Develop a Model for Harvesting Energy from Human Foot Strike

Longhan Xie[1] and Ruxu Du[2]

[1]The Chinese University of Hong Kong, lhxie@mae.cuhk.edu.hk
[2]The Chinese University of Hong Kong, rdu@mae.cuhk.edu.hk

ABSTRACT

It is known that human body contains rich chemical energy, part of which is converted to mechanical energy up to 200W when in motion, so it is ideal to harvest the human body kinetic energy to power the mobile electronic devices. It was reported that up to 67 Watts of power can be available from human foot strike. In this paper, a new model for harvesting energy from human foot strike is developed. For the consideration on stability and efficiency, a spring-slider-crank mechanism is used in the proposed harvesting method to covert the up-down foot strike motion into unidirectional rotation to drive the AC generator. The spring and slider compose an oscillating system to absorb the foot strike motion, and crank and slider make up of the motion conversion mechanism to transfer the bi-directional translation into unidirectional rotation. Gear sets are used to speed up the rotation.

Keywords: energy harvesting, human energy, foot strike.
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1 INTRODUCTION

In recent years, humans have become increasingly dependent on electronic devices, such as mobile phones, PDAs, and etc. Especially for soldiers in wild area, they need electronic devices for communication and other necessary functions, such as the Land Warrior system of US Army, which provides radio, navigation, computer and other electronics devices [1]. The total power requirement of such necessary devices is more than 20 Watts, and the design goal of such system is to work at least 72 hours. Nowadays, most of these mobile electronic devices are powered by batteries. Although substantial progresses have been made in reducing the power requirements of the electronic devices and increasing the power densities of batteries, the limited energy storage of battery and its considerable weight hinder the extensive use of electronic devices. Furthermore, discarded battery generates billions of wastes every year, resulting in negative environment impacts. The above-mentioned Land Warrior system needs 5 kg of battery to reach the design goal, which is obviously inconvenient for application. Therefore, it is necessary to find alternative methods to solve the energy problem for mobile electronic devices.

The human body is a tremendous resource of chemical energy. Just one gram of fat can be converted to 9000 calories or 37.7 kJ [2]. Also, an average person of 68kg with 15% body fat stores energy approximately equivalent to 384MJ. Thus, if even a very small fraction of this stored energy could be extracted, a portable device would have a large and renewable resource to draw on. Some

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researchers have explored to extract energy from body heat [3, 4], breathing [5], typing [6], arm motion [2], and walking [7-10]. Walking is a main energy consumption activity which also has mechanical power to be exploited. It has been calculated that up to 67 Watts of power are available from heel strike during normal walking for a 68 kg person with the walking frequency at 2 step per second and heel moving 5 cm. There are mainly two methods to harvest the heel strike energy during human walking. One is to use piezoelectric effect to convert the pressure generated when the foot strikes the ground to electricity [7]. Unfortunately, the energy density is very low (only 8.3 mW at the heel and 1.3 mW at the toe). Another is to use electromagnetic induction to convert body motion to electricity. Chen [11] and Lakic [12] reported electromechanical generators to harvest the foot step motion. However these designs are very complex with many parts, and can only harvest the press-down motion, which make these device is fragile, expensive and lower efficiency.

This paper is focused on how to harvest the mechanical energy from human foot strike motion during normal walking. Compared to the existing designs, the proposed harvesting model in this paper will be simpler and stronger, and can harvest not only press-down motion but also the release-up motion. The rest of this paper is organized as follows. Section 2 discusses the foot strike pattern during normal walking. Section 3 will propose the harvesting method. Section 4 will give the description of the proposed harvesting apparatus. Section 5 contains the conclusions and the future works.

2 HUMAN WALKING MOTION

Mechanics of human body in normal walking are very complex, which can be modeled as rigid parts linked by joints. The motion of body's center of mass (COM), which is nearly the same position with the hip, is the basis of human movement and the lower limb of human body supports the whole body. Figure 1 shows the motion trajectory of body's center of mass and knee joint in one walking cycle. In human bipedal locomotion trunk displacement is achieved by means of lower limbs movements which primarily result in a forward displacement of the COM. Human walking movement can be modeled as two coupled pendulums, where the stance leg behaves like an inverted pendulum moving about the stance foot, and the swing leg like a regular pendulum swinging about the hip [13]. In the human single support phase, the inverted pendulum supports the COM without requiring work or force, similar to the ball's flight phase. During double support, the COM velocity must be redirected, with each leg's force directed along the leg. The trailing leg performs positive work on the COM, and the leading leg negative work. Although zero net work is performed during double support, the overall effect is to accomplish the redirection required for the next step.

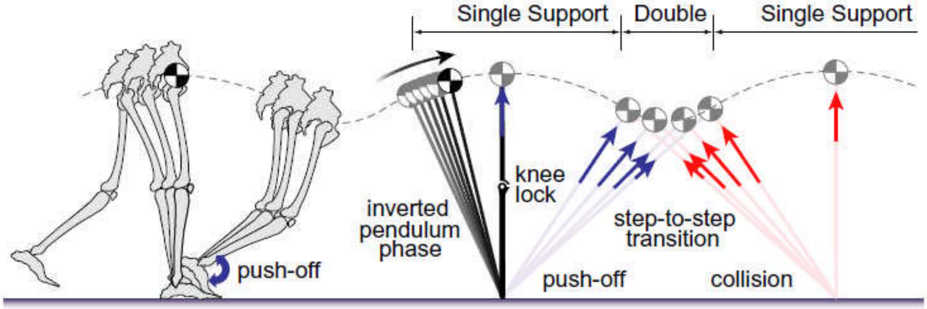

Fig. 1: Schematic diagram of the simple inverted pendulum model of walking [14].

Walking motion is generated by the ground reaction force of the stance foot. For straight forward walking, detailed analyses have been implemented as part of biomechanics. The relation between walking phase, step duration and reaction force is shown in Fig. 2. The vertical reaction force of one foot has two peaks: one is at toe off of the other foot; the other is at heel strike of the other foot. The duration of one step, T, can be obtained from the step length w and the locomotion velocity v as

$T = w / v$, or from the step frequency. The time duration of double foot support T^{ad} can be approximated as $T^{ad} = 0.25 \cdot T$ [15].

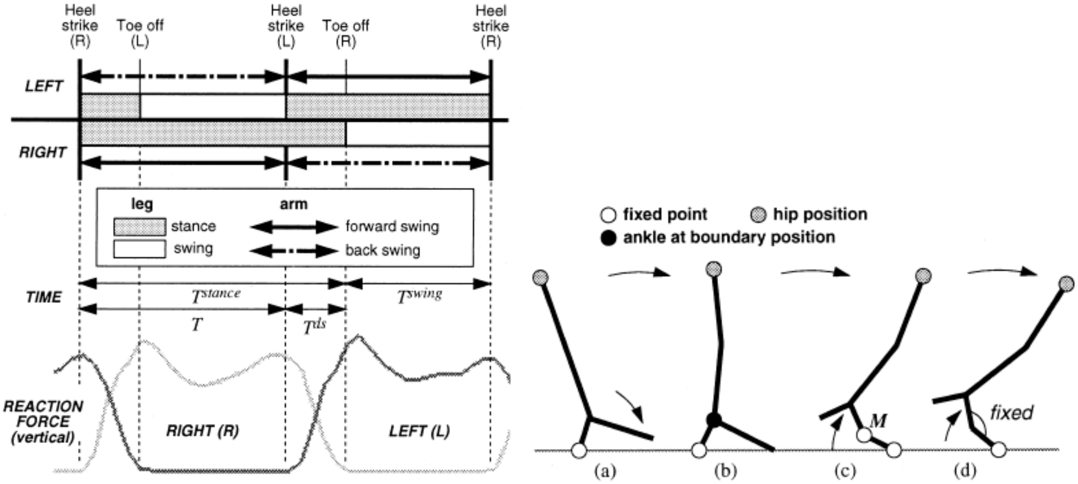

Fig. 2: Step duration during normal walking (left) and Interpolation of stance leg (right) [15].

3 PHYSICAL MODEL OF THE ENERGY HARVESTER

From the above discussion, the human foot movement during normal walking can be seen as the up and down strike movement relative to the ground, which has the largest displacement amplitude on the shoe heel. In this paper, the authors focused on developing a new method and its apparatus, inserted into shoe heel, to harvest the mechanical energy from foot strike during human normal walking. As we know, shoe heel has limit space, especially its height. Therefore, the dimensions of the proposed harvesting device should be a critical concern. Moreover, since the shoe heel will be subjected to most of the body weight, the harvester should be strong enough and reliable. For wider application, the manufacturing cost should also be a design concern. From the above considerations, the harvesting device should be as simple as possible, which can reduce the failure opportunity and the economic cost.

Based on the above analysis, a conceptual design of the foot strike harvesting device is proposed, as shown in Fig. 3, which is built in the space of 70mmX60mmX40mm. In order to improve the harvesting efficiency, the device is symmetric with two identical gear set and AC generator but only with one set of crank-slider-spring mechanism.

The harvester mainly includes a fixed part and a moving part, where the moving part can glide relative to the fixed part guided by guiding pins and holes. The springs around the guiding pins provide the rebound force. The harvester adopts the crank slider mechanism to transmit the motion of the moving board from foot strike to the gear train and finally to the AC motor. In the crank slider mechanism, one end of the crank coupler is pinned to the moving board, and the other end is pinned to the crank. In this mechanism, the moving board serves as the slider which is the driven motion, and the crank transmit the rotation to gear train.

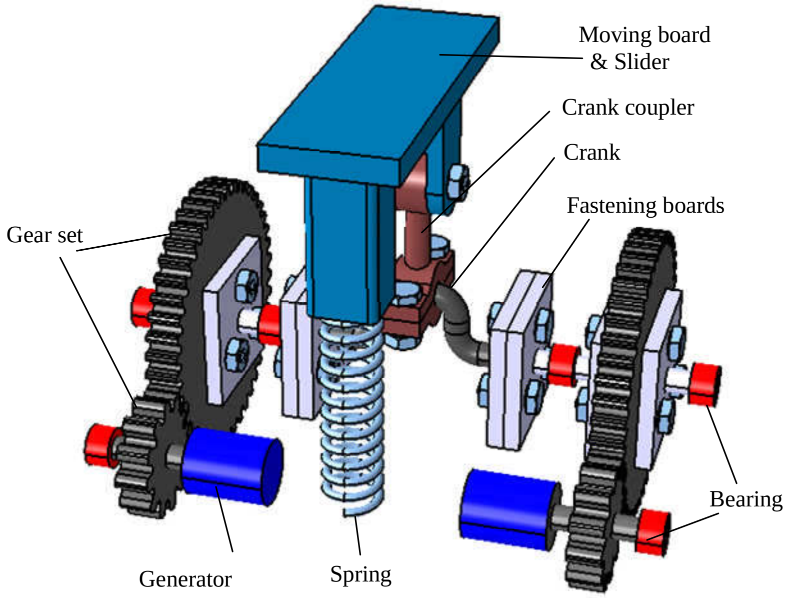

Fig. 3: Conceptual design of the foot strike harvesting device.

4 ANALYTICAL STUDY ON THE HARVESTER

The proposed energy harvester in this paper adopts spring-crank-slider mechanism, gear set and generator to harness heel strike motion, as shown in the left figure of Fig.4. First of all, the heel strike motion is up and down linear motion and the generator can only receive rotation, so the device uses a crank-slider mechanism to convert the linear motion into rotational one, which includes a slider, gear as the crank and their pin-jointed crank coupler. Secondly, in order to continuously drive the harvesting device, a recovery mechanism for the slider is needed. In this design, a spring, constrained in a cylinder hole, is used to provide the recovery function for continuous motion. When heel touches the ground, the spring is pressed down; and the spring is released up when the heel pushes off the ground. Therefore there is reciprocating motion during normal walking. The displacement of heel strike in each foot step is small, and the step frequency is low, acceleration gear set is used to speed up the rotation. The flow chart in the right figure of Fig.4 shows the motion harvesting process.

Crank-slider mechanism is the most critical mechanism in this proposed harvesting device. Extracted from the physical model in Fig. 3, Figure 5 shows the offset crank-slider linkage, where the grounded pivot O of the crank dose not lie on an extension of the line along which the pivot B is pin-jointed to slider. For a given set of linkage dimensions L_1, L_2, the offset distance L_0, and displacement of slider L_3, the following equations can be obtained by geometric and trigonometric relations. If the dimensions L_0, L_1 and L_2 are known, and the slider displacement L_3 is known too, then the angular displacement of the crank can be solved by these two equations.

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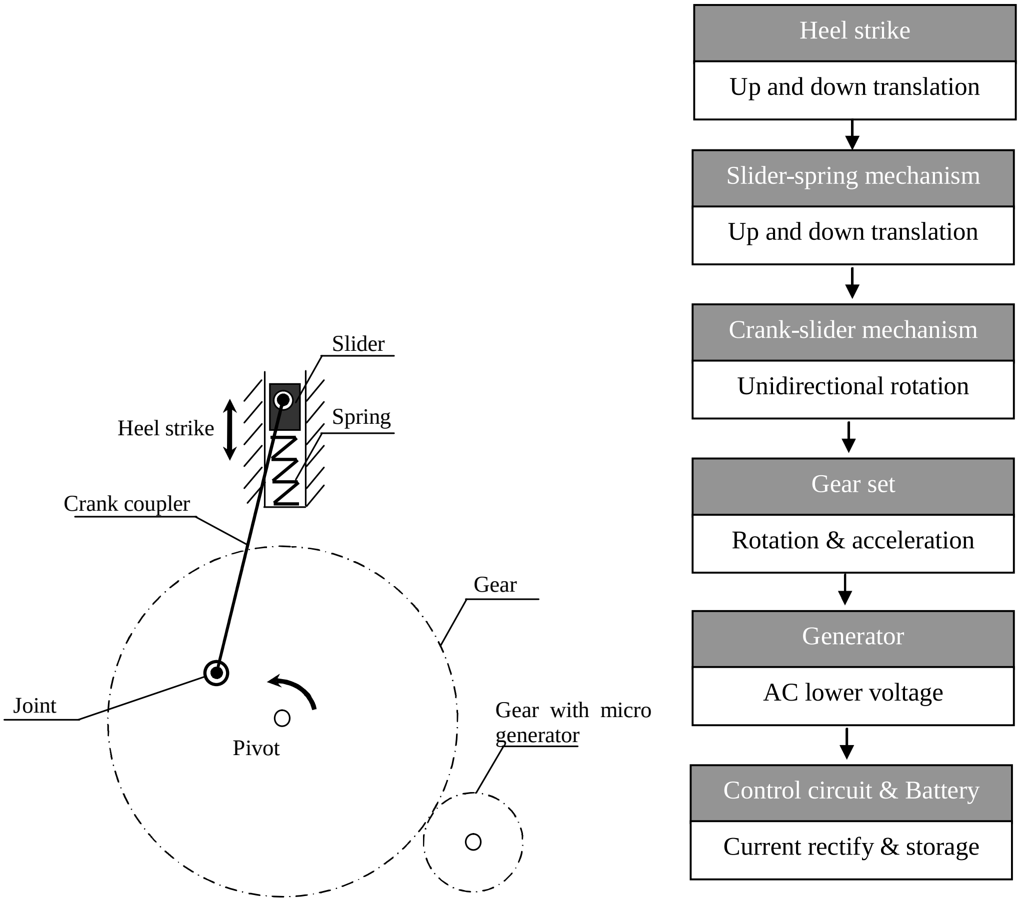

Fig. 4: Schematic diagram of the proposed harvesting model (left) and flow chart (right).

$$L_1 \cos\theta_1 + L_2 \cos\theta_2 = L_3 \tag{1a}$$

$$L_0 + L_1 \sin\theta_1 + L_2 \sin\theta_2 = 0 \tag{1b}$$

For the offset crank slider mechanism, if the slider moves with constant velocity v_B from upper extreme point B^1 to lower extreme point B^2, then the crank rotates from position A^1 to position A^2 with the angle $\angle A^1OA^2 = \pi - \alpha$, however it will rotates with the angle $\angle A^2OA^1 = \pi + \alpha$ when the slider moves from B^2 to B^1. If both of time elapsed Δt are same, then the angular velocity of crank is different, which can be deduced from the following equation. Thus there is velocity fluctuation between the back stroke and the up stroke, which is not good to the generator. From the Fig.6, the angle α is related to the offset distance L_0, that is, the bigger offset distance L_0, the greater angle α under the condition that other variables are constant. Therefore, it is best to set the offset distance zero, i.e. in-line crank-slider mechanism.

$$TR = \frac{\omega_1}{\omega_2} = \frac{\angle A^1OA^2 / \Delta t}{\angle A^2OA^1 / \Delta t} = \frac{\pi - \alpha}{\pi + \alpha} \tag{2}$$

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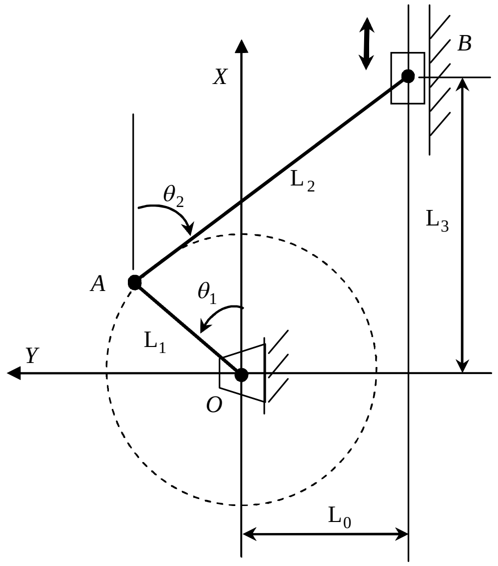

Fig. 5: Offset crank-slider mechanism.

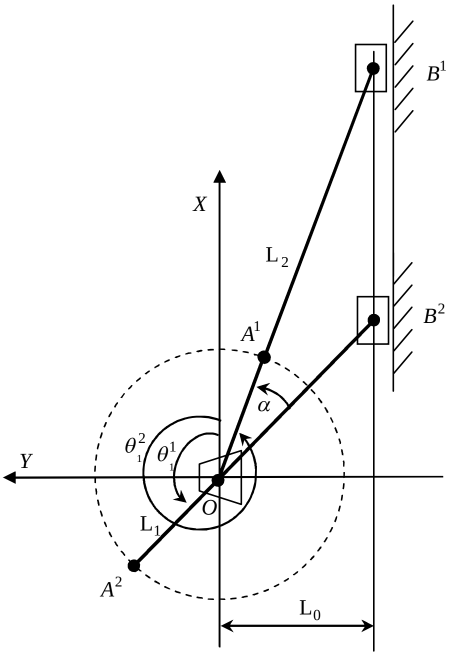

Fig. 6: Extreme positions in offset crank slider linkage.

Figure 7 schematically shows the in-line crank slider linkage, where the grounded pivot lies on the extension line of the slider translational track. Obviously, the in-line crank-slider linkage is a single degree-of-freedom mechanism because the slider moves up and down to cause crank rotates. Simplified from offset crank slider mechanism, the motion expression of the in-line crank slider linkage can simplified from Eq. (1a) and (1b), shown as following. For given crank dimensions L_1 and L_2, the angular displacement θ_1 can be solved directly by Eq. (3c) with the slider displacement and its movement direction. When the slider is on the upper extreme position, that is, $\theta_1 = 0, \theta_2 = 0$, then $x_B^1 = L_1 + L_2$, however when on lower extreme position, $\theta_1 = 0, \theta_2 = 180^o$, then $x_B^2 = L_1 - L_2$, so the stroke distance $S = x_B^1 - x_B^2 = 2L_1$.

$$x_B = L_1 \cos\theta_1 + L_2 \cos\theta_2 \tag{3a}$$

$$y_B = L_1 \sin\theta_1 + L_2 \sin\theta_2 = 0 \tag{3b}$$

$$\cos\theta_1 = \frac{{L_1}^2 + {x_B}^2 - {L_2}^2}{2L_1 x_B} \tag{3c}$$

The force transmission is an important concern in the device design. Because the coupler link L_2 is pivoted at both ends, it is capable of transmitting force only along and parallel to its length. For a given pressed force $\mathbf{F}$ on pivot B, then a component $\mathbf{F}_f$ along the coupler link and a component $\mathbf{F}_c$ perpendicular to the coupler link can be resolved, as shown in Fig. 8. The component $\mathbf{F}_f$ usefully serves as the driving force to rotate the crank, which can be computed by $\mathbf{F}_f = \mathbf{F}\sin\mu$, where the variable μ is called transmission angle. Obviously, the bigger transmission angle, the bigger driving force. The position in Fig. 7 is the extreme value of transmission angle, where $\mu = \cos^{-1}(L_1 / L_2)$. Thus,

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in order to obtain large transmission angle, the ratio between the crank and coupler, $\rho = \frac{L_2}{L_1}$, should be greater than some lower threshold. Usually, the transmission angle should not be less than 40°. If $\rho = 2$, the transmission angle is 60°, satisfactory with the above-mentioned rule.

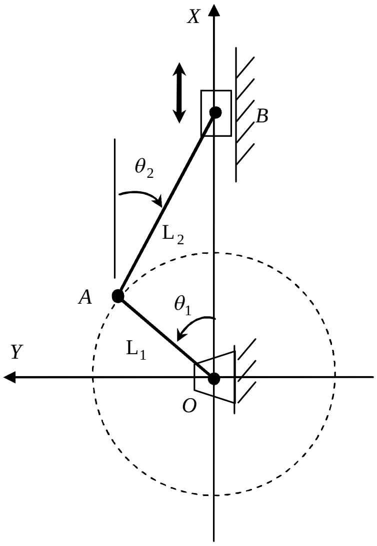

Fig. 7: In-line crank slider linkage.

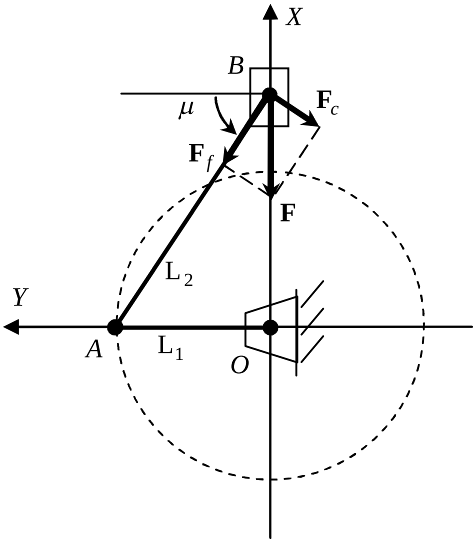

Fig. 8: Extreme value of transmission angle.

The interference between the slider-crank mechanism and other component should be taken into consideration. Before designing the slider-crank mechanism, its trajectories are drawn using Matlab®, as shown in Fig. 9, from which other components should be arranged outside of the maximum profile of the trajectories to avoid interference.

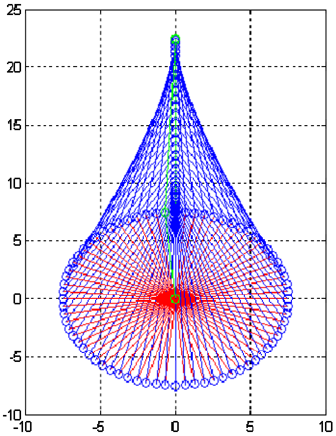

Fig. 9: Trajectories of the slider crank mechanism.

5 CONCLUSION AND FUTURE WORKS

In this paper, a new model is developed for harvesting energy from human foot strike. This model uses spring-slider-crank mechanism to efficiently convert the bi-directional up-down translation of human foot step into unidirectional rotation to drive AC generator. Further research will include building such a harvester for experiment validation.

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