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Research Article

Investigation of Kinetic Energy Harvesting from Human Body Motion Activities using Free/Impact Based Micro Electromagnetic Generator

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Abstract

In this work, a micro-electromagnetic vibration energy harvester based on free/impact motion (FIMG) is tested with human body motion. The harvester under investigation was previously fabricated, studied and tested with horizontal harmonic vibrations. It shows an effective performance output with low frequency – large amplitude vibrations. In addition, it has a simple construction which allows fabrication with small sizes. Hence, the harvester can be recommended for powering portable electronics, wearable, and implantable devices by harvesting energy from the human body movements. However, human body motion during daily activities is basically unsteady, and multi-directional. Hence, in order to correctly evaluate the performance of FIMG with human body applications, it should be tested with the actual human body movements. In this work the harvester is selected to be tested at three different body locations during three common activates. The harvester is attached to three body parts which are the ankle, pocket place (upper-leg) and wrist, and tested during walking with 75 m/min moving speed, fast walking with 108 m/min, and jogging with 150 m/min. Two harvester prototypes of D9×L12 mm cylindrical total size are considered; one is fabricated with ball magnet and another with cylindrical magnet. Voltage waveforms produced by each prototype are measured and recorded during each activity. The results show that significant power could be generated by FIMG from the movement of body limbs, that can reach 445 μW RMS with a power density of about 0.6 mW/cm^3. The amount of power generated depends on the moving activity, and the body location where the harvester is attached. The ball-magnet prototype shows a superior performance over cylindrical-magnet one. The results also show that increasing the body moving speed generally increases the harvested power from different body locations. In addition, the maximum power harvesting could be achieved from ankle then pocket place, and the lowest from wrist during the same activity.

Key words: *Micro-Electromagnetic kinetic energy harvester, free/impact motion, human body motion activities, portable electronics, ball magnet, cylindrical magnet.*

Introduction

Achieving self-powering, self-sustaining or even long-lasting become an important issue in the developing of portable electronics, wearable or implantable devices. Chemical batteries are the conventional way of powering those systems. However, they require a periodic replacement or recharging. Moreover, long-life batteries are usually associated with larger size which obstructs minimization of the total system size.

Harvesting energy from the human body motion is considered as a way of this development. A recent advance shows a success in miniature of kinetic energy harvesting systems. The majority of those systems are able to convert high frequency – low amplitude vibrations into electrical energy [1-3], which is mostly available in industrial environment and machine mediums. However, the motion of the human body during daily activities such as the motion of human limbs during walking are categorized as a low frequency – large amplitude vibrations. Some kinetic energy harvesters are developed to address such low frequency vibrations, which utilize different techniques [4-9]. The key challenge of developing human body- associated harvesters is the ability to scavenge significant amount of energy while keeping small size system. Previously, a micro-electromagnetic vibration energy harvester or generator based on free/impact motion (FIMG) is presented [10]. It has been studied, analyzed and tested with horizontal harmonic vibrations. It shows an effective performance with low frequency – large amplitude vibrations. The output power increases with input amplitude and/or frequency. FIMG also has a simple design which promotes fabrication with small sizes. Therefore, it can be well suited for human body applications. In fact, there is an argument for the convenience of FIMG and its effective performance with these important applications, since human body motion during daily activities are away from harmonic, unsteady, and multidirectional. Such complicated dynamics could have different effects on the harvester performance or another issues may arise when applied with human-powered devices. Thus, the performance of FIMG cannot be guaranteed with human body – associated devices unless it is tested with the actual body motion.

In this work micro-electromagnetic generator based on free/impact motion (FIMG) is tested with human body motion. Energy harvesting from three body locations which are the ankle, wrist, and pocket place (upper leg) are investigated during three different activates, which are walking with speed of 75 m/min, fast walking with 108 m/min, and jogging with 150 m/min. Two harvester prototypes

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are tested. One is fabricated with a ball magnet and another with cylindrical magnet. Voltage waveforms produced by each prototype during the three activities are measured and recorded. The harvester performance is investigated through the experimental results and the input vibration provided by the body motion. The experimental results generally show an effective performance of FIMG with human body motion. The ball-magnet prototype has a superior performance over cylindrical-magnet one. Increasing body moving speed generally increases the output power, as well as higher power could be generated from ankle movement compare to other body parts.

Harvester design and fabrication

Figure 1-a shows a perspective drawing of Micro electromagnetic generator based on free/impact motion (FIMG) [10]. It simply consists of a flanged tube made from polyformaldehyde plastic, with 4 mm inner diameter, and 0.25 mm thickness. The tube is closed at both ends over an inside NdFeB permanent magnet by two thin polyslider washers, which act as stoppers to the magnet during oscillation. Both the tube and the end-stopping washers are made from non-magnetic material (polymers) to avoid sticking with the magnet or affect its free oscillation. An enamelled copper wire of 0.2 mm diameter is wounded over the tube outer surface and secured in position by the tube flanges to form an electrical coil with 300 turns. Giving an input vibration to the tube in the tube axis direction will resulted in a magnet/tube relative motion, which generate an electrical voltage across the coil by induction.

The harvester takes a cylindrical shape with total diameter and length of 9 mm and 12 mm respectively as shown in Figure 1. Two prototypes are tested in this work. The first is fabricated with 3.5 mm diameter ball magnet and the second with D3×L3.5 mm cylindrical magnet.

Human body input vibration

The performance of FIMG mainly depends on the input vibration. It was previously studied and tested with unidirectional harmonic vibrations [10]. The output power increases with the input amplitude and/or frequency. However, the input vibration provided by the human body are not purely harmonic, multidirectional, and complicated in nature, which could have a different effect on the tube/magnet relative oscillation and consequently the overall harvester performance. Thus, the correct way to evaluate the harvester performance with human body applications is to directly test it with the physical body motion.

Energy harvesting during three common natural gaits are investigated in this work, which are walking with a speed of 75 m/min, fast walking with 108 m/min and jogging with 150 m/min. During each, the body parts and limbs have certain movement patterns which affect the input vibration at the different body locations.

Energy harvesting is tested at three body locations, which are the human wrist, ankle and pocket place (upper-leg). Those specific locations are selected for three reasons. First, some human body-related devices and portable electronics such as mobile phones, music players, and wrist watches are associated with those locations. Second, more motion or vibrations are expected from those locations [11]. The last is that passively energy harvesting could be obtained without making discomfort in the human daily activates [12]. The harvester is attached to the body at each location by keeping the harvester tube axis initially coincident with the body moving direction while the body is in the correct standing posture as shown in Figure 2. This orientation generally can guarantee that most of the input vibrations to the harvester are in the direction of the harvester tube axis.

Input vibration during walking

Human moving speed during walking mainly depends on stride rate or frequency and stride length [13, 14]. Stride frequency relates to the leg movement rate while stride length relates to how much distance covered by stride. The input frequency and amplitude to the harvester while attached to the leg (ex: at the ankle or pocket place) could be increased by increasing the stride frequency and stride length respectively. Since, the walking speed increases by increasing the stride frequency and/or stride length. We can expect an increase in the output power of a harvester placed at the ankle or pocket place by increasing the walking speed.

Regarding wrist energy harvesting during walking, the input vibration to the harvester mainly appears through arm swing. The frequency ratio between the arm and leg movement at a walking speed less than 0.8m/s is 2:1, while it is 1:1 and the arm moves in-phase with the leg at a speed higher than 0.8m/s, [15, 16]. The amplitude of the arm swing increases with the walking speed [17]. Hence, increasing the walking speed can increase both the input amplitude and frequency to the harvester at the wrist which in turns increase the output power.

In addition to large amplitude – low frequency movement of the body limbs during walking, there is some degree of impact on the heel of the foot at each step. This impact is transmitted from the foot to the whole body and quickly damped through by the body joints [17, 18]. Hence, this impact is expect to significantly affect the harvester at the ankle over any other location.

Input vibration during jogging

The main difference between jogging and walking is that both feet could leave the ground at one step during jogging however, at least one foot should be kept in contact with the ground all the time during walking [19]. Accordingly, the leg has a different movement pattern during jogging. Foot impact with the ground is more significant. In addition, the lower arm has much bent over the upper arm. Thus, the gravitational force may has more effect on the magnet/tube relative motion of the wrist-attached harvester.

Experimental results

In this experiment, voltage waveforms produced by each harvester prototype while attached to the body limbs are measured and recorded during the three activities. Hence, nine waveforms are obtained for each prototype as indicated by Figure 3-5 for cylindrical-magnet prototype and Figure 6-8 for ball-magnet prototype. The experiment is carried out on a male of 70 Kg weight, 176 cm height, and 27 years age.

The results show that signficant power could be harvested by FIMG from the motion of the body limbs. The amount of harvested power depends on the body location where the harvester is attached, and the human activity. During the three activities, the highest power is obtained from ankle, then pocket place, and the lowest from wrist (Figure 9-11), which could be a result of high input acceleration to the harvester at the ankle [17]. RMS power of about 445 μW is harvested from ankle by the ball-magnet prototype during jogging, while 221 μW and 174 μW are harvested from the pocket place and the wrist respectively (Figure 9). Also, the cylindrical-magnet prototype generates an RMS power of about 175 μW from ankle, while it generates 126 μW, and 86 μW from pocket place, and wrist respectively during jogging (Figure 9).

Increasing the body moving speed increases the output power as expected before, which is a result of increasing the input amplitude and/or frequency to the harvester at different body locations. RMS powers of 160 μW, 189 μW, and 221 μW are generated during walking, fast walking, and jogging from pocket place by ball-magnet protoype respectively. However, there is one case of the obtained results that the output power obtained from the ankle during jogging is less than that obtained during fast walking. This case appears in the cylindrical-magnet prototype results (Figure 5). The power generated during jogging is about 175 µW, while that generated during fast walking is about 187 µW. This difference could be a result of the high impact force on the ankle during jogging. The impact force component normal to the harvester tube axis with high coloumb's friction involved in the cylindrical-magnet prototype can affect the magnet/tube relative oscillation and consequently the genertated voltage by induction. This effect does not signficantly appear in the ball-magnet prototype which has a lower frictional charractristics (Figure 8).

The ball-magnet prototype generally can generate higher power than cylindrical-magnet one from different body locations during different actvities, which is a result of low coloumb's friction associated with the ball magnet. Lower friction resulted in higher magnet/tube relative motion from such low frequency motion and consequently higher induced voltage. In case of very low input vibration acceleration provided by the body motion such as that appears at the wrist during walking, the high coloumb's friction involved in the cylindrical-magnet prototype does not allow sensable magnet/tube relative motion to exist. Consequently, no or neglegable power could be generated in that case (Figure 3-a, Figure 11).

It is worth mentioning that, the rate of increase of the generated power by increasing the moving speed (ex. increasing the input acceleration at different body locations) is higher in case of cylindrical-magnet prototype (Figure 12). The associated rolling motion with the ball magnet causes an orentation change of the magnet diapole during oscillation. This orientation change makes the increase of the time varying magnetic flux with the input acceleration less in case of ball-magnet prototype [9]. However, it still has a superior performance over cylindrical-magnet prototype under the speed limit of the human body motion.

Conclusion

In this work, micro-electromagnetic vibration energy harvester based on free/impact motion previously presented in [10] is tested with human body motion. Two harvester prototypes of total cylindrical size of D9×L12 mm are considered; one is fabricated with 3.5 mm diameter ball magnet, while the other is fabricated with D3×L3.5 mm cylindrical magnet. Both prototypes are attached to three different body locations which are the wrist, ankle, and pocket place (upper-leg), and tested during three different moving activities which are walking with 75 m/min speed, fast walking with 108 m/min, and jogging with 150 m/min. Voltage waveforms produced by each prototype are measured and recorded during each activity which show the harvester ability to generate significant amount of power from the motion of body limbs. The power can reach 445 µW RMS, with an average power density of about 0.6 mW/cm^3. This significant amount of power relative that obtained from harmonic vibrations [10] can be a result of high amplitude oscillations of the body limbs during walking and jogging. The ball-magnet prototype shows a better performance over cylindrical-magnet one at different body locations during different activities, owing to low coulomb's friction associated with the ball magnet oscillation. For instance, the ball-magnet prototype can generate an RMS power of 445µW from the ankle during jogging, 167 µW from pocket place during walking and 160µW from wrist during fast walking. However, the cylindrical-magnet prototype generates an RMS power of about 175 µW from the ankle during fast jogging, 48µW from pocket place during walking, and 38 µW from wrist during fast walking.

The maximum power harvesting during the three activates appears at the human ankle, owing to the high input acceleration to the harvester at this location. Increasing the body moving speed generally boost the power harvesting from different body locations. The power generated during jogging is higher than that generated during fast walking which is higher than that generated during walking with in most cases. One case of cylindrical-magnet prototype results that the power generated during fast walking is higher than that generated during jogging. The prototype at the ankle generates an RMS power of 186.7 µW during fast walking, while it generates 174.6 µW during jogging. This difference can be a result of the high impact force exerted on the ankle during jogging.

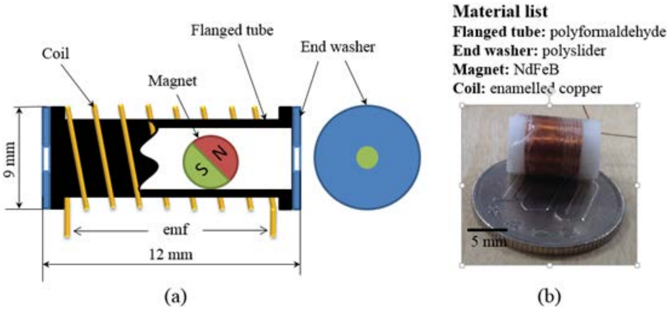


Figure 1: (a) Schematic of micro-electromagnetic generator based on free/impact motion (FIMG) (b) photograph of FIMG shown with 100 yen coin (22.6 mm diameter).

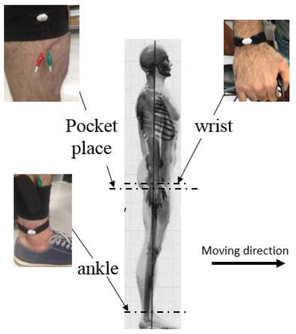


Figure 2: shows the different body parts where the harvester is attached

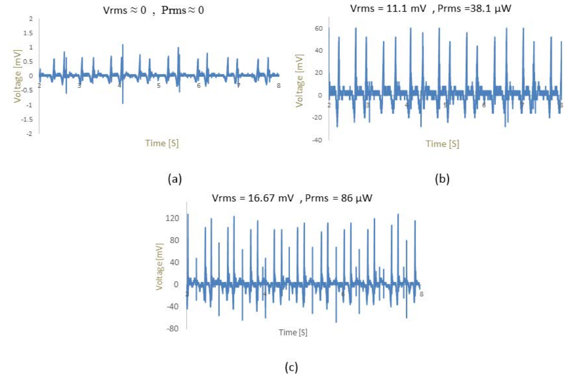


Figure 3: Measured voltage waveform of the cylindrical-magnet prototype while attached to the wrist (a) during walking (b) fast walking (c) during jogging.

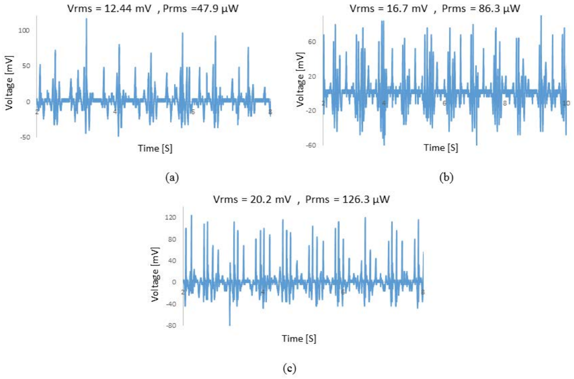
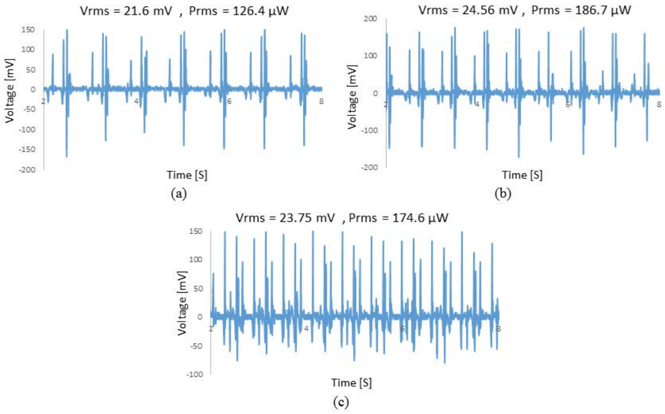
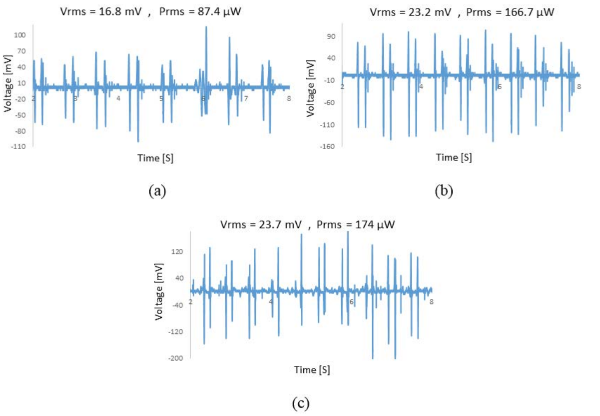


Figure 4: Measured voltage waveform of the cylindrical-magnet prototype while attached to the pocket (a) during walking (b) during fast walking (c) during jogging.



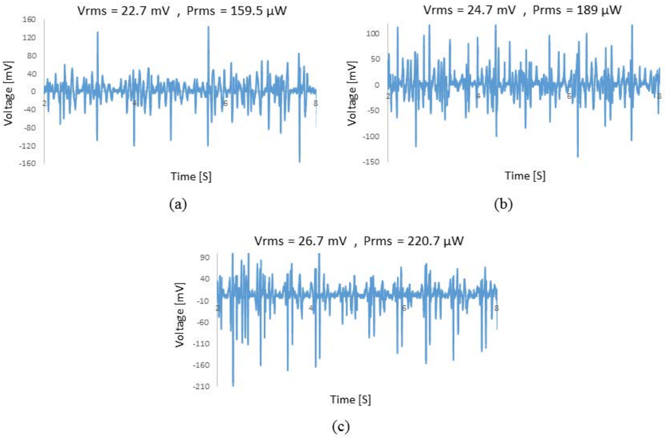
(a) (b) (c)

Figure 5: Measured voltage waveform of the cylindrical-magnet prototype while attached to the ankle (a) during walking (b) during fast walking (c) during jogging



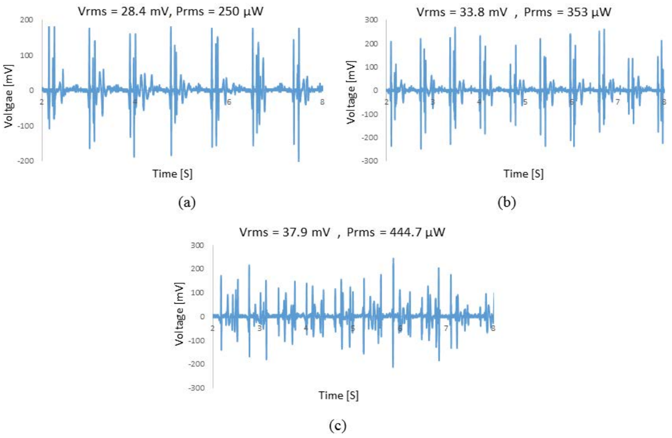
(a) (b) (c)

Figure 6: Measured voltage waveform of the ball-magnet prototype while attached to the wrist (a) during walking (b) during fast walking (c) during jogging.



(a) (b) (c)

Figure 7: Measured voltage waveform of the ball-magnet prototype while attached to the pocket (a) during walking (b) during fast walking (c) during jogging.



(a) (b) (c)

Figure 8: Measured voltage waveform of the ball-magnet prototype while attached to the ankle (a) during walking (b) during fast walking (c) during jogging.

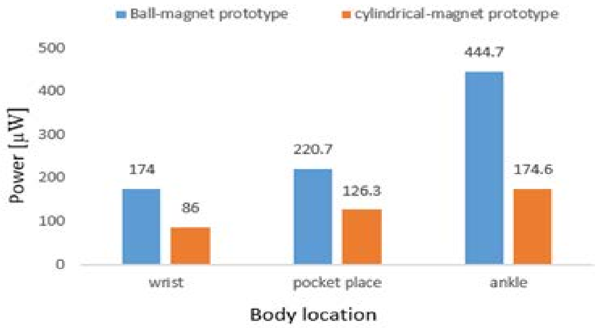


Fig. 9. RMS power generated by each prototype at different body locations during jogging with 150 m/min.

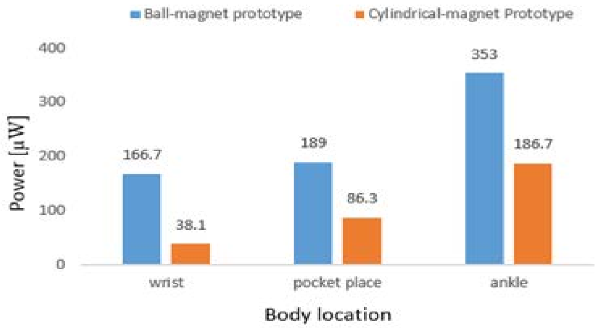


Fig. 10 RMS power generated by each prototype at different body locations during fast walking with 108 m/min.

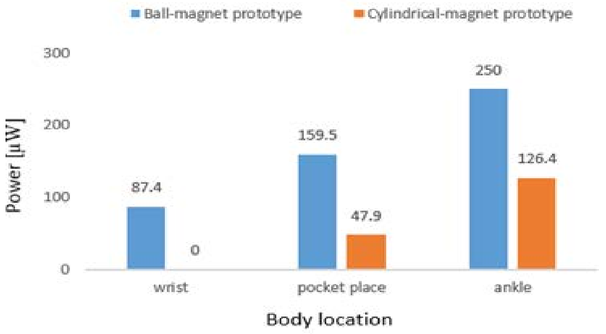


Fig. 11. RMS power generated by each prototype at different body locations during walking with 75 m/min.

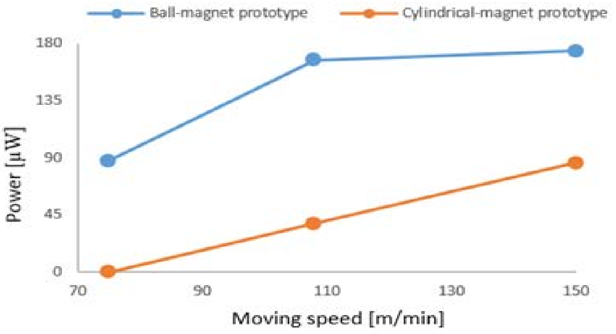


Fig. 12. RMS power generated by each prototype at wrist with the moving speed of the three activates.

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