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Micro linear generator for harvesting mechanical energy from the human gait

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A B S T R A C T

A type of multipolar linear permanent magnet generator (MLPMG) was developed in order to harvest human lower-limb motion energy to meet the increasing power supply needs of portable electronic devices. A large acceleration of the foot, particularly at the heel, was noted when analyzing human lower-limb motion during walking, so an energy harvester was placed on the heel. A series of MLPMGs were then designed and the static magnetic induction intensity vector diagram was obtained from each. A key parameter of MLMPG efficiency was found to be the gap between the stator and mover. Another important factor is the thickness of the mover spacers between magnet pieces. Finally, a number of experiments were conducted, which supported the conclusion that the output power of harvesters have negative relation with length of gap and thickness of spacers. It was found that a subject, walking at a speed of 5 km/h with a matched resistor load, can produce an output power of 20 mW.

1. Introduction

With the rapid development of electronic information technology during recent years, an abundance of mobile electronic devices are now widely used, leading to higher requirements for power, as well as the need for portable power supplies. The dominant power supplies for mobile electronics are currently batteries [1]; however the energy density is limited, which limits the battery‘s capacity and thus the volume and life of mobile electronic devices; this has become the main constraint of wearable technology [2,3]. Furthermore, eco-friendly disposal presents other problems when batteries are no longer functional.

Obtaining energy from the ambient environment is becoming a pivotal area of research as a way to address the above issues. There is a tremendous amount of solar, mechanical and thermal energy in the natural environment and the harvest, storage and use of this energy is of great engineering and environmental significance [4,5]. However, external environmental conditions are constantly changing, which makes maintaining a continuous power supply difficult. In contrast, the environment of the human body is relatively stable and provides a rich source of energy [6]. Harvesting upper-limb kinetic energy is difficult due to motion complexity and multiple degrees of freedom. In contract, the amplitude and strength of lower-limb motion is large, making the lower limbs a better choice for energy scavenging. And using the body's negative motion to collect energy is more effective than using positive motion [7]. The use of a dynamic nonlinear model can increase the sensitivity of the harvester to the movement, but it does not perform well in real human walking exercise tests. Therefore, the energy harvester needs to consider a lower operating frequency in order to adapt to the human walking movement [8]. The current study aims to efficiently collect this dissipated energy, while affecting the human body as little as possible.

D. P. Mitcheson et al. introduced the working principle, application scope, specific application and research status of different types of energy devices based on human kinetic energy [9]. The most common energy harvester is made up of piezoelectrics, which are fragile and unable to produce big enough current. The piezoelectric energy harvesting is small and fits the shoes well. However, due to limitations in the frequency of motion and the power generation efficiency of the material, piezoelectric materials generally generate less electricity. T.Y.Minami et al. used an unimorph piezoelectric cantilever, under a resonance free vibration, to enhance the piezoelectric vibration frequency [10]. Sari I et al. and Khaligh A et al. realize the frequency up-conversion by making use of an array of cantilevers [11,12]. Due to the crystal structure of

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piezoelectrics, the output power of these piezoelectric energy harvesters is less than 1 mW.

The second type of energy harvester is electromagnetic harvester. There are primarily two kinds of electromagnetic harvesters for harvesting human mechanical energy, namely, the rotary harvester and the linear harvester. Harvesters generate electric power by using several means, such as air pressure, water pressure, inertia, and foot strike, to name a few. As for rotary harvester, a linear-to-rotary movement converter, complicated and inefficient, is a must. A. M. Purwadi et al. propose a rotary electromagnetic energy harvester, using an alternating current motor instead of a direct current motor. Rather than testing on the human body, an actuator was used to simulate walking, producing 1.1 W of power over the entire gait cycle. The authors suggest that the combination of shoes also requires better mechanical design [13]. H. O. C. Houng et al. proposed two energy harvesting devices. One is a linear electromagnetic energy harvester, and the other is a rotary electromagnetic energy harvester, which is based on a hand-cranked generator in a flashlight. Under a test condition of 13.26 cm/s, the two energy harvesters can get 0.008987 mJ, 0.48666 mW of maximum power and 187.41 mJ, 256.91 mW of maximum power respectively [14].

Linear harvesters have the advantage of structural simplicity and attract a lot of attentions for human mechanical energy harvesting. The power plant proposed in reference [15] consists of a horizontally magnetized square magnet made of laminated silicon steel. At a speed of 4.5 m/s, 674 mW of power can be generated. The device can't be installed in the shoes because of its large size. The device proposed by S. Cheng and D. P. Arnold replaces a single magnet by a smaller array of magnets with alternating magnetic poles, increasing the time rate of change of the magnetic flux, thereby increasing the output power. According to the data provided in the literature, the volume of the device is at least 37.26 cm^3. Experimental measurement of the load condition at 9.2 Hz, and the maximum output power was 0.55 mW at 400 Ω [16]. Patel et al. designed a linear electromagnetic harvester which is of AA battery size and capable of producing power from 0 to 38 mW at low frequencies of 0–35 Hz [17]. The power density of the harvester was calculated to be $4.44 * 10^{-4}$ mW/cm^3. In another study, an energy harvester which exploits the swing motion of the foot was proposed [18], and the highest measured average power of the harvester was 0.84 mW at a motion speed of 6 km/h on a treadmill.

These linear harvesters are either too low in energy output for power supply requirement or too big in volume to be integrated into a shoe, so a trade-off has to be made between harvester size and output power, which is a key challenge for energy harvesting from human gait. These linear harvesters all consist of a mover and a stator. To improve the efficiency of energy conversion, various structural and operating parameters of harvester such as travel range of mover, shape of magnets pieces that make up mover, turns of windings and walking speed of wearers are tested. In this study, detailed structural parameters, namely, thickness of spacers and length of air gap between the stator and the mover of the harvester, are optimized through experiments.

In this manuscript, a profound analysis of the human foot motion was made, as an aid to finding the best location for harvester in a shoe and ultimately making a good use of mechanical energy of human gait. In addition, considering the structure of human foot and comfort of wearer, a multipolar linear harvester was proposed with innovative structure, optimized structural parameters, and good integration into a shoe. Moreover, the magnetic field analysis and experiments in different states of the proposed harvester are presented.

2. Human lower-limb motion analysis

A thorough study of the human gait was needed in order to use it most efficiently. Romero et al. tested several locations on the body, while subjects were walking and running on a treadmill and found that the most power was obtained when the energy harvester was mounted on the ankle vs. the knee, hip, chest, wrist, elbow, shoulder or side of the head [19]. Therefore, in the current study, acceleration data was collected from three different parts of the foot, the tiptoe, sole and heel. The part of the foot, which accelerated the most while walking was determined, without taking into account the walking pattern. This analysis helped ascertain the most efficient way to harvest the lower limb kinetic energy of humans. A data acquisition system was used to obtain the lower limb acceleration data.

2.1. Human's lower limbs motion data acquisition system

The gait acceleration data was measured by an accelerometer (RealTagSensor) and sent via Bluetooth (Texas Instruments CC2540) to USBDONGLE (Webee4.0), then sent to computer through a serial port and analyzed via Matlab. Accelerometers were placed simultaneously on three parts of the foot of each subject as shown in Fig. 1. Gait acceleration data was obtained while subjects walked on a treadmill at a speed of 3 km/h.

Unfortunately, there were transmission delays and other problems due to differences in the accelerometers, thus when obtaining subsequent acceleration measurements, only one accelerometer at a time was placed on each part of the foot being tested. The same accelerometer was then used on the other two parts of the foot and acceleration data from those areas was obtained. All data were obtained using the same walking speed and time. The integrals of the absolute values from the three sets of data were compared to determine the best location for placement of the MLPMG.

2.2. Human lower-limb motion data processing and results

When a person is walking, the speed variation along the x axis is more intense compared with the y and z axes; in other words, there is more energy potential. An example time-series plot of acceleration data versus time for the accelerometer placed, in turn, on three different locations of the foot is shown in Fig. 2.

As shown in Fig. 3, the speed variation along the x axis is largest at the heel compared with the sole and tiptoe. Thus, the heel was chosen as the optimal position for MLPMG placement.

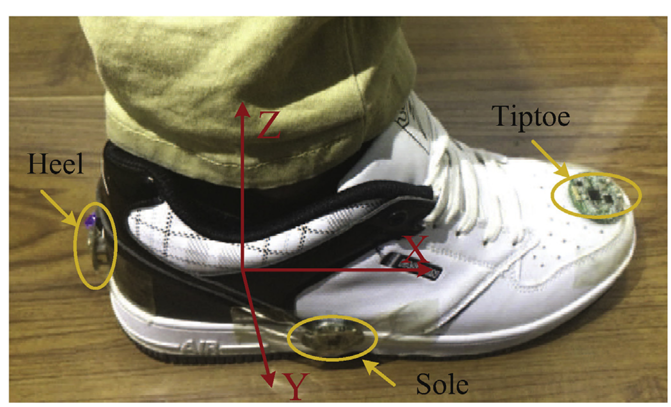

Fig. 1. An example of the RealTagSensors putted on three positions (heel, sole and tiptoe) of foot.