need to save and reuse energy; on another hand, there is a need to dissipate energy to be healthy. Harvesting human energy can conjugate these two needs. The development and better efficiency of piezo-resistive devices is a key point in the development of technology for energy harvesting as well as energy storage methods. The rapid development of technologies for the reuse and storage of human-produced energy means that they can now be adopted affordably in several settings. Finally, the psychological benefits of producing energy through movement must be considered, especially regarding the reward of a socially useful utilization of energy. The idea to harvest human energy is not new, but the required technology is now at a point where it is possible and economically convenient to develop harvesters. The technology readiness level now allows the development of commercially useful systems for human energy harvesting based on different devices (mainly piezoelectric) and the storage of this energy in appropriate capacitors.

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