A DYNAMIC MODEL OF ARM-EQUIPPED ROTATIONAL ENERGY HARVESTER DURING HUMAN LOCOMOTION

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Abstract. A dynamic model of arm-equipped rotational energy harvester (EH) during human walking is proposed. The model describes realistic arm swing based on a two link with shoulder and elbow joints rotation, and includes the electro-mechanical coupling with a rotational electret EH. It is found that output power around 77 µW can be obtained with a rotational electret EH at the walking speed of 1.22 m/s, with minimum output power of 40 µW. Optimum design of rotational electret EH for human walking can be made with this type of model.

1. Introduction

Energy harvesting from human walking is suitable for powering battery-less wearable devices. In such applications, rotational energy harvesters (EHs) have advantages over vibration EHs due to the fact that low-frequency 3-D vibration with 3-axis rotation is dominant for human motion. In previous studies [1, 2], sinusoidal external vibration or actual vibration of a specific person is employed to characterize rotational EHs, so that it is not straightforward process to estimate the output power for human walking in general. In the present study, we develop a dynamic model of arm-equipped rotational EH for examining the effect of various parameters of the EH on the output power.

2. Arm Swing Model

Figure 1 shows the present model of rotational EH fixed on an arm modeled with a two link. Segment data of arm is referred to Ref. [3]. In this study, EH is assumed to be fixed at a wrist, near a hand.

Hejrati et al. [4] showed that the shoulder joint angle is approximated with a sinusoidal oscillation. In the present study, based on their statistical analysis, the applied sinusoidal angle in shoulder is given by

$$\theta_{\text{sh}} = A_{\text{sh}} \sin (2\pi f_{\text{sh}} t),$$

where $A_{\text{sh}}$ is the amplitude of shoulder joint, $f_{\text{sh}}$ is the frequency. Using the parameters given in Ref. [4], $A_{\text{sh}}$ and $f_{\text{sh}}$ are expressed by human parameters:
where \( h \) is height, \( m \) is mass, \( g \) is gender (\( g = 0 \) for females, and \( g = 1 \) for males), \( v \) is walking speed, and \( s \) is surface slope on which human walks.

In the present study, the height, weight, and walking speed are assumed to be 1.64 m, 66 kg, and 1.2 m/s, respectively. Also, the gender is assumed to be female. Figure 2 shows temporal change of the modeled shoulder joint angle, which is in good accordance with the actual experimental data [4]. On the other hand, the elbow joint angle exhibits somewhat complex behavior, and it is difficult to approximate with a sinusoid oscillation. However, for the zeroth-order approximation, we employ the following equation for the elbow joint angle as the shoulder angle,

\[
\theta_{el} = A_{el} \sin(2\pi f_{sh} t) + \theta_{0el}
\]

where \( A_{el} \) is the amplitude in degree, and \( \theta_{0el} \) is the offset angle. Using the parameters in Ref. [4], \( A_{el} \) and \( \theta_{0el} \) are given by

\[
A_{el} = 6.39v - 1.59g + 0.117s - 0.182vs + 0.101,
\]

\[
\theta_{0el} = 26.4v - 6.69g + 0.458s - 0.722vs + 2.155,
\]

Figure 2b shows the elbow joint angle versus gait cycle percentage. The temporal profile of the modeled elbow joint angle exhibits similar amplitudes with the data [4] and qualitative accordance. These results indicate that the proposed model describes the arm swing motion during human

\[
A_{sh} = -359h + 74.07v + 107h^2 + 0.289mv - 0.267m - 50.1hv + 0.0995s + 353,
\]

\[
f_{sh} = 0.361v - 0.0141s - 0.561h + 0.00340vs + 1.46,
\]
locomotion with reasonable accuracy. Note that the accuracy of the model can be improved only with more plausible model for the elbow joint angle.

3. Rotational EH Model

In the present study, rotational electret EH [5] shown in Fig. 3a is assumed as an example of rotational EHs. The rotational mass is 15 g, and the eccentricity is 3 mm. Other physical parameters are similar with those in Ref. [5]. Figure 3b shows the one-dimensional electrostatic model [6]. Applying the Gauss’s law, the Kirchhoff’s law, and the conservations of charges, a differential equation for the output voltage is given by

$$\left\{ C_p + \frac{\varepsilon_0 e_E}{d + e_{EE}} (A_1 + A_2) \right\} \frac{dV}{dt} = - \left\{ \frac{\varepsilon_0 e_E}{d + e_{EE}} \left( \frac{dA_1}{dt} + \frac{dA_2}{dt} \right) + \frac{1}{R} \right\} + \frac{\sigma d}{d + e_{EE}} \frac{dA_1}{dt},$$

where $C_p$ is the parasitic capacitance, $\varepsilon_0$ and $e_E$ are the permittivity of vacuum and the relative permittivity of the electret, $d$ and $g$ are the thickness of the electret and the gap distance between the electret surface and the counter electrode. $A_1$ and $A_2$ are the overlapping area in between electret and the counter electrode, and in between the guard electrode and the counter electrode. $\sigma$ is the surface charge density of the electret.

Acceleration in a two-dimensional plane by the arm swing as well as the rotational acceleration is applied to the EH. Estimated mechanical damping of the bearing as well as the electrical damping are assumed as in the following equations:

$$T_{\text{mech}} = D_{\text{mech}} \theta_{\text{EH}},$$

$$T_{\text{elec}} = V R \frac{1}{\theta_{\text{EH}}}$$

These damping torques represent the mechanical energy dissipated in the oscillating system and the electrical energy converted from the kinetic energy of rotor.

Using the present arm swing model and the EH model, we calculate the rotational angle and the output voltage. The output power is computed as a time average for 10 s, where transient response still exists.

4. Results

Figure 4a shows the simulation result of rotational angle of EH for different walking speeds. For the walking speeds in this range, the rotor rotates back and forth, and EH sometimes rotates in one direction continuously at higher walking speeds. The output power is shown in Fig. 4b. The peak to

![Figure 3](image)

**Figure 3.** (a) Schematic of rotational electret EH [5], (b) One-dimensional electrostatic model of rotational electret EH.
peak output voltage is approximately 100V at the walking speed of 1.2 m/s, and output power of 69 µW is obtained.

Figure 5a shows the output power for different walking speeds. In this range of normal walking speeds, it is shown that the maximum output power 77 µW is obtained at 1.22 m/s, and minimum output power 40 µW at 0.6 m/s. The EH at 1.22 m/s keeps rotating leading to large output power. At a higher speed of 1.5 m/s, on the other hand, the lower output power drops due to smaller rotation angle in the time period of the present simulation.

Figure 5b shows the output power for different rotor mass with constant eccentricity of 3 mm. It is found that the output power is increased with the mass, but levels off at 7 g, showing the existence of minimum rotor mass for an efficient rotational EH.

5. Conclusion
A dynamic model of arm-equipped rotational EH for human walking is proposed based on the knowledge of biomechanics. Under the assumption of this study, up to 77 µW is obtained in the normal walking speed range. In addition, it is shown that the present model can provide information for effective design of high-performance rotational EH for human walking.

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