Abstract

Harvesting energy from biomechanical motion of a human poses a promising replacement for batteries in a modern day where portable devices ran out of batteries much faster than before. We developed an energy harvesting device that is focused on heel strike of a gait cycle. The device works by converting the vertical motion of a heel strike to a rotational motion that would generate power from an AC motor. AC motor was used instead of DC because of its capability to generate power in two directions. To further increase the power generation, spur gears were attached to the device as to amplify the rotational motion with a ratio of 27.5:1. The device managed to generate a power of 1.1W throughout a gait cycle. Biomechanical energy harvesting proved to be capable of storing powers in exchange of putting an extra effort and discomfort to the user while wearing it. Nevertheless, future versions of energy harvester should pose no problems and is a promising source of energy to power up portable modern gadgets such as cell phones and mp3 players.

1. Introduction

Even in this modern society where technology advances exponentially, the gadgets which people always brought with them everywhere seems to lack the ability preserve its energy. The power consumption of those features they provide were still too big compared to the power provided by the batteries they had. It could be seen from modern teenager and even young adults with at least a Smartphone with them were having trouble when their
gadgets suddenly ran out of power, to counter this problem, a portable charger was brought in place. The problem
with this portable charger is, portable charger is apparently just a chunk of bigger batteries that outputs current to
other batteries. In other words, it was still a battery that will run out of energy sooner or later. Even though they
managed to build a higher capacity e.g. 20000mAh, the time that it took to charge the portable batteries are just too
long. While some people are busy finding out new source of energy, people sometimes forget that an unlimited
source of energy lies in human body itself. A normal human with average size could have energy equal to 1000 kg
of batteries stores in their fat\(^1\). The calories stored in human are easily dissipated into heat energy which could waste
around 5 W/sec\(^2\). Some researches about converting these energies exerted from human to electrical energy had
been done numerously in recent years, either using body heat or human mechanical motion. Among these, walking
had been viewed as the most convenient and flexible way of energy harvesting due to a lot of energies could be
converted during the motion\(^3\). While some had proposed using a backpack type\(^4, 6\), there are also some ideas about
using piezoelectric on the shoes\(^3\). According to U.S. Energy Information Administration (EIA), the total of
renewable energy consumption as per 2011 as per Fig.1 is about 9\%, in which the biomechanical motion did not
even contribute 1\% to it. The reason behind this could be seen from the researches done previously. Even though
human motion has a potential to be the most reliable source of renewable energy, human has yet to achieve the
maximum potential of it. This particular research will be focusing towards finding the more efficient way to harvest
energy from human motion. The proposed method was to develop a device that focuses on the heel strikes.

![Fig. 1 Total energy consumption 2011](image)

2. Methods

2.1 Power generation

There have been a lot of researches on harvesting energy using human energy, particularly in using human
biomechanical motion such as arm motion, centre of mass, knee motion and heel strike\(^8\). There were also researches
on using human perspiration system by using epidermal bio fuel cells based on temporary transfer tattoos, as
demonstrated by Wenzhao Jia and colleagues\(^9\).

Using the centre of mass had proven to generate the most power out of all the design, by using suspended-loaded
backpack as proposed by L. Rome et al.\(^8\), they have managed to generate power as much as 7.4 W during fast
walking using a 38-kg load on the backpack. The idea of the design was to make the load to move freely up and
down during walking motion, and that load helps to generate electricity by attaching a toothed rack to the load plate.
By attaching a geared dc motor to the backpack frame and connect it to the toothed rack on the load plate, the
system acts as a generator. Another similar approach had been done by Granstrom et al., they managed to generate
an extra 50 mW by attaching a piezoelectric material on the shoulder strap of a 44-kg backpack\(^5\). The downside of
using backpack is the inconvenience it brings, by carrying 40-kg backpack; it could hinder in a lot of human daily activities.

Niu et al. proposed another design using knee motion when walking\textsuperscript{10} and was developed further by Donelan et al\textsuperscript{11}. The device was designed to harvest the negative work during human gait cycle, as it was observed that during the cycle; almost 90% of the muscle work on the knee joint was negative work. The design of the device is simple, a chassis and generator was mounted on an orthopaedic knee brace\textsuperscript{11}. The chassis acted as a gearbox that converts the high torque during the knee motion into high velocity for electrical generation. Furthermore, as the device only uses one-way clutch system, it only engages during knee extension but not in knee flexion, to make the device work in both extension and flexion, a more complex system must be implemented, which will cause the increase in total weight and discomfort for the user, which was the same problem encountered when using backpack. Even then, the device managed to generate power of 2.5 W per knee. However, during the research, it was stated that the subject had an increase of metabolic cost of 19.2%. A study by Howells managed to come up with a heel strike generator, the idea was to convert mechanical strain using a piezoelectric materials into electric current\textsuperscript{1}. The design used four Lead Zirconate Titanate piezoelectric materials which would be stacked upon each other to create four different phases. These phases would then be regulated and converted into DC voltage signals by using rectifier circuit. The device managed to have an electric output of 90mW average, while not being able to properly run a modern Smartphone; it was able to keep some communication devices such as pagers in a standby mode.

A magnetic spring generator was proposed by Saha, C. R. et al\textsuperscript{2}. The idea was to use the low vibration from walking and convert it into electrical current by the means of magnetic coil generating system. The device itself consists of two fixed magnets at the top and bottom, and a free magnet that will bounce up and down when the user walks. A coil was put in the middle section of the device so that when the device was to be given a vibration, the free magnet would bounce up and down to generate electricity. A higher efficiency device was proposed where it still uses the same principle but instead of 2 fixed magnets on the top and bottom of the tube, the top fixed magnet was set to free magnet. The higher efficiency device could generate an average power of 2.46mW during slow running.

2.2 Device design

This energy harvesting device presented two challenges. The first one was to design a device as per the Fig.2 that is small enough to be installed near the heel but still effective enough to generate electricity. The second challenge was to make the device as per Fig.3 that could convert the linear force from the heel strike to drive the gears in rotary motion.
We have evaluated different kinds of methods in producing electrical energy from mechanical work which could be installed in a small device. The first one is by using a piezoelectric material to generate power. While its design is simple, the results were not that satisfying as it did not produce high mechanical-to-electrical energy conversion efficiency. The second alternative is by driving a motor as a generator on the device. While it is more difficult to apply than its counterpart, motor as a generator has been used for decades. It has a great mechanical-to-electrical energy conversion efficiency since it usually works and driven by gears. The gear ratio will help in determining the angular velocity of the motor which will affect the energy output from the motor.

To calculate the energy output and efficiency of the design, the following equations could be used:

\[ \omega_g = \omega_i \cdot r_t \]  \hspace{1cm} (1)

where \( \omega_g \) is the angular velocity applied to the generator, in this case the motor, \( r_t \) is the gear ratio and \( \omega_i \) is the input angular velocity, which in this case the angular velocity applied to the first gear. Since the design uses heel strike as input, the angular velocity could be derived from

\[ V = \omega_i \cdot r \]  \hspace{1cm} (2)

With \( V \) is the velocity of the heel strike and \( r \) is the radius of the handle/lever. With the generator angular velocity is found, the equation could be used further to find the output energy by applying the equation:

\[ E = K_g \omega_g \]  \hspace{1cm} (3)

Where \( K_g \) is the back-EMF constant which would be dependent on the motor itself.

The device has a dimension of 5.9cm x 3.1cm x 2.5cm and consists of 4 gears and 1 AC motor. AC motor was used instead of DC motor to compensate the alternating movement of the device. DC motor only allows power generation in one direction whilst AC motor could generate power in either direction. This way, the device could generate power during the heel strike and when the heel is off the ground. The device also has a gear ratio of 27.5:1. However, while the device is ready to be implemented to shoe or any part of the human body, it has not been done so due to the second challenge that was briefly mentioned above. Despite of that, the idea was to have a lever or a handle and connected it to the generator with torsion spring attached to it so that the handle could rotate to its original position after the heel strike.

2.3 Device testing

Since the device was still in a prototype phase and was not ready to be tested on a human subject, an alternative testing apparatus was designed to act as the human foot striking the ground. The idea was to replace the human foot with an actuator and connected it to the device. With this, the generator could generate power by imitating the heel strike motion of a human foot. While not completely the same and accurate, the results from this method could provide a general idea of what the device is capable of.

3. Results and Discussions

The first time the device was tested on the platform, it outputs a fluctuating voltage as shown in Fig.4 from positive to negative because of the AC motor. To be able to charge a battery, a DC voltage is needed, hence, a rectifier circuit consists of 4 rectifier diode (IN4003) was used. However, by doing this, some energy loss would happen due to the conversion. Without any additional circuit, the device could generate up to a maximum of 11.8 W during the heel strike, but of course this is not a reliable value because there was no load. Moreover, fluctuating voltages are not acceptable on any electrical devices, which was another reason why a voltage regulator and a
capacitor were added into the circuit. This helped the voltage output to be as constant as possible throughout the gait cycle.

![Fig. 4 Voltage output](image1)

The device managed to scavenge 3.3 J of energy out of 12.375 J applied from the gait cycle. The total amount of power as shown in Fig. 5 could generate is approximately 1.10 W. This results in an efficiency of 26.7%. However, it was still not enough to charge an Iphone 4 which requires a minimum of 2.5 W. Comparing it to other devices, a different approach was done by Qingguo Li et al. which uses the knee movement instead of the heel strike managed to build a device with an efficiency of 64.7% compared to our device that had an efficiency of 26.7% \(^{11}\). However, the device weighs around 1.6kg, which is still considered quite heavy for something that needs to be put on the knee for long. Nevertheless, the knee brace design proved to be much more efficient than the heel strike device because it purely uses knee joint rotation movement with addition of gearing ratio which will amplify the rotation of the generator. Even the most common energy harvesting method that uses piezoelectric material on the sole of a shoe by Howells could only produce around 90mW average compared to our device 1.10 W\(^1\). Even though spring loaded backpack which weighs around 38-40kg could generate 7.4 W in average during fast walking\(^5,7\), it requires more energy consumption from the user to carry the load which are not advised to be used on daily activities. However, the spring loaded backpack would prove itself useful on military activities where soldiers are needed to carry backpacks that are similar in weight. On contrary, the heel strike device is much smaller and lighter compared to the knee brace device; in fact, it only weighs around 500g. The magnetic spring generator however, even though it was not able to generate enough power to run any portable devices, it was still one of the smallest and flexible design\(^2\). The device was made in such a way that it could be attached to pants or backpacks by using key hanger.

However, the heel strike device is more complicated to be applied in daily activity. As of now, the device needs to be attached to at least a shoe, making it inseparable. Compared to the knee brace design, it only needs to be strapped on the knee and could be removed whenever the user wanted. The heel strike devices are not able to be detached from one shoe to another as the user wanted. The problems with all energy harvester devices that had been researched for decades are almost the same. Even though the device managed to output more than 50% of efficiency\(^1\), however, the fatigue and comfort of the subject was not put into account. Qingguo Li et al. mentioned that their subject had an increase in metabolic cost of 19.2% while wearing the device in a disengaged mode, which means the increase of metabolic cost was purely because of carrying an extra load on the knee\(^1\). Not to mention the spring loaded backpack that weighs 38-40kg. While it would not be necessary the case with heel strike device, it still has comfort-to-generation problem. In order to maximize the generation output, the device would need to be installed to a shoe in such a way that it will produce the maximum angular velocity. However, by doing this, it would mean to sacrifice the comfort of the user while walking, especially during the heel strike. The discomfort that the user would feel is a sensation like stepping on something. Torsion spring would also need to be installed on the handle to have continuous generation. The addition of the torsion spring will greatly increase in the discomfort of the user during the heel strike since the torsion spring would always try to counteract the movement of the heel strike. Another issue would be the way of storing or transferring the energy generated from the device. While it is possible to charge a battery, it is unlikely for the device to charge directly to the phone while walking. The possible idea is to use the energy harvesting device to charge an onboard battery, which would then be able to charge the phone when needed. Even with this idea, the user would need to stop for him/her to charge their phone since they...
would not want a foot long cable hanging around their attire from their pocket to their shoe.

4. Conclusion

We have developed an energy harvesting device that could generate peak power of 11.8W by taking advantage of human gait cycle, specifically during the heel strike. The device uses AC motor as a generator to convert the mechanical rotation power to electrical power and 27.5:1 ratio spur gears to amplify the rotation motion. The device itself proves to have a maximum of 42.9% efficiency during the heel strike. The efficiency was believed to decrease much further if it was to be implemented in a human test subject. In order to tackle all the problems stated above, including the lack of efficiency on the device, future energy harvester device might have to use specific generators that are built for this application to reduce any internal losses. Other materials could be used to reduce the weight and increase the rigidity of the device itself, an example of it is a carbon fiber. While energy harvester devices still poses a lot of problems when worn on daily activities such as fatigue, comfort and aesthetic looks on the user, future version of energy harvester device might prove to be one of the most reliable sources of energy. However, this could only happen after there is a better way to transfer energy without using cables.

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References