Investigation of piezoelectric energy harvesting from human walking

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Investigation of piezoelectric energy harvesting from human walking

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Abstract. Energy harvesting from human foot motion is attractive for the electrical power source of wearable sensors. For human foot motion, three types of energies are available: bending in the sole, heel strike and swing motion. In this study, the magnitudes of these energies were analyzed by dynamic measurements using various sensors. Then, appropriate piezoelectrics and device structure for the energy harvesting were discussed for each energy. From these results, it was concluded that utilizing bending in the sole and organic piezoelectrics such as PVDF is the best way for the energy harvesting from walking.

1. Introduction
Wearable devices have been rapidly developing, and there is an increasing demand for self-sustaining power source. Energy harvesting from human motion is one of the solutions. Since the energy derived from foot motion is the largest among the various human motions [1], there are various reports, which demonstrate prototypes of shoes with energy harvester [2, 3].

Conversions from mechanical energy to electrical energy can be realized through four basic mechanisms, including electromagnetic, electrostatic, inverse magnetostrictive and piezoelectric. Since the piezoelectrics have features of large power density and ease of miniaturization, various piezoelectric harvesters attached to shoes have been reported. For example, Shenck N et al. reported the harvester for shoe sole, which produced an output power of 8.4 mW [4].

In this study, the maximum electrical power that can be expected for piezoelectric harvesters equipped in shoes is discussed. Three types of energy can be obtained from human foot motion: bending in the sole, heel strike and swing motion. The magnitudes of these energies were analyzed by dynamic measurements using various sensors and maximum electrical power converted from these energies during walking was calculated. Moreover, the optimum structure for efficiently converting to electrical power by utilizing piezoelectric effect is investigated.

2. Experiments
Bending strain during walking was measured to investigate the input energy to shoes by bending in the sole. Strain gauges (KFEM-5-120-C1L3M2R, KYOWA, Japan) were used for the measurement. PET sheet with a thickness of 500 μm and Young’s modulus of 2 GPa was cut into a foot shape. Four strain gauges were attached to the both sides of the PET sheet as shown in figure 1(a). The PET sheet was placed under the insole of a shoe. For unrestricted measurements, the portable strain amplifiers were fabricated, and the output voltage from the strain amplifiers was recorded by Arduino UNO during walking. The force by the heel strike was measured by pressure sensors (Flexiforce, Nitta, Japan)
which were put on the insole. The swing motion was measured by a 9-degree sensor attached to the side of the shoe. The direction of acceleration and angular velocity are also shown in figure 1(a). These signals were also detected by Arduino UNO at the same time.

3. Results and discussion

The measurement results of bending strain in the sole, the force of the heel strike and swing motion are shown in figure 1(b). From the measurement of bending strain, it was found that the maximum strain was obtained at [C], which is around the boll of the foot. While similar strain was observed at [A] and [B], the strain at [D], which is around the arch of the foot is much lower than at other positions. The pressure of the heel strike reached about 0.9 MPa. From the measurement result of acceleration and angular velocity, walking state can be analyzed. It can be separated stance phase and swing phase.

The calculated bending stress in the PET sheet at the boll of the foot is shown in figure 2. The bending stress is about ten times larger than the pressure of the heel strike shown in figure 1(b). This indicates that larger electrical power can be expected for the bending in the sole. For the detailed analysis, the output power was estimated for the bending and the heel strike. The assumed structure of the harvester for the bending is the piezoelectrics attached on the PET sheet. The strain energy $U$, which is stored in the piezoelectrics, is calculated by

$$U = \iiint \frac{1}{2} \varepsilon \sigma \, dx \, dy \, dz$$

$$= \frac{1}{2} \sigma^2 \int V$$

where $\varepsilon$ is strain, $\sigma$ is stress and $E$ is Young’s modulus. The bending strain in the piezoelectrics is proportional to the distance from the neutral plane. Therefore, the bending strain $\varepsilon$ can be expressed by

$$\varepsilon = \varepsilon_{\text{Measure}} \frac{h_{\text{Piezo}}}{h_{\text{PET}}}$$

where $\varepsilon_{\text{Measure}}$ is measured strain, $h_{\text{Piezo}}$ and $h_{\text{PET}}$ are thickness of piezoelectrics and the PET sheet, respectively. From equations (1) and (2), it is indicated that the stored strain energy for the bending is proportional to the cube of thickness of the piezoelectrics. For the energy harvesting from the heel strike, the piezoelectrics are placed simply under the heel. The stress in the piezoelectrics is independent of the thickness, so the stored strain energy is

Figure 1. (a) Direction of acceleration and angular velocity and strain measurement points. (b) Measurement results from various sensors during walking.
proportional to the thickness. For the non-resonant type piezoelectric energy harvester, the electrical power $P$ converted from the strain energy is given by $P = k^2 W = k^2 \frac{du}{dt}$, where $k$ is electromechanical coupling coefficient of the piezoelectrics. In this study, Pb(Zr,Ti)O$_3$ (PZT) and Poly Vinylidene DiFluoride (PVDF) are selected as typical piezoelectrics. The properties of PZT, and PVDF as well as PET are summarized in table 1. While PZT has an advantage of high $k$, it has a disadvantage of brittleness. PVDF has completely opposite properties, which are low $k$ and high flexibility.

Figure 3 shows the harvested power from the heel pressure and the bending strain around the ball of the foot as a function of the thickness of PZT and PVDF. The thickness of the PET sheet was assumed to be 500 $\mu$m. For the piezoelectric transduction, 33 mode and 31 mode are used for the heel pressure and the bending strain, respectively. While PZT has about 40 times higher $k^2$ than PVDF, for the heel pressure, the harvested electrical power for PZT and PVDF is almost same. This is because the deformation and the input energy for PZT by the heel pressure is one-fortieth of those for PVDF. As a result, the low $k^2$ of PVDF is compensated by the high input energy.

On the other hand, large differences are observed for the bending in the sole as shown in figure 3(b). PZT can harvest larger electrical power than PVDF at the same thickness. However, the electrical power is limited at 60 $\mu$W/cm$^2$ due to the fracture limit for PZT, which is about 1250 $\mu$e at the thickness of 125 $\mu$m. PVDF can harvest larger electrical power than PZT, when the thickness is more than 900 $\mu$m. While the use of such thick PVDF sheets is not easy, it is not necessary to be a single sheet. Bimorph structure composed of non-piezoelectric plate and PVDF, and multilayer structure can harvest the almost same amount of the electrical power, when the total thickness of PVDF is same. It is also revealed that electrical power harvested by the bending is more than 100 times larger than that by heel strike, although $k$ of 33 mode is higher than that of 31 mode. These

### Table 1. Properties of piezoelectrics and PET.

|               | PVDF | PZT | PET |
|---------------|------|-----|-----|
| Young's modulus (GPa) | 2.0  | 80  | 2.0 |
| Bending strength (MPa)   | 75   | 100 | 73  |
| Thickness ($\mu$m)       | Various | Various | 500 |
| $k_{31}$                  | 0.11 | 0.35 | -   |
| $k_{33}$                  | 0.69 |      |     |

**Figure 2.** Bending stress on PET at the boll of foot.

**Figure 3.** The dependence of the electrical power on the thickness of PVDF and PZT. (a)Heel (33mode) (b)Bending (31mode).
results indicate that the increase of the input mechanical energy is quite effective to increase the harvested electrical power.

Figure 4 shows the electrical power as functions of the thickness of PVDF and PET. The electrical power increases with increasing the thickness of PET as well as PVDF. This is because the strain of PVDF increases with increasing the thickness of PET. The electrical power more than 10 mW can be expected when the actual device size becomes more than 10 cm².

The energy harvesting from the swing motion is also discussed. In this case, the kinetic energy is transferred to the mass attached to the piezoelectric oscillators. The kinetic energy of a 1 g mass in a shoe during walking is calculated as shown in figure 5. The average kinetic energy is about 500 μJ/s. From this result and the theoretical conversion efficiency of the piezoelectric oscillators, it can be expected that maximum electrical power is less than 50 μW. This calculation is consistent with the previous results, in which the obtained output powers from the swing motion are less than ~mW [5]. Hence, the direct application of the force to piezoelectrics such as the bending in the sole is superior to the use of the kinetic energy of the swing motion.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** The dependence of the electrical power on the thickness of PVDF and the substrate.  **Figure 5.** Kinetic energy of a 1 g mass in the shoe during walking.

4. Conclusion
In this study, three types of input energy to the shoes, which are bending in the sole, heel strike and swing motion, were analyzed by dynamic measurement using various sensors. Input mechanical energy by bending in the sole is largest among three energies. It is suggested that utilizing bending in the sole with organic piezoelectrics such as PVDF is the best way for energy harvesting from walking.

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