Pendulum Generators to Power Wearable Devices from Human Motion

Edwar Romero, PhD[1], Jose Montoya, MS[2], Eduardo Castillo, PhD, Bernardo Restrepo, PhD[1],
Albert Espinoza, MS[1], Dulce Mariscal, BS[2]
[1]Universidad del Turabo, USA, eromero@suagm.edu, jmontoya5@email.suagm.edu, ecastillo@suagm.edu,
restrepob1@suagm.edu, espinozaa1@suagm.edu, 2University of Pittsburgh, USA, dum5@pitt.edu

Abstract–This work analyzes the energy generation capability from human walking using pendulum-based generators. Energy harvesting is the process to extract energy from the surroundings to power small portable electronics. Literature for energy harvesters is mostly for linear devices whereas body motion has rotational components as well. The periodic swinging of the limbs is more suited for oscillating generators based on pendulum geometries, such as self-winding wristwatches. Wearable devices can benefit of harnessing energy from everyday activities, such as walking, to reduce battery size or the need for frequent battery recharges. This study discusses the energy availability of using inertial passive generators on body locations while walking. It is estimated that a miniature planar generator using an oscillating pendulum can scavenge from 0.1 mJ to over 20 mJ of energy from walking.

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restrepob1@suagm.edu, espinozaa1@suagm.edu, [2]University of Pittsburgh, USA, dum5@pitt.edu

Abstract*–This work analyzes the energy generation capability from human walking using pendulum-based generators. Energy harvesting is the process to extract energy from the surroundings to power small portable electronics. Literature for energy harvesters is mostly for linear devices whereas body motion has rotational components as well. The periodic swinging of the limbs is more suited for oscillating generators based on pendulum geometries, such as self-winding wristwatches. Wearable devices can benefit of harnessing energy from everyday activities, such as walking, to reduce battery size or the need for frequent battery recharges. This study discusses the energy availability of using inertial passive generators on body locations while walking. It is estimated that a miniature planar generator using an oscillating pendulum can scavenge from 0.1 mJ to over 20 mJ of energy from walking.

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I. INTRODUCTION

Traditional energy scavenger designs follow the model of linear generators to produce electrical energy. Nonetheless motion from external sources is not limited exclusively to one direction. Motion or vibration can be planar or three dimensional where rotational devices can be employed. Oscillating rotational mechanisms can use pendulum-based approaches to take advantage of linear or angular displacements for energy generation. Mechanical pendulum generators have been explored successfully in the past, since self-winding wristwatches have employed this technique for decades. The most recognizable device is produced by Seiko using the Automatic Generating System (AGS), where an eccentric mass (1.6 g and 2.3 cm outer diameter) acting as a pendulum is connected to a set of gears and to a small permanent magnet generator. The AGS can produce about 10 μW when worn on the wrist or up to 1 mW if shaken forcefully [1]. Because of its availability, this generator has been tested by researchers to evaluate its potential to power pacemakers. One test placed the generator on the chest of office workers for 8 over hours where the power produced varied from 0.2 to 3.1 μW, the median was 0.5 μW [2]. The same generator was tested by this group with continuous rotations at 200 Hz producing a power output of 1.8 mW. This indicates the design is capable of producing a relatively high power output under the right conditions. This was evaluated by Sasaki et al. using numerical models and experiments [3]. The analysis of the AGS proved that self-excited rotations are possible in addition to swinging motion. For this mechanism, if the input motion is on the order of 1 Hz the motion is reduced to swing oscillations. However, if the input frequency is 2 Hz, the system can rotate and maintain the rotations (self-excited rotation). The experimental results showed over 200 μW of power output when self-excited (over 10 times the average power output). More recently another group tested another wristwatch mechanism from ETA employing a generator from Kinetron (oscillation weight of 3.5 g) [4]. The contraction of cardiac muscle was used to wind up the main spring of this device. Once the spring reaches a threshold, the elastic energy is transferred to the electromagnetic generator. In vitro experiments produced 30 μW while in vivo tests on a sheep heart produced 16.7 μW (1 hour duration), enough to power some pacemakers requiring 8 μW [4]. Thus, it may be possible that an optimized generator can produce a higher power output from the chest location from office workers without requiring to be attached to the heart tissue.

The purpose of this work is to analyze body locations and the analysis of pendulum-based generators under walking conditions. This approach may help designers to develop energy harvesters from motion based on the application and body location. The proposed energy harvesting system is nonlinear due to pendulum dynamics. The mechanics of walking motion and governing equations will be presented, as well as the results of the computer simulations.

II. BODY MOTION

Since walking is the most common body motion it will be analyzed as the energy input source for pendulum-based generators. It is commonly represented as an inverted pendulum motion. The gait cycle is divided into two phases: stance and swing. The stance phase is when the foot is on the ground which is 60% of the cycle, while the swing phase is when the leg swings to repeat the cycle, the other 40%. During locomotion the center of mass (COM) moves up and down following approximately a sinusoidal pattern. This vertical displacement varies depending on the walking speed from 3 cm to 8 cm (from 0.8 m/s to 2.2 m/s). The vertical displacement is found to be between 4 to 5 cm for the most common walking velocity of 1.4 m/s (frequency of 2 Hz) [5]. Walking requires alternating the foot support from left to right forcing the center of gravity to move as well with a sinusoidal

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shape on the lateral direction. This lateral displacement varies proportionally to the walking speed from 7 cm to 3.8 cm (0.7 m/s to 1.6 m/s) being 4 cm for the preferred walking speed of 1.4 m/s [6]. Therefore, the motion of the COM can be represented with a sinusoidal equation on the forward and lateral direction with 4 cm displacement for the preferred walking speed of 1.4 m/s (as shown in Fig. 1).

The swinging of the leg and arms are also analyzed for the kinematics based on the work of Collins [7]. The shoulder joint moves following a sinusoidal pattern with an average amplitude of 30°. Next section will discuss the basics of the pendulum kinematics for the mathematical models. Models using the COM as a reference point and using the shoulder location will be used for the pendulum generator.

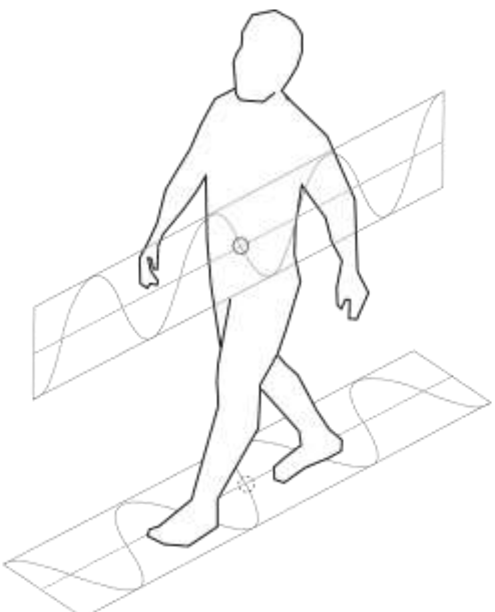
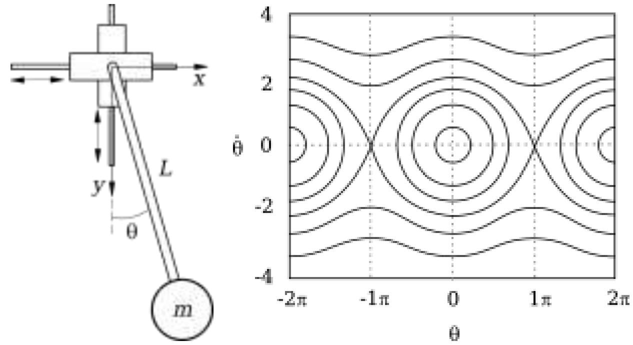


Fig. 1 Walking trajectory of the center of mass

III. PENDULUM SYSTEM

A pendulum subjected to a harmonic excitation is a particular system based on the external oscillatory conditions (Fig. 2). A pendulum under vertical harmonic motion can behave either oscillatory (the closed loops in Fig. 2) or rotatory (the region outside the loops in Fig. 2), as evaluated by Sasaki et al [3]. The phase diagram of Fig. 2 compares the angular velocity against the angular displacement. The closed trajectories are oscillations with different amplitudes. The trajectories outside the boundary (separatrix) are complete revolutions. Since some body locations move resembling a simple harmonic motion during walking, a pendulum model is developed to evaluate for rotational behavior.

The pendulum is modelled with a mass *m* hanging from a rod with length *L* at an angle θ form the vertical, as shown in Fig. 2.



(a) (b)

Fig. 2 Pendulum system. (a) Schematic and (b) phase diagram

The pivot can move along horizontally a distance *X* and vertically a distance Y. The kinetic energy *T* is then presented as $\frac{1}{2}m\left(\dot{X}^2+\dot{Y}^2+L^2\dot{\theta}^2+2L\dot{\theta}(\dot{X}\cos\theta-\dot{Y}\sin\theta)\right)$ whereas the potential energy is $-mgL\cos\theta - mgY$. The total energy (kinetic and potential energy) is then

$$E = \tfrac{1}{2}mL^2\dot{\theta}^2 - mgL\cos\theta + \tfrac{1}{2}m\left(\dot{X}^2+\dot{Y}^2\right) + mL\dot{\theta}\left(\dot{X}\cos\theta-\dot{Y}\sin\theta\right) - mgY \qquad (1)$$

While the first two expressions of (1) represent the kinetic and potential energy of a pendulum with fixed support, the last three terms are the energy imparted by the moving pivot (the energy that can be extracted).

The phase diagram also represents the limits required to start the rotations. The potential energy is at its maximum (the pendulum mass is on the inverted position) at $V_{max} = 2mgL$, which represents the potential barrier. When the energy is less than V_{max}, the pendulum swings. If the energy is higher than V_{max}, there is the possibility for full rotations.

IV. ANALYSIS

The energy available for a generator is the combination of the last three terms of (1). Equation (1) will compare the energy of a fixed support (the first two terms, required to keep the oscillations) versus the energy of a moving support at different body locations during walking. The pendulum angular position and angular velocity equation was evaluated using a fourth order Runge-Kutta method. Once calculated, (1) was used to determine the energy contribution.

Fig. 3 shows the phase diagram for a pendulum situated at the COM and subjected to the up and down sinusoidal pattern during walking with different initial conditions (L = 1 cm). When the initial angular displacement is less than 120° with respect to the vertical, there are only swinging oscillations. Rotations require initial angular displacement higher than 120°. At 1.6 cm length the 90° becomes the separatrix as shown in Fig. 4. For higher pendulum lengths (15 cm), the angle to start the rotations decrease to 60° from 90° as shown in Fig. 5.

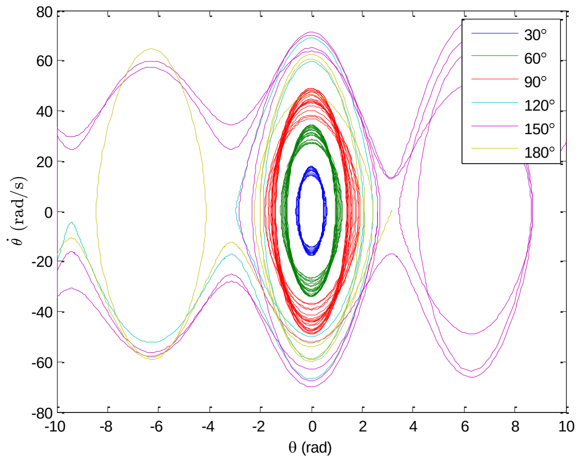


Fig. 3 Phase diagram for 1g mass with L = 1 cm

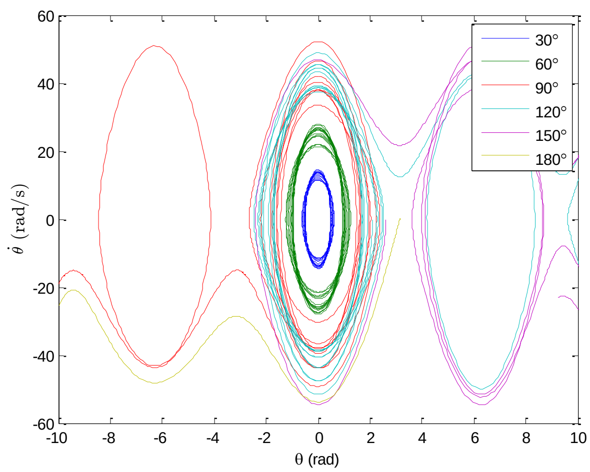


Fig. 4 Phase diagram for 1g mass with L = 1.6 cm

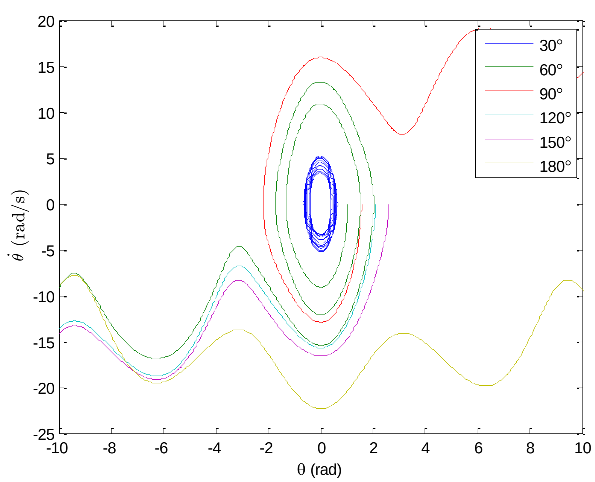


Fig. 5 Phase diagram for 1g mass with L = 15 cm

The simulations were evaluated at different angular initial conditions at every 10° angle (pendulum released at different angles from the vertical, initial angular velocity of zero). Mass was evaluated from 1 g to 10 g. Pendulum length was varied from 1 to 5 cm as well.

The Root Mean Squared (RMS) energy obtained from a pendulum with a moving support at the COM (moving with the walking person) using (1) was found to be 10 times higher than a pendulum with a fixed support as summarized in Table 1. Fig. 6 indicates an example of this simulation. In addition, fig. 7 shows the phase diagram for the shoulder location while walking. At this location even the pendulum with 0° from the vertical starts multiple rotations. Energy availability is twice from the previous case as depicted in Fig. 8.

TABLE I
ENERGY FROM A PENDULUM

Prof mass (g)	Fixed support (mJ)	Moving support (mJ)
1	0.01-0.11	1.01-1.07
10	0.29-1.08	10.05-10.76

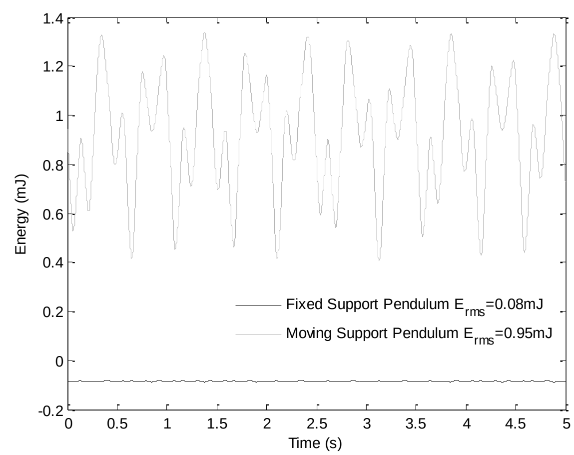


Fig. 6 Energy from a pendulum-based generator on a moving reference frame vs. a fixed reference frame

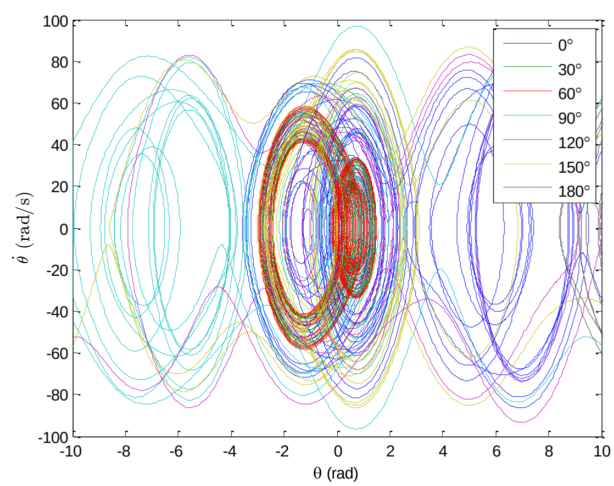


Fig. 7 Phase diagram for shoulder location (L=1 cm)

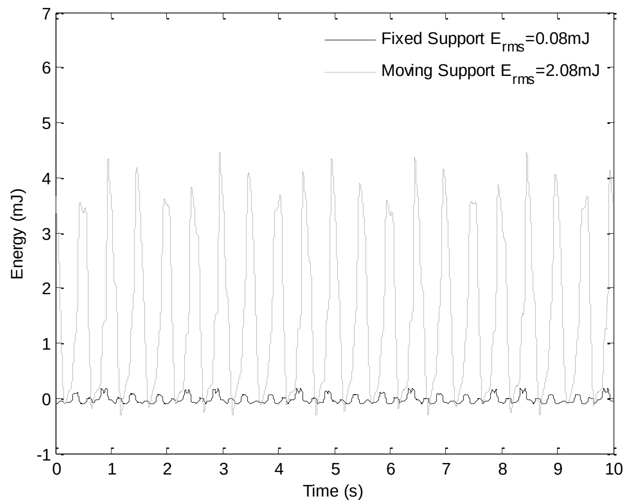


Fig. 8 Pendulum at shoulder (L = 1 cm, m = 1 g)

The system was also analyzed using the lateral oscillation while walking (corresponding to a pendulum-base generator placed on the chest). The phase diagram for this location is shown in Fig. 9 where only large initial angular displacement produces rotations for a length of 1 cm. Figure 10 displays a device modeled with a pendulum length of 2.4 cm. In this case the separatrix decreases to 60°. Increasing the pendulum length distance decreases this angle. Figure 11 presents that for 3.3 cm in length the angle reduces to 30° to start the rotations, while at 3.7 cm even the 0° initial condition can start multiple rotations as depicted in Fig. 12. Figure 13 illustrates a model of the energy availability for this location. Results suggest that a larger mechanical device may be more practical since self-induced rotations can be easily produced, however the physical size of the generator may limit the final application.

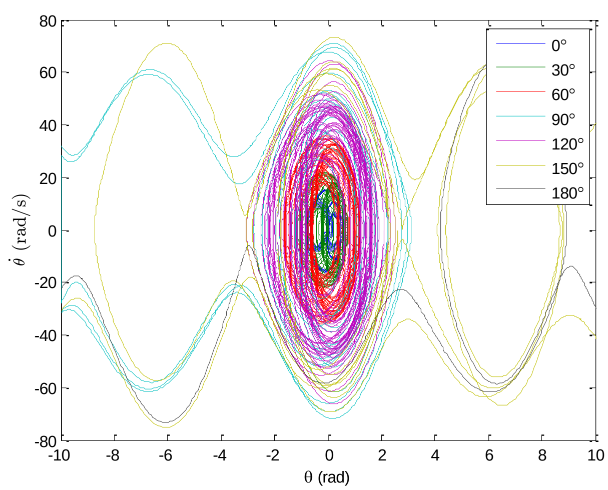


Fig. 9 Phase diagram for chest location (L=1 cm)

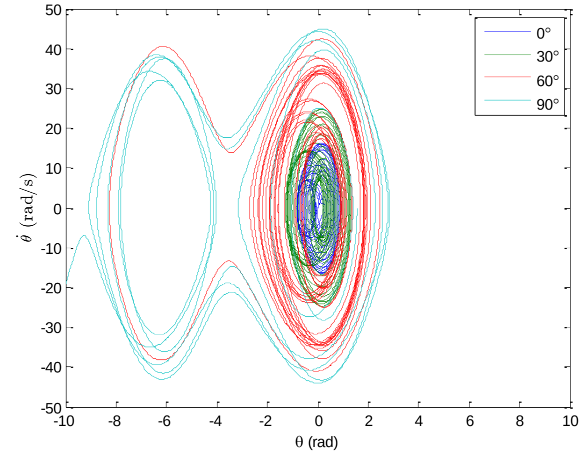


Fig. 10 Phase diagram for chest location (L=2.4 cm)

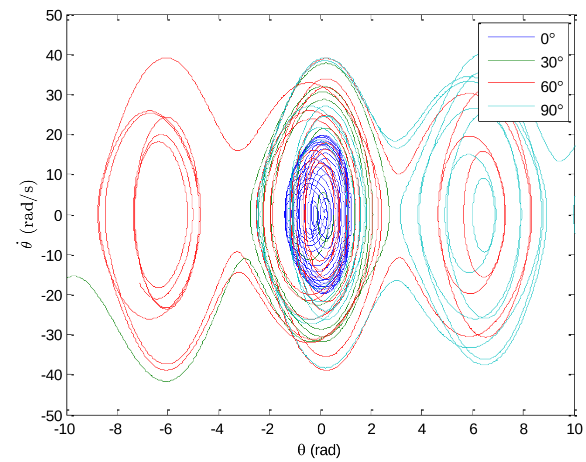


Fig. 11 Phase diagram for chest location (L=3.3 cm)

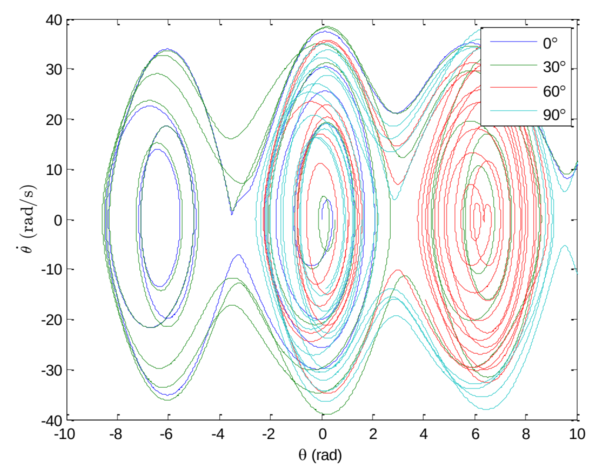


Fig. 12 Phase diagram for chest location (L=3.7 cm)

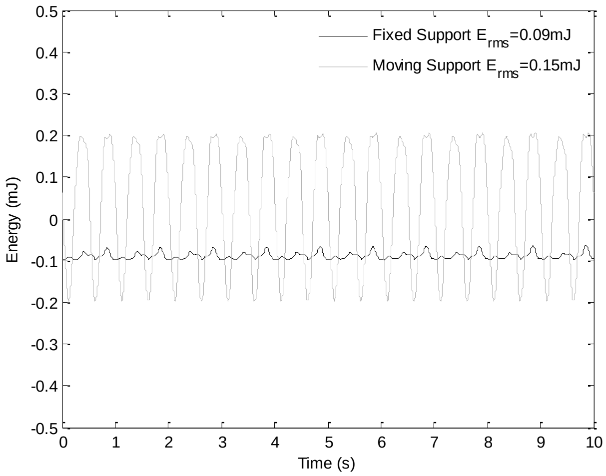


Fig. 13 Pendulum at chest (L = 1 cm, m = 1 g)

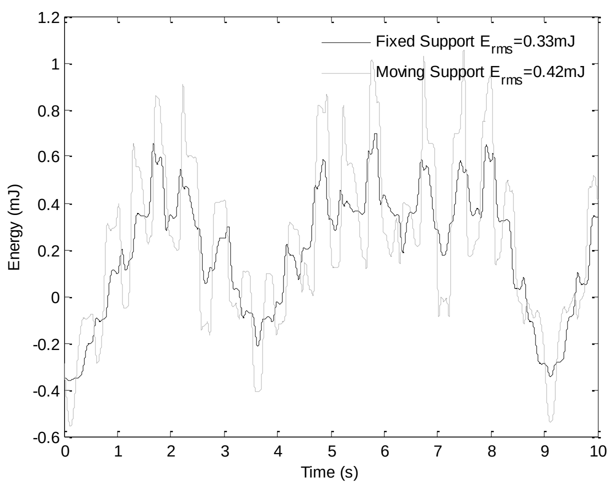


Fig. 14 Pendulum at chest (L = 3.7 cm, m = 1 g)

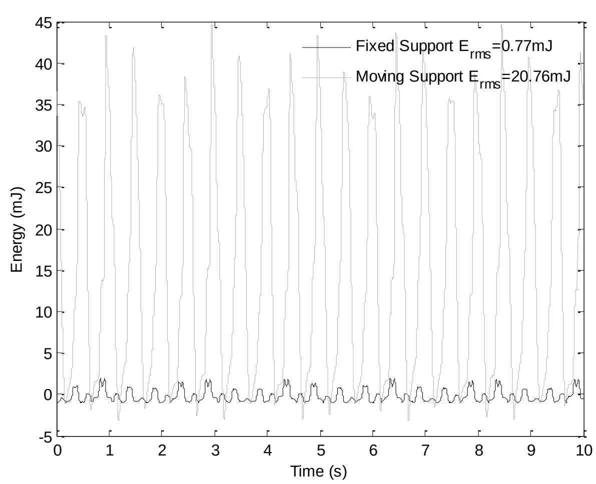


Fig. 15 Pendulum at shoulder (L = 1 cm, m = 10 g)

Energy increases with the possibility of multiple rotations, as shown in Fig. 14 for the chest location. However, the energy that can be extracted is the difference between the two presented in the figure, which is highly dependent on the initial conditions. It may be possible to design devices that optimize the dynamic performance in order to extract more energy from the external system.

At the same time energy output is directly proportional to the proof mass of the inertial generator. This is modeled in Fig. 15 in contrast with Fig. 8 for the same conditions. If only 10% of the available energy could be harvested effectively from a miniature generator, about 2 mJ of energy could be used at the shoulder location.

Further models need to be carried out on other locations such as elbow, hip, knee and ankle in order to understand the behavior given the motion of these joints during walking. Experimental test also need to be performed to compare against the computer simulations.

V. Conclusion

Literature shows that electronic self-winding mechanisms can generate up to 10 times more energy if self-induced rotations are present. This study examined the behavior of the self-induced rotations with human walking. The COM, chest and shoulder location were analyzed to evaluate this pattern. A model of the energy available was developed for a pendulum-based generator on a moving reference frame during walking. Preliminary results show that under regular walking conditions there is an optimal pendulum length for the start of the multiple rotations according to the phase diagrams. Computer models also suggest energy availability up to 10 times of what a pendulum-base device can generate under a fixed reference frame. This opens the possibility for oscillating rotational devices in addition to linear-based generators for energy generation.

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