International Journal of Academic Research and Development
www.multidisciplinaryjournal.in
ISSN: 2455-4197
Received: 23-06-2024, Accepted: 22-07-2024, Published: 08-08-2024
Volume 9, Issue 4, 2024, Page No. 55-60

Electromagnetic systems for the harvesting of energy from the human body with applications

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Abstract

The purpose of this work is to review passive electromagnetic energy collection and production systems with applications, regarding the source and distribution of the energy of the human body in recent technological developments. In addition, the various ways of harvesting energy from the human body, such as the thermoelectric, pyroelectric generator, and the comparison between them are discussed. Finally, useful conclusions are drawn on the international literature, as well as possible future steps in the context of this work.

Keywords: Passive electromagnetic systems, energy harvesting, energy production, human body energy

Introduction

Energy is the cornerstone of the development of human civilization. The contradiction between the ever-increasing demand for energy and the reduction of existing energy resources is a serious problem, facing the world today. In addition, environmental pollution caused by the excessive use of fossil energy is also increasing. Therefore, it is urgent to find and develop new sources of energy that are sustainable and environmentally friendly.

The discovery and use of new energy sources, including water energy, wind energy, solar energy, ocean energy, and biological energy, have greatly promoted the development of human society. In addition to the above sustainable new sources of energy, derived from the natural environment, energy from the human body has recently been shown to be a potentially clean energy for sustainable use. The human body relies on food intake to obtain energy, which is mainly used to maintain the body temperature and function of body organs, except for some waste energy that is dissipated into the environment [1]. If human energy could be harnessed properly, the benefits would be immeasurable in terms of the current global population base.

From every heartbeat to every step, human beings radiate energy all the time. Researchers are trying to harvest energy from the human body and convert it into electricity, which can be supplied to electronic medical devices closely related to human health. Such a form of energy recycling is currently a research hotspot in the fields of energy harvesting and bioelectronics. Accordingly herein, applicable energy harvesting technologies and corresponding operating mechanisms for different energy sources are introduced. Some typical demonstrations and practical applications of each type of energy harvesting technology from the human body are also presented. In particular, the advantages and critical issues of different energy harvesting technologies are summarized and corresponding promising solutions are also provided. In addition, the interaction strategies between various energy harvesting devices and the human body are summarized from the aspects of wearable and implantable applications [2].

Human sources of energy

The human body is a natural energy conversion factory. Through food intake, the carbohydrates, fats, proteins and other nutrients in the food will be absorbed. Some of the nutrients will be converted into glycogen, lipids, amino acids and other energy substances stored in the human body, while the other part will be converted into adenosine triphosphate (ATP) [3], the minimum unit of energy substances that the human body uses directly. It is also utilized through various metabolic pathways. The total amount of ATP in the human body is about 0.2 mol, which is equivalent to the energy of one AA battery. An adult usually consumes ATP energy (equal to about 100–150 mol) equivalent to his/her body weight in one day to maintain normal functions and major life activities [4]. This energy will be consumed and released by the human body through different forms of energy flow. Specifically, three forms of energy flow in the human body are mainly summarized as thermal energy, chemical energy and mechanical energy. From every breath and heartbeat to every movement, energy will be released all the time. These energy flows are the primary basis of the human body as a potential energy source [5].

In terms of thermal energy flow, the human body consumes a large amount of energy every day to maintain a constant body temperature [6]. Most of the thermal energy is released to the environment in the form of heat exchange between the body and the environment, while the rest of energy is dissipated through respiration or the evaporation of sweat on the skin. In terms of chemical energy flow, after digestion and absorption, food will be converted into glucose and delivered to various parts of the body in the form of blood glucose for further use and energy production [7]. In addition, after intense exercise, the human body will produce excess lactic acid in the muscles, part of which will be slowly consumed and decomposed in the muscles, while the other part will be excreted with water and electrolytes in the form of sweat. In terms of mechanical energy flow, limb movements including leg lifting, stepping, arm lifting, kicking, etc. [8], the respiratory movement, the heartbeat, and even the contraction and relaxation of blood vessels, are accompanied by the consumption and release of energy.

Mechanical energy mainly depends on the contraction and relaxation of muscles in corresponding parts of the human body to perform external work to transmit energy flow.

Some researchers have theoretically calculated the strength of the different energy flows during the transmission process, to further evaluate their potential as human energy sources. It is worth noting that the actual energy of the human body that can be used to collect and convert into electricity must be much less than the total energy consumed by the energy flow of each part of the human body, to avoid possible negative effects in the human body [9]. This is the fundamental condition to which all human body energy harvesting technologies discussed below must comply. The relevant emerging energy harvesting technologies are also summarized, according to different energy sources of the human body, which are mainly presented in the following sections. Thermoelectric generator (TEG) and pyroelectric generator (PEG) are applicable to thermal energy harvesting. Biofuel cell (BFC) and hydrovoltaic generator (HEG) apply to chemical energy harvesting. Piezoelectric nanogenerator (PENG) and triboelectric nanogenerator (TENG) are applicable to mechanical energy harvesting [10].

Harvesting technology of human energy

This section successively introduces the recent research progress of energy harvesting technology related to three forms of human energy flow, including thermal energy, chemical energy and mechanical energy [11]. Specifically, for each energy harvesting technology, the operating mechanism is elaborated and representative research works from demo to practical applications are introduced [12]. In addition, the advantages, critical issues and promising solutions for different energy harvesting technologies are also summarized in this section.

Thermal energy of the human body

At present, the harvesting of thermal energy from the human body mainly depends on the thermoelectric effect and the pyroelectric effect, which respectively correspond to two types of energy harvesters as a thermoelectric generator (TEG) and a pyroelectric generator (PEG) [13]. Although both types of thermal energy harvesters can collect heat from the human body and convert it into electricity, they work in different ways. TEGs depend on spatial temperature difference for energy conversion, while PEGs depend on temporal temperature difference [14]. Therefore, these two types of thermal energy harvesters have their applicable states and specific forms when harvesting thermal energy from the human body. Then TEG and PEG are mentioned below from the aspects of work principles and standard tasks respectively.

Thermoelectric generator

The thermoelectric generator is a type of thermal energy collector based on the thermoelectric effect, which can directly convert thermal energy into electrical energy [15]. The thermoelectric effect presented here refers to the first thermoelectric effect, also known as the Seebeck effect [16]. The Seebeck effect is mainly caused by the diffusion of carriers from the hot end to the cold end. Both metallic conductors and semiconductors can produce the Seebeck effect, while the Seebeck effect of metals is much smaller than that of semiconductors, since the carrier concentration and position of the Fermi energy level of metals basically do not change with temperature [17].

The P-type semiconductor is taken as an example for description. Holes will diffuse from the high-temperature end to the low-temperature end, due to the high concentration of holes at the hot end [18]. Space charges will thus form at both ends of the p-type semiconductor in an open circuit (negative charges accumulated at the hot end and positive charges accumulated at the cold end), which leads to an electric field appearing inside the semiconductor [19]. When the displacement of the electric field neutralizes the diffusion action and a steady state has been reached, an electromotive force appears, caused by the temperature gradient across the two ends of the semiconductor, which is called the thermoelectric force.

A TEG is a direct current generating device made from sets of semiconductor thermocouples, connected in series or parallel. Each thermocouple consists of an n-type semiconductor and a p-type semiconductor in series [20]. The connected end of the two semiconductors is in contact with the heat source and the non-connected ends are connected to the heat sink via wires. Due to the temperature difference between the hot and cold ends, there is accumulation of positive charges on the cold end of the p-type semiconductor and accumulation of negative charges on the cold end of the n-type semiconductor, thus forming a potential difference between the cold ends of two semiconductors [21]. If the two semiconductors are connected to an external circuit by wires, there will be current flowing through the external circuit. In order to achieve high output power, several pairs of thermocouples are usually connected in series or parallel to form a larger thermocouple [22].

Kim Sun Jin *et al.* [14] reported a thin, light, flexible and portable TEG based on glass fabric and self-supporting structure. The power density of this device can reach 3.8 mW/cm^2 and 28 mW/g temperature difference of 50K. Although this output performance is good for flexible TEGs, it is still difficult for the human body to reach a temperature difference of 50 K, unless the ambient temperature is at least minus ten degrees [23].

Kim Min-Ki *et al.* [15] presented a fabric TEG that can be embedded with clothing. Two types of thermoelectric materials are incorporated into the polymer fabric by dispenser printing to fabricate thermocouples. When the ambient temperature is 5 °C, the TEG consisting of 12 sets of thermocouples on the user's chest can produce an output power of 146.8 nW [24].

Ren *et al.* [16] designed a stretchable, self-healing, recyclable and reconfigurable portable TEG, which is fabricated with modular thermoelectric chips, dynamic covalent polyimine and liquid metal, using a “soft motherboard” rigid unit of additional architecture [25]. In addition, a radiatively cooled metamaterial film is integrated on the cold side of the TEG, to improve the performance of the device under sunlight. Under a temperature difference of 95 K, the device achieved a record open-circuit voltage of up to 1 V/cm^2 between flexible TEGs.

Pyroelectric generator

The pyroelectric generator (PEG) is another type of thermal energy collector, which is based on the pyroelectric effect. For a crystal with the property of spontaneous polarization, when the crystal is heated or cooled, the intensity of the spontaneous polarization changes due to the change in temperature, which leads to the creation of surface polarization charges in a particular direction of the crystal. This phenomenon is called the pyroelectric effect [26]. Crystals that can produce pyroelectric effects are called pyroelectrics. Pyroelectric systems generally have first and second order pyroelectric effects.

The first-order pyroelectric effect describes charges generated in the absence of strain, which is commonly present in ferroelectric materials such as titanite zirconate lead (PZT) and titanite barium (BTO) ceramics. The corresponding operating mechanism is based on the random oscillation of the thermally induced electric dipole near the alignment axes [27]. The angle of oscillation will increase as the temperature increases. At room temperature (RT), the electric dipoles will randomly oscillate in their respective alignment axes to some extent. At constant temperature, the total mean intensity of the spontaneous polarization of the electric dipole is constant and there is no electron flow [28].

Consequently, when the temperature increases, the electric dipoles oscillate more violently about the axes and the overall mean spontaneous polarization decreases with increasing oscillation angle [29]. As a result, the amount of induced charge on the electrode decreases, leading to electron flow. When the temperature decreases, the electric dipole oscillates over a smaller angle range, due to the lower thermal activation energy, leading to increased spontaneous polarization. As a result, the amount of induced charge on the corresponding electrode increases and causes the electrons to flow in the opposite direction.

The second-order pyroelectric effect describes the charge induced by the strain caused by thermal expansion, which exists in ZnO, CdS and other wurtzite structure materials with piezoelectric effect [30]. The temperature change causes the material to deform initially and then a piezoelectric potential is generated due to the piezoelectric effect, driving the flow of electrons in the external circuit [31]. The corresponding output is related to the piezoelectric coefficient and the thermal deformation of the material. If the rate of temperature change remains unchanged, PEG usually generates pyroelectric charges of the same amount and opposite polarity when the temperature rises and falls.

Yang *et al*. [24] presented the first pyroelectric nanogenerator (PyNG) based on ZnO nanowire arrays. The fabricated pyroelectric nanogenerator can produce a voltage/current pulse of 5.8 mV and 120.4 pA, when the temperature is rapidly increased from room temperature 295 to 304 K.

Lee *et al*. [27] presented a flexible and highly elastic pyroelectric nanogenerator made of P(VDF-TrFE) polymer, polydimethylsiloxane (PDMS) composite carbon nanotubes, and graphene nanosheets. This highly elastic PyNG can be attached directly to human skin and generate a voltage pulse of up to 400 mV, when the temperature is rapidly changed between high and low positions.

Thermal energy harvesting applications

After harvesting the thermal energy of the human body and converting it into electrical energy, thermal energy harvesting devices can be used as a power supply for some low-power electronics. At the same time, these thermal energy harvesting devices can also be used as self-powered temperature sensors due to the specific relationship between the output and the temperature difference. Some representative works of thermal energy harvesting devices are presented here in terms of TEG and PEG applications [2].

Sun *et al*. [22] presented a stretchable all-fabric TEG, based on woven thermoelectric fibers; π-type thermoelectric modules are woven through doped carbon nanotube fibers, wrapped with alternating acrylic fibers. The 3D substrate-free TEG fabric is stretchable and fully aligned with the heat flow direction, benefiting from the elasticity of the interconnected thermoelectric modules. When the temperature difference is 44 K, the maximum power density of the TEG fabric can reach 70 mW/m^2, which is enough to drive some low-power electronics.

Li *et al*. [23] used the organic thermoelectric polymer PEDOT: PSS and 3D spacer fabric to fabricate a thermal energy collector. The device consists of 100 thermoelectric modules, integrated with a T-shirt that can obtain an output voltage of 203 mV, when the temperature difference is 40 K. A thermoelectric wrist strap was presented to harvest energy from body heat, which can light an LED at an ambient temperature of 25 °C. They also demonstrated a portable, self-powered array of temperature-pressure sensors that can be fabricated on a large scale. The temperature detection resolution and response time of the sensor are 0.1 K and 1 s respectively.

Yang *et al*. [24] presented a stretchable and shape-adaptive TEG (S-TEG) for human body heat harvesting, which can be applied to complex and dynamic heat source surfaces. The p-type (Sb2Te3) and n-type (Bi2Te3) thermoelectric elements are made cuboidal by hot pressing and connected with a wavy serpentine structure to form thermocouples. The S-TEG consists of 10×Array of 10 thermocouples that can produce an output power of 0.15 mW/cm^2 when the temperature difference is 19 K. The S-TEG attached to the wrist can collect body heat and provide voltage for force sensor movement to detect finger movement.

Zhang *et al*. [37] fabricated a self-powered dual-parameter temperature-pressure sensor based on independent thermoelectric and piezoelectric effects. The device made of organic thermoelectric materials, supported by a microstructure framework, can operate under a natural temperature gradient, without an external power supply. The temperature resolution and pressure sensitivity of the sensor can reach 0.1 K and 28.9 kPa respectively. They also demonstrated an integrated array of 1350-pixel e-finger sensors in a fabric frame with an area of 2×3 cm^2.

Yang *et al*. [20] presented a pyroelectric nanogenerator composed of a titanite zirconate lead (PZT) micro/nanowire. When the temperature is increased from 296 to 333 K, the device can produce an output of 60 mV and 0.6 nA. A liquid crystal display is lit by the device under a large temperature change (~180 K). Obviously, such a large temperature difference is not suitable for harvesting human thermal energy, but it can be used as a self-powered sensor to detect finger tip temperature.

Lee *et al*. [27] fabricated a highly elastic PyNG, which consists of P(VDF-TrFE) pyroelectric material, PDMS elastomer and Ag/AgNWs electrode. By using micropatterned architectures and different coefficients of thermal expansion of materials, the output performance of PyNG has been significantly improved. When the temperature difference is 22 K and the temperature change rate is 105 K/s, the stretched PyNG can produce an output voltage of 2.5 V and a current density of 570 nA/cm^2. By storing the energy from PyNG in a capacitor, LEDs and LCDs can operate.

Sun *et al.* [28] presented a flexible transparent tribo-piezo-pyroelectric hybrid generator for human body energy harvesting and physiological monitoring. A leaf-hole-like network of silver nanowires is prepared as high-efficiency transparent electrodes (TEs) for the construction of the hybrid generator. An optical thermometer, by integrating the transparent hybrid generator with a thermochromic liquid crystal film, is also presented. When the user breathes weakly and normally at an ambient temperature of 15 °C, the device can produce an output voltage of 25 V and 35 V respectively, meanwhile turning red and green accordingly.

Xue *et al.* [43] presented a self-powered breathing sensor based on a portable PyNG, which is made of electrodes covered with PVDF film on both sides and an N95 respirator. The PVDF film is embedded in the middle of the respirator to sense the airflow a user exhales. When the user breathes at an ambient temperature of 5 °C, PyNG can produce 42 V / 2.5 µA output signals due to the temperature variation. PyNG's high output performance can be used to monitor human breathing status and ambient temperature.

Human body heat harvesting with TEGs

Human energy comes from food (carbohydrates, fats and proteins). The efficiency of energy conversion in the human body is estimated to be 15–30%. Therefore, most of the energy is lost to the environment as heat energy. The magnitude of power proportional to body heat emission, associated with a range of human activities and postures, is shown in the table below [32].

Table 1: Power dissipated as heat by the human body during different activities

Activity	Total Power
Sitting at rest	100
Sitting, light work (e.g. typing)	120
Sit down, eating	170
Walking at 1.5 m/sec	305
Heavy work (e.g. lifting)	465
Sport	525

The data show that this is an important resource/basis for the development of energy harvesting technologies that could be used to power electronic devices. In all physical activities, human endurance is an inverse function of mechanical performance. The relative temperature between the human body and the environment ranges from 5–10 °C. It has been argued that a TEG is the best way to harvest human body heat as, due to their small size and light weight, these units can easily be built into clothing [2].

Among all areas of the human body, the neck is the most accessible part and a good location for TEG. The core area of the body should always be warm. Therefore, a generator can be easily removed by the user without causing discomfort. It is estimated that approximately between 0.2 and 0.32 W could be recovered using a neck brace [2].

In efforts to develop techniques to harvest energy from passive human power, a wearable TEG system was developed. Xie *et al.* [2] developed a power generator consisting of a 1 cm^2 chip, fabricated with more than 30,000 thermocouples and capable of producing 16.7 V and 1.3 µW output power at a temperature difference of 5 K. This was capable of powering ultra-low power medical implants, such as medical implant communication system and wireless sensors.

Comparison between TEG and PEG

The human body is a natural constant source of heat. The human body consumes a large amount of energy every day to maintain a constant body temperature and emits heat to the environment continuously [2]. Therefore, the thermal energy from the human body can be recycled and used as a continuous energy source.

Most importantly, this form of energy harvesting does not cause negative effects on the human body itself, so human heat is an ideal energy source that can be used continuously at any time. However, there are still some limitations to the actual use of human heat. First of all, the energy conversion efficiency of TEG and PEG is limited by the second law of thermodynamics (Carnot Efficiency). A high energy conversion efficiency requires a large temperature difference. Since the normal temperature of the human body is constant at 36–37 °C, the temperature difference that can be used for energy harvesting mainly comes from the temperature difference between the human body and the external environment. Therefore, it is usually impossible to achieve a large temperature difference, except in an extremely cold environment. In addition, although the temperature inside the human body is more stable, it is difficult to directly create the temperature difference with the outside, so TEGs and PEGs are rarely used *In vivo* [2].

TEGs are currently the primary way to harvest thermal energy from the human body. TEGs adopt a solid-state energy conversion method without chemical reaction or fluid medium, which has the advantages of no noise, no vibration, no wear, no medium leakage, small size, light weight and long life in the production process. Despite these advantages, some critical issues remain for TEGs. TEGs are based on a spatially graded temperature distribution. Compared to PEGs, TEGs are more dependent on heat exchange between the human body and the external environment. In addition, TEGs are generally composed of multiple sets of semiconductor thermocouples in series and parallel, which leads to a complex structure and high cost [2].

PEGs can only harvest heat energy that changes in temperature over time, so there are relatively few applicable scenarios for harvesting human body heat energy, such as non-continuous heat breathing through the mouth and nose. However, PEGs can be used as ideal self-powered sensors, particularly suitable for detecting human activities and temperature changes. Compared with TEG, PEG generally has a simple device structure and relatively high output voltage, but it is not as stable as the former. When the temperature is higher than the Curie temperature, then the spontaneous polarization of pyroelectric materials will disappear. In addition, the extremely high humidity atmosphere also reduces its performance [2].

In summary, TEGs and PEGs currently applied in human body thermal energy harvesting can only provide relatively low power output with low energy conversion efficiency [2].

Increasing the thermal contact area and using an efficient power management system can suitably improve the output and conversion efficiency. For TEGs, the main content of the current research is to continue the in-depth study of thermoelectric conversion materials, to develop high thermoelectric value (ZT) thermoelectric materials with high Seebeck coefficient, high conductivity and low thermal conductivity.

In addition, increasing the number of series and parallel thermocouples to make a more efficient thermocouple for the use of space, creating a suitable structure to match the heat flow direction, and using an auxiliary heat dissipation unit to improve the heat collection efficiency can also partially improve the output efficiency of TEGs. For PEGs, the development of pyroelectric materials with a high pyroelectric modulus, further optimization of the device structure, and the use of advanced packaging technology are promising methods [2].

Energy harvesting by using electromagnetic induction

Electric field always produces magnetic field. In contrast, a time-varying magnetic field always produces an electric field. Faraday’s law of induction describes the modification that a magnetic field will induce an electric current.

The principle of magnetic induction has been used to develop an adaptation to harvest energy from motion in the knee joint based on negative muscle work [33]. The system included an orthopedic knee brace driving a transmission system via a one-way clutch. Only the extension motion of the strut is transmitted to a brushless DC generator. This device was capable of generating 2.5 W per knee, at a walking speed of 1.5 m/sec. The additional metabolic cost of energy production (not including the cost of transporting the device) was estimated to be 4.8 W, i.e., 12.5% of the metabolic cost required for conventional human energy production.

In a major breakthrough, researchers from the University of Auckland developed artificial muscles with dielectric elastomers, which are capable of generating good force when stretched and contracted [2]. In an experiment, it was found that the 110 mm wide piston-shaped generator was capable of producing 10 mW of power. When incorporated into clothing, its elastic nature allows it to passively harvest energy from large and slow movements, making it a potential option for replacing bulky and heavy components from conventional energy harvesting generators. McKay *et al.* [2] developed a generator with 42×40 μm thick, 11 mm diameter dielectric elastomer layers stacked in parallel electrical connection and sandwiched between 3 mm thick silicone caps at both ends. They were able to produce a maximum power of 300 μW in 3 mm compression, thus making it capable of powering wireless sensor nodes.

From the data summarized above, energy from passive human activity appears to be the most underutilized source of ambient energy. It has been estimated that humans are capable of operating machines to produce power in the range of a few milliwatts to more than 500 W, the upper end of this range corresponding to short-duration athletic performance. However, average-sized and physically fit individuals could generate several electrical watts with virtually unconscious effort, by deforming tiny electromechanical components fitted to wearable items such as footwear. Reimer and Shapiro theoretically demonstrated that up to 4 W could be generated by 4 mm compression of a shoe sole, easily achieved at a natural rate of two steps per second (or 1 Hz per insole) by an 80 kg person. The maximum energy that can be produced, assuming that 50-80% of the walking energy is stored as elastic energy in the shoe, would be 2 W. It has been argued that human walking at a normal pace is a potential source of electrical energy, which could operate low-power electronics or recharge a battery [2].

Conclusions

With the development of the electronic industry, mobile healthcare and Internet of Things technology, everything in the world can be connected to each other in an informational way. The energy structure of the world is undergoing enormous changes today. In addition to the traditional large-scale accumulated energy sources for the development of human society, distributed, mobile and divergent small energy sources are also required in this era of the Internet of Things, that is, the energy of the new era. In fact, everything contains inexhaustible energy, and the human body itself is a typical form of energy of the new age. In recent years, research on harvesting energy from the human body has made significant progress, some low-power electronic medical devices and portable devices can be successfully powered by energy from the human body itself.

This survey summarized three main sources of energy flow contained in the human body, which are thermal energy, chemical energy, and mechanical energy. Considering the characteristics of the three energy streams, corresponding energy harvesting technologies are successively introduced: thermoelectric generator and pyroelectric generator for thermal energy harvesting, biofuel cell and hydrovoltaic generator for chemical energy harvesting, piezoelectric nanogenerator and triboelectric nanogenerator.

Overall, the potential to harvest passive energy from human activity appears to be the most underutilized energy resource of the environment. Several concepts based on the collection of passive human power, i.e., those with limited substantial distraction from normal activities, are considered practical means of converting human energy into usable electrical energy.

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