

Article

Modeling and Analysis of the Power Conditioning Circuit for an Electromagnetic Human Walking-Induced Energy Harvester

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Abstract: Among the various alternative energy sources, harvesting energy from the movement of the human body has emerged as a promising technology. The interaction between the energy harvesting structure and the power conditioning circuit is nonlinear in nature, which makes selecting the appropriate design parameters a complex task. In this work, we present an electromagnetic energy harvesting system suitable for recovering energy from the movement of the lower limb joints during walking. The system under study is modeled and simulated, considering three different scenarios in which the energy source is the hip, knee, and ankle joint. The power generated by the energy harvester is estimated from kinematic data collected from an experimental gait study on a selected participant. State-space representation and Recurrence plots (RPs) are used to study the dynamical system's behavior resulting from the interaction between the electromagnetic structure and the power conditioning circuit. The maximum power obtained through the simulation considering a constant walking speed of 4.5 km/h lays in the range of 1.4 mW (ankle joint) to 90 mW (knee joint) without implementing a multiplier gear.

Keywords: energy harvesting; human walking; power conditioning circuit; electromagnetic induction; recurrence plot



Citation: Molina Arias, L.; Iwaniec, J.; Iwaniec, M. Modeling and Analysis of the Power Conditioning Circuit for an Electromagnetic Human Walking-Induced Energy Harvester. *Energies* **2021**, *14*, 3367. <https://doi.org/10.3390/en14123367>

Academic Editor: Luigi Costanzo

Received: 10 May 2021

Accepted: 7 June 2021

Published: 8 June 2021

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1. Introduction

In recent years, as a result of the wide usage of small-scale electronic devices, the requirement for portable and efficient energy sources has been increasing. The energy demanded by portable electronic devices is conventionally supplied by batteries. However, the energy stored in the batteries is limited, which leads to the need to recharge it after a limited period of operation or eventually replace it [1]. This fact entails an important limitation for portable electronic devices, mainly when the user performs fieldwork and cannot guarantee the supply of electrical energy. As a consequence of this situation, alternative methods for supplying portable electronic devices are explored. Energy harvesting from human body motion has become a promising technology for powering portable electronic devices [2]. Numerous investigations have estimated the energy associated with the motion of the joints of the human body during daily activities [3].

Among the daily activities performed by an average person, walking is one of the most engaging activities to recover energy. During walking, lower limb muscles perform positive and negative work to accelerate and decelerate the movements. These movements have been widely studied, and researchers know well the angular displacements, velocities, and accelerations of each joint during walking. Numerous walking-based energy harvesters have been designed, employing mainly electromagnetic, electrostatic, and piezoelectric transducers [4]. Donelan et al. [5] developed an energy harvester consisting of an orthopedic knee brace. The knee joint drives a gear train in the proposed device, transmitting

the knee extension movement at adequate speeds to a DC brushless motor. The motor serves as a generator producing an average of 5 watts of electricity. Liu et al. [6] proposed a rotational energy harvester consisting of a permanent magnet rotor and a set of coils embedded in a fixed housing. This device does not implement any complex transmission mechanism and produces a maximum output power of 10.4 mW at a driving frequency of 8 Hz and a load resistance of 100 Ω . Furthermore, Lin et al. [7] proposed a rotating energy harvester with a rotor made of neodymium iron and a stator consisting of permanent magnets. This energy harvester obtained a maximum measured output voltage of 1.92 V and a power density of 0.92 mW/cm³.

Conventionally, an energy harvesting system consists of three components: a harvester structure that usually generates an alternating current according to selected phenomena; a power conditioning circuit that rectifies and modulates the output voltage; and the electric load. The impedance characteristic of the power conditioning circuit influences the performance of the energy harvester structure [8]. However, the interaction between these components is not considered in most of the energy harvesting devices found in the literature [9]. Among the different power conditioning circuits, classical switching regulators have the advantage of not suffering low inherent efficiency as linear regulators do. The interaction between the energy harvesting structure and the power conditioning circuit is nonlinear in nature, which makes selecting the appropriate design parameters a complex task. To approach this issue, many studies have investigated the effect of the power conditioning circuit on the power generated by energy harvesting devices, assuming that the impedance of the electrical circuit has a constant value that depends on the circuit components and the PWM duty cycle [10,11]. Although the circuit equivalent resistance concept offers a simple approach for predicting the output power of the energy harvesting system, this approach ignores the nonlinearities that the power conditioning circuit adds to the system.

Understanding the interaction between the energy harvester structure and power conditioning is crucial for developing an energy harvesting system. However, up to now, little has been reported on modeling energy harvesting devices where nonlinearities associated with the power conditioning circuit are taken into account. Therefore, this paper aims to model and analyze the performance of an electromagnetic energy harvesting system suitable for harvesting energy while walking, in which the nonlinearities originated by the switching converter are considered. The numerical modeling of the power conditioning circuit is used to predict the harvested power. Within the model, the energy harvesting structure is attached to the human lower limb. The performance of the energy harvesting structure is evaluated and compared, considering the various joints of the lower limb. The location and configuration of the attached electromagnetic transducer are shown in Figure 1a. There is scattered information on the amount of energy collected from the hip, knee, and ankle joints obtained by different research groups using devices of different parameters in the literature. The novelty of the conducted experimental study consists of acquiring the kinematic data of the lower limb joints by conducting an experimental gait study and using the collected data to predict and analyze the system's dynamic response by implementing state-space averaging representation and applying recurrence plots (RPs) and RQA methods. Likewise, an analysis of the influence of the duty cycle and the load resistance was carried out in order to estimate the maximum energy captured by the system. In the research carried out, the application of the recurrence analysis seems to be natural due to the cyclic character of the analyzed system motion. Moreover, it provides the possibility of analyzing the system dynamic properties on the basis of measured time histories of system responses only.

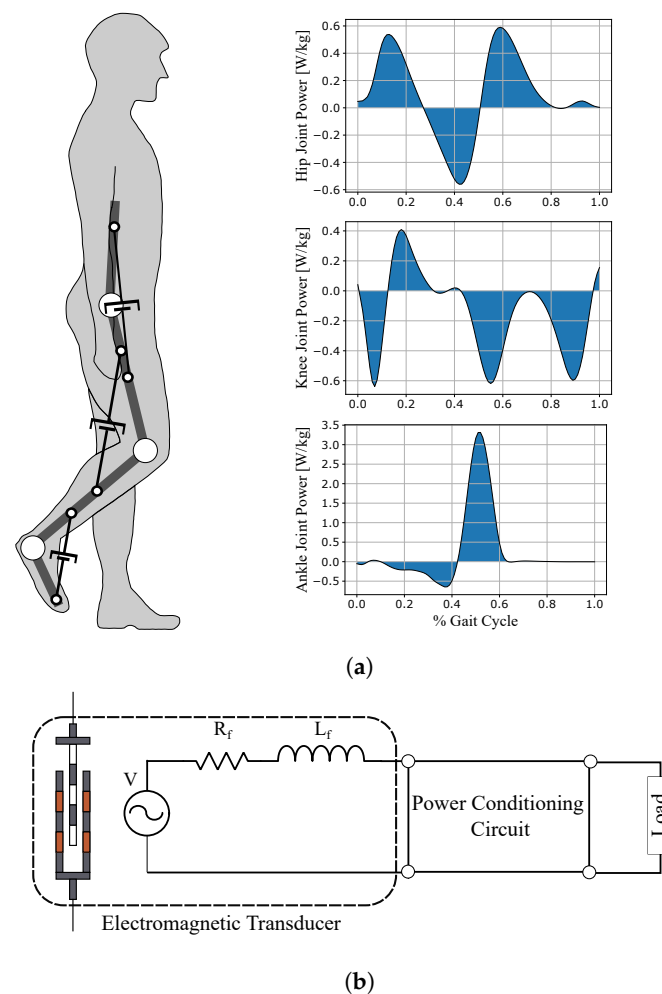


Figure 1. (a) Location of the electromagnetic transducer and estimated joints power throughout the gait cycle; (b) Scheme of the comprehensive system under study.

2. System Description and Modeling

The structure of the comprehensive system consisting of an electromagnetic energy harvester and the power conditioning circuit is shown in Figure 1b. For this application, the chosen electromagnetic transducer is a translational device of a tubular shape composed of permanent magnets that move inside a set of air coils. The kinetic energy associated with the angular motion of the lower limb joints is transformed into electrical energy because of the principle of electromagnetic induction.

The output voltage of the electromagnetic transducer is rectified, amplified, and smoothed before being supplied to the electrical load by the implementation of a power interface conditioning circuit. The role of the power conditioning circuit is to bring the output voltage to the desired level by adjusting the duty cycle of the switching converter. However, adding an extra impedance to the system influences the performance of the comprehensive system. Since the interaction between the energy harvesting structure and the power conditioning circuit has a nonlinear character, the system is modeled through the state-space averaging method.

2.1. Electromechanical Modeling

An electromagnetic harvester is basically an electromagnetic motor that, instead of producing a movement according to a supply voltage, generates electrical power from a given motion while providing a resistive force. The implemented electromagnetic transducer consists of a series of air coils localized inside the stator and a series of permanent magnets with a ring shape mounted on a moving shaft. Figure 2 depicts the structure of the energy harvester with its notation. This configuration can be found in regenerative braking

for automotive applications [12,13], vibration reduction for buildings [14], and energy extraction from ocean waves [15].

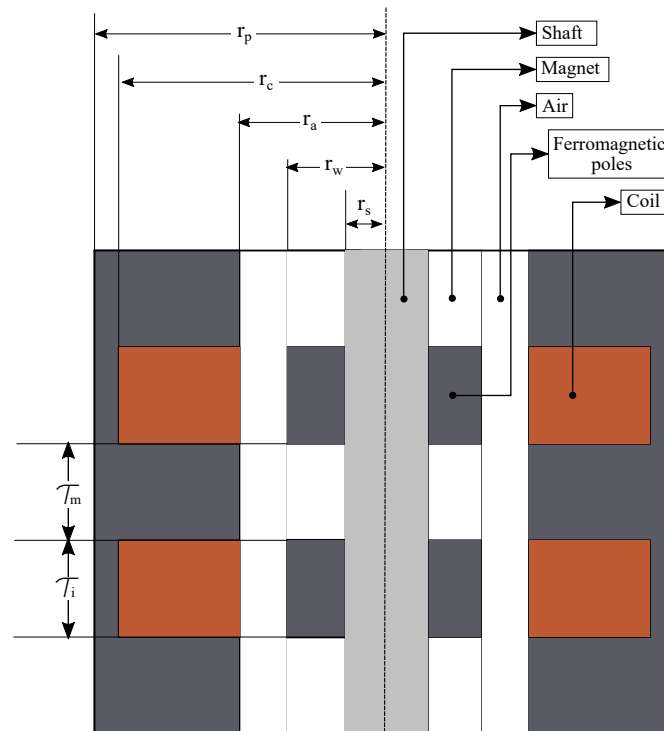


Figure 2. Notation used for the electromagnetic transducer.

The magnetic flux inside the linear transducer is produced by the permanent magnets located on the device shaft, according to the expression:

$$\phi = \int \vec{B} \cdot d\vec{A} \quad (1)$$

where $\vec{B}$ is the magnetic field vector and $\vec{A}$ is a vector area.

According to Faraday's Law, the voltage induced at the terminals of the generator coils is proportional to the rate at which the magnetic flux changes over time. If the magnetic flux is time dependent on the x -axis direction, the flux can be derived with respect to time, and the induced voltage is expressed by:

$$V = - \frac{\partial \phi}{\partial x} \frac{dx}{dt} \quad (2)$$

The open-circuit voltage induced in the generator coils is obtained by applying Faraday's law to a single coil and assuming that the magnetic flux has a sinusoidal shape:

$$V = -2\pi\phi \cos\left(\frac{\pi}{p}x\right) \frac{dx}{dt} \quad (3)$$

where the term p refers to the pole pitch of the translator.

The mathematical expression that accompanies the velocity in (3) is known as the EMF transducer constant, and it is expressed in volts seconds per meter (Vs/m) in SI units. We usually use the letter K_v to refer to this constant. Since the magnetic flux depends on the permanent magnet point operation, the magnitude of the expression for $K_v(x)$ depends finally on the geometric arrangement of the permanent magnets, the coils, and the magnetic properties of the materials that constitute the machine. An analytical expression for the

magnitude of the EMF linear machine constant can be found in [16] where the lumped equivalent magnetic circuit method. The amplitude of the EMF transducer constant is given by the expression:

$$K_v = -N \frac{2\pi(r_w^2 - r_s^2)B_r\tau_m}{\tau_m\tau_i + \mu_r\tau_i(r_w^2 - r_s^2) \left(1 - \frac{2r_s^2}{(r_w^2 - r_s^2)} \ln\left(\frac{r_w}{r_s}\right) + \frac{(\tau_i + \tau_m)}{\mu_0\mu_{Fe}(r_p^2 - r_c^2)} + \frac{2}{\mu_0\tau_i} \ln\left(\frac{r_c}{r_w}\right) \right)} \quad (4)$$

where N is the number of turn coils, B_r is the remanent magnetic field of the permanent magnets, μ_r is the recoil permeability, μ_0 is the permeability of free space, and μ_{Fe} is the relative permeability of the ferromagnetic material.

2.2. Power Conditioning Circuit Modeling

The power conditioning circuit is used to rectify the voltage induced at the terminals of the transducer coils and bring the load voltage to an appropriate level. The electronic circuit under study is depicted in Figure 3. It includes three subsystems: the electromagnetic device, the rectifier circuit, and the switching converter. The electromagnetic device is represented by an AC voltage source, the amplitude and frequency of which depend on the input movement of the translator. Additionally to the voltage source, an inductance coil and a resistor are connected in series representing the impedance of the transducer. The rectifier circuit consists of an arrangement of four diodes with neglected internal resistance and a capacitor for smoothing the signal. The last subsystem is a fixed duty cycle buck-boost converter, which increases or decreases the rectifier voltage according to the duty cycle of a switching element. The output voltage resulting from this configuration has an opposite polarity to the rectifier voltage.

A PWM signal is responsible for setting the switch stage, changing the operation of the circuit, and regulating the output voltage. When the switch is closed during the time interval dt_1 , the buck-boost converter constitutes the circuit presented in Figure 3a. In contrast, when the switch is open during the time interval dt_2 , the circuit assumes the form of Figure 3b. Each circuit may be described as a set of differential equations with four state variables: the inductor current, the rectifier voltage, the buck-boost inductor current, and the capacitor voltage.

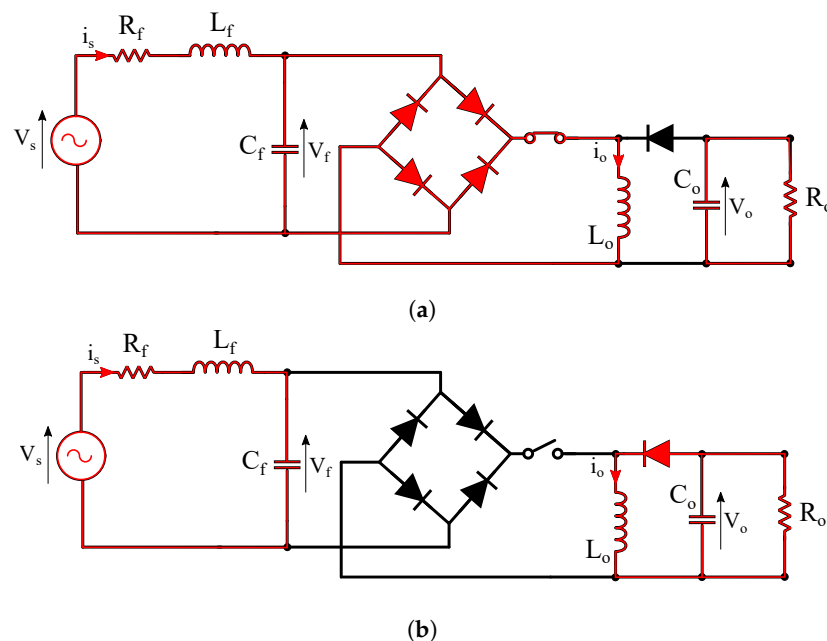


Figure 3. Power conditioning circuit (a) on state switch ON and (b) on state switch off.

By using the PWM duty cycle D and the switching frequency f_w , the time intervals of each stage are defined by the expressions [17]:

ON stage:

$$\Delta T_{ON} = D \frac{1}{f_w} \quad (5)$$

OFF stage:

$$\Delta T_{OFF} = (1 - D) \frac{1}{f_w} \quad (6)$$

Applying Kirchhoff laws, the dynamic behavior of the electronic circuit when the switch is on is described by the following state-space equations:

$$\begin{aligned} \frac{di_s(t)}{dt} &= -\frac{R_f}{L_f} i_s(t) - \frac{1}{L_f} V_f(t) + \frac{1}{L_f} V_s(t) \\ \frac{dV_f(t)}{dt} &= \frac{1}{C_f} i_s(t) - \frac{\text{sign}(V_f(t))}{C_f} i_o(t) \\ \frac{di_o(t)}{dt} &= \frac{\text{sign}(V_f(t))}{L_o} V_f(t) \\ \frac{dV_o(t)}{dt} &= -\frac{1}{R_o C_o} V_o(t) \end{aligned} \quad (7)$$

Otherwise, when the switch is off, the dynamic behavior is given by the following state-space equations:

$$\begin{aligned} \frac{di_s(t)}{dt} &= -\frac{R_f}{L_f} i_s(t) - \frac{1}{L_f} V_f(t) + \frac{1}{L_f} V_s(t) \\ \frac{dV_f(t)}{dt} &= \frac{1}{C_f} i_s(t) \\ \frac{di_o(t)}{dt} &= \frac{\lambda}{L_o} V_o(t) \\ \frac{dV_o(t)}{dt} &= -\frac{1}{R_o C_o} V_o(t) - \lambda \frac{1}{C_o} i_o(t) \end{aligned} \quad (8)$$

where the term λ is a binary term which value depends on the state of the diode, according to the expression:

$$\lambda = \begin{cases} 1 : i_o \geq 0 \\ 0 : i_o < 0 \end{cases} \quad (9)$$

Finally, assuming that the switching frequency is sufficiently high, we can apply the state-space averaging method. The idea behind this approach is that the global effect of one period can be obtained by weighted summing the contribution of each of the stages of the switching converter [18]. This method describes the circuit's low-frequency behavior (with average currents and voltages) [19]. Multiplying (7) times the duty cycle D and (8) times the expression $(1 - D)$, we obtain the average state-space representation of the proposed power conditioning circuit:

$$\frac{d}{dt} \begin{bmatrix} i_s \\ V_f \\ i_o \\ V_o \end{bmatrix} = \begin{pmatrix} -\frac{R_f}{L_f} & -\frac{1}{L_f} & 0 & 0 \\ \frac{1}{C_f} & 0 & -\frac{D \text{sign}(V_f)}{C_f} & 0 \\ 0 & \frac{D \text{sign}(V_f)}{L_o} & 0 & \frac{\lambda(1-D)}{L_o} \\ 0 & 0 & -\frac{\lambda(1-D)}{C_o} & -\frac{1}{R_o C_o} \end{pmatrix} \begin{bmatrix} i_s \\ V_f \\ i_o \\ V_o \end{bmatrix} + \begin{pmatrix} \frac{1}{L_f} \\ 0 \\ 0 \\ 0 \end{pmatrix} V \quad (10)$$

In the case of a standard buck-boost converter in continuous current mode, the output voltage varies according to the PWM duty cycle following the expression below:

$$V_{output} = \frac{-D}{(1-D)} V_{input} \quad (11)$$

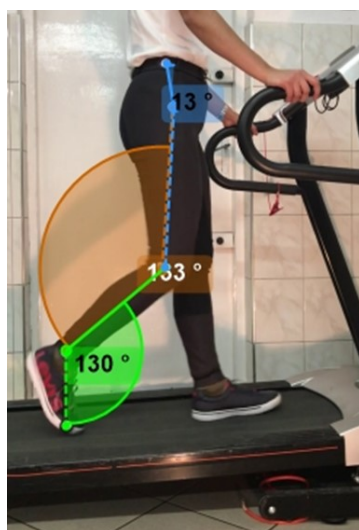
In the implemented circuit, this expression still works. However, the input voltage to the converter is the voltage output of the bridge rectifier, and the PWM duty cycle influences

its value. The influence of the PWM duty cycle on the voltage rectifier makes the model complex, which makes the relation between the generated voltage by the electromagnetic transducer and the load voltage does not have a linear expression as in the case of a standard buck-boost converter.

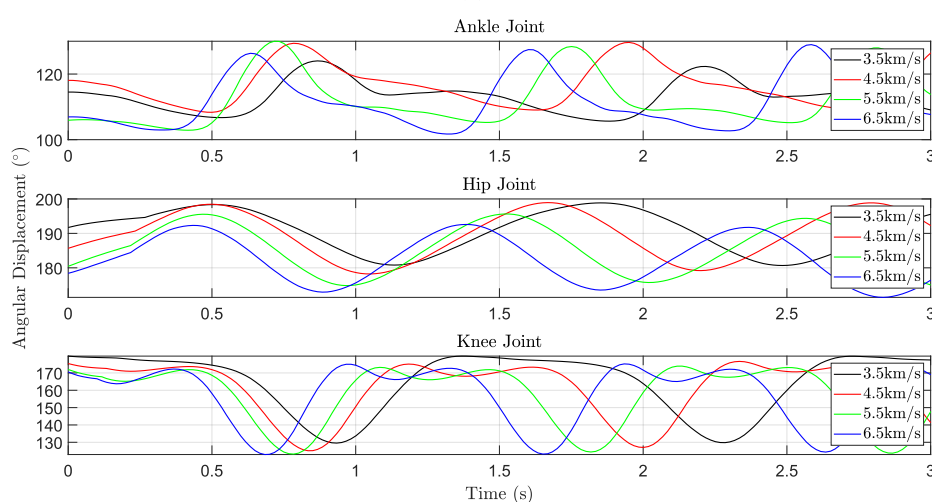
3. Data Collecting and Methods

3.1. Gait Parameter Measurement

A human walking experiment was conducted to obtain the hip, knee, and ankle joint rotational movements used as an input to the modeled energy harvesting system. One young, healthy female subject participated in this study. Four markers were mounted on the participant to signalize the position of the lower limb joints on the sagittal plane. The participant was asked to walk on a treadmill at different speeds ranging from 3.5 km/h to 6.5 km/h. The motion of the participant was recorded with a simple camera with 60 fps. We tracked the motion of the markers in the recorded video using Kinovea software, which is a tool that allows motion tracking by analyzing the frames that composed the video [20]. Finally, the data were smoothed using a moving average filter. The obtained data correspond to the angular displacement of each joint. The convention used for measuring the angles is shown in Figure 4a.



(a)



(b)

Figure 4. (a) Experimental gait study; (b) Lower limb joint angular displacement at different walking speeds.

To characterize the input of the modeled energy harvesting system, we calculated the angular velocity by using a simple linear approximation. Furthermore, we smoothed the calculated data. With the use of the processed data, the transducer motion and the induced coil voltage were calculated.

3.2. Kinematic of the Energy Harvester

The rotational movement of the joints is transmitted to the electromagnetic transducer by directly attaching the device to the links that make up the joint, as shown in Figure 5.

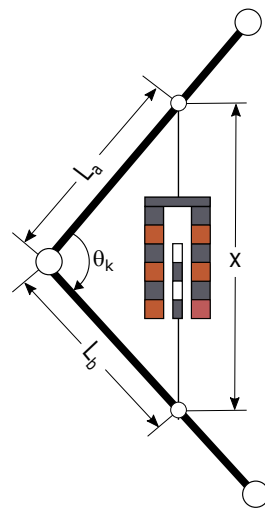


Figure 5. Kinematic scheme of the electromagnetic transducer.

The stator and translator relative displacements are calculated by relating the joint angular displacement and the distance from the joint to the point of connection with the transducer and using the cosine law:

$$x = \sqrt{L_a^2 + L_b^2 - 2L_aL_b \cos \theta_k} \quad (12)$$

Taking the derivative of (12), we find an expression to correlate the linear velocity of the translator with the angular velocity:

$$\dot{x} = \dot{\theta}_k \frac{2L_aL_b \sin \theta_k}{\sqrt{L_a^2 + L_b^2 - 2L_aL_b \cos \theta_k}} \quad (13)$$

where $\dot{\theta}_k$ is the angular velocity of the studied lower limb joint.

3.3. Recurrence Plot (RP) and Recurrence Quantification Analysis (RQA)

Recurrent behavior is typical for a variety of technical but also natural systems. Recurrences, understood as returning to the previously observed states, are observed in linear as well as nonlinear dynamical systems. The concept of recurrence goes back to 1890 when Henri Poincaré's pioneering work [21] was published. A century later, based on the results of Poincaré's research, a powerful method for visualization and analysis of recurrent properties was proposed [22]. The main idea of the method, known as the Recurrence Plot (RP) method, involves revealing instances when the system phase space trajectory visits roughly the same area in the phase space. In the literature, under the term of recurrence plot, a graphical representation of the two-dimensional recurrence matrix is known [23]. The elements of the recurrence matrix R are given by the expression:

$$R(i, j) = \Theta(\varepsilon - \|x_i - x_j\|) \quad (14)$$

where N denotes the number of considered states x_i , ε is the threshold distance, and Θ is the Heaviside function

Recurrence plot can also be understood as a graphical representation of the matrix R , in which ones are denoted by black dots and zeros by white points. Therefore, the matrix R can be expressed by:

$$R(i, j) = \begin{cases} 1 : x_i \approx x_j \\ 0 : x_i \neq x_j \end{cases} \quad (15)$$

where x_i and y_i are the points belonging to the neighborhood of radius ε , which are marked by black points on the RP.

Correctness of the estimated recurrence plot depends heavily on the proper selection of the values of threshold ε , the time delay τ , and the embedding dimension m . For the purposes of determining the reasonable value of time delay τ , the auto-correlation or mutual information function [23,24] can be used. The advantage of the mutual information function (MI) application consists of taking into account also nonlinear correlations.

In practice, the value of τ corresponding to the first minimum of the mutual information function is used. A sufficient embedding dimension m is usually established with the application of the false nearest neighbors method [25].

In order to provide the objective interpretation of the computed RPs, the Recurrence Quantification Analysis (RQA) [26,27] method is commonly used. The RQA measures aim at quantifying the number and duration of recurrences of a dynamical system represented by its state space trajectory. Definitions of the most popular RQA measures are discussed in detail in [23,26,27].

3.4. Simulation Setup

The electronic components that make up the power conditioning circuit are selected to ensure the good behavior of the output signal, which means to get a semi-stable signal with a short stabilization time. The induced voltage depends on the geometry and magnetic properties of the materials that constitute the electromagnetic transducer.

The analysis of the proposed energy harvester and power conditioning circuit system is carried out through dynamical simulation. The EMF transducer constant was calculated according to the geometric and magnetic parameters presented in Table 1.

Table 1. Dimensions and magnetic properties of the electromagnetic transducer.

Symbol	Value	Description
τ_m	10 mm	Magnet Height
r_s	3 mm	Shaft Radius
$r_w - r_s$	8 mm	Magnet Width
$r_a - r_w$	1.5 mm	Air Gap between stator and slider
τ_i	10 mm	Tooth Height
$r_c - r_a$	9.5 mm	Coil Width
$r_p - r_c$	3 mm	Stator Shell Thickness
d_z	0.4 mm	Wire Diameter Width
B_{rem}	1.23 T	Remanent Magnetic Flux Density
N	593	Turns Coils Width
nC	5	Number of Coils

The parameters corresponding to the power conditioning circuit are presented in Table 2. To define the value of the internal inductance and resistance of the transducer, we used the analytical expression found in [28].

Table 2. Parameter values of the power conditioning circuit and electromagnetic transducer.

Symbol	Value	Description
R_f	42.7 Ω	Transducer resistance
L_f	286 mH	Transducer inductance
C_f	0.8 mF	Rectifier capacitance
L_o	50 mH	Converter inductance
C_o	8.5 mF	Converter capacitance
R_o	750 Ω	Load resistance

The lengths (L_a , L_b) used for the calculation of the transducer motion, shown in Figure 5, were assumed to have a value of 0.2 m. For the simulation, as the input to the system, lower limb joint motion data collected at a speed of 4.5 km/h were used. The time response of the state-space averaging model under a fixed PWM duty cycle and the input voltage generated by the electromagnetic transducer were calculated using a code written in Matlab, where the Euler Method was employed.

Additionally, a sensitivity analysis consisting of running several simulations varying the PWM duty cycle and load resistance was performed. The obtained data were used for the purposes of plotting and localizing the maximum RMS power for each lower limb joint. Time histories of the considered state-space variable responses calculated for the ankle, knee, and hip joints while walking at constant speed were analyzed with the application of the RP method. Interpretation of the patterns visible on the obtained RPs was supported by the estimation of the RQA measures. Phase space of the considered system was reconstructed by delay embedding. For the purposes of consistency, in all computations, the threshold value $\varepsilon = 0.1$ and the *FAN* criterion were assumed. The smallest sufficient embedding dimension m was estimated with the application of the false nearest neighbors method. The time delay τ was defined by searching for the first minimum of the mutual information function.

4. Results and Discussion

In the course of the carried out research, the linear motion of the transducer, the generated voltage, the state-space variables associated with the power conditioning circuit, and the power consumed by the electrical load for each joint were calculated. Since the angular velocity and the frequency content influence the generated electric power, the analysis results carried out for each joint are presented separately.

4.1. Hip Joint

Figure 6a shows the resulting motion of the electromagnetic transducer attached to the hip joint. The linear displacement covers a reduced range of no more than 6 mm, and the maximum speed encountered is around 0.016 m/s. The induced coil voltage was computed according to (3) and (4) for the previously determined transducer motion. The time history of the induced coil voltage is presented in Figure 6b.

The RMS power for different duty cycle values and load resistance was determined using the induced coil voltage as input to the state-space averaging model of the system under study. Figure 7 illustrates the changes in the RMS voltage with respect to different PWM duty cycle and load resistance values. The maximum power was encountered at a duty cycle of 0.5 and load resistance of 1200 Ω .

For further investigation, a PWM duty cycle of 0.8 and a load resistance of 750 Ω were selected. These parameters were chosen to ensure a proper output voltage with minimum variation and a short stabilization time. The time response of the state-space averaging model derived from the analyzed power conditioning circuit is presented in Figure 8, and the output power is presented in Figure 9. The stabilization time of the system is close to 20 s, and the generated power estimated is about 1.4 mW.

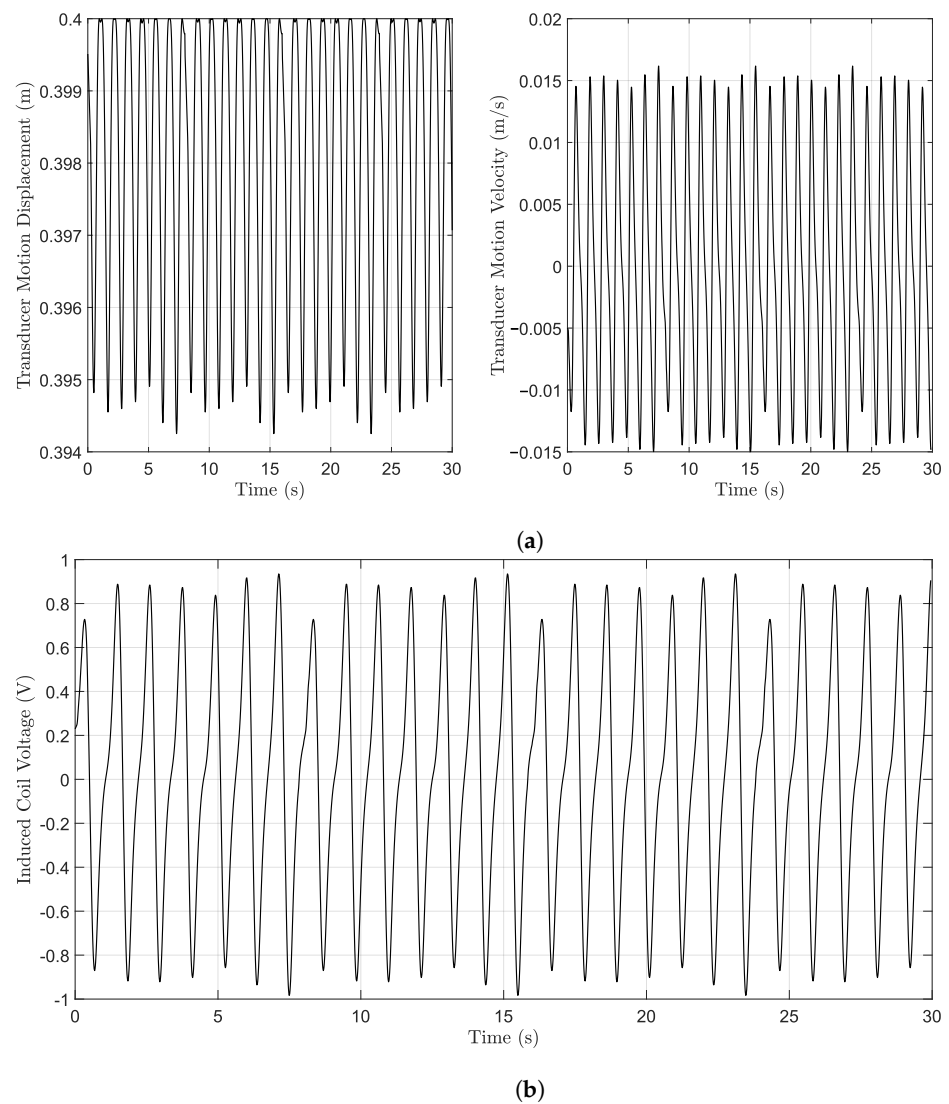


Figure 6. (a) Linear motion; and (b) Induced coil voltage of the hip-mounted electromagnetic transducer at a walking speed of 4.5 km/h.

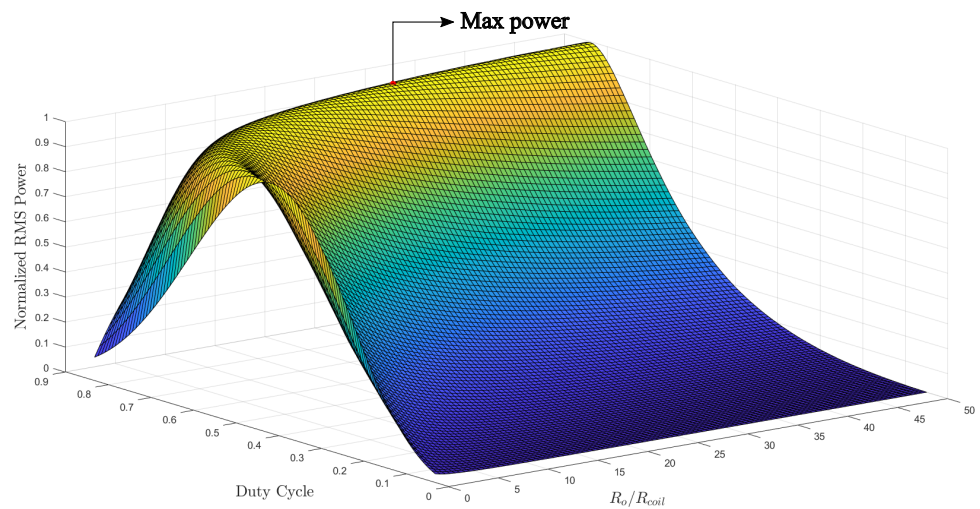


Figure 7. RMS output power of the hip-mounted energy harvesting system with respect to the duty cycle and load resistance.

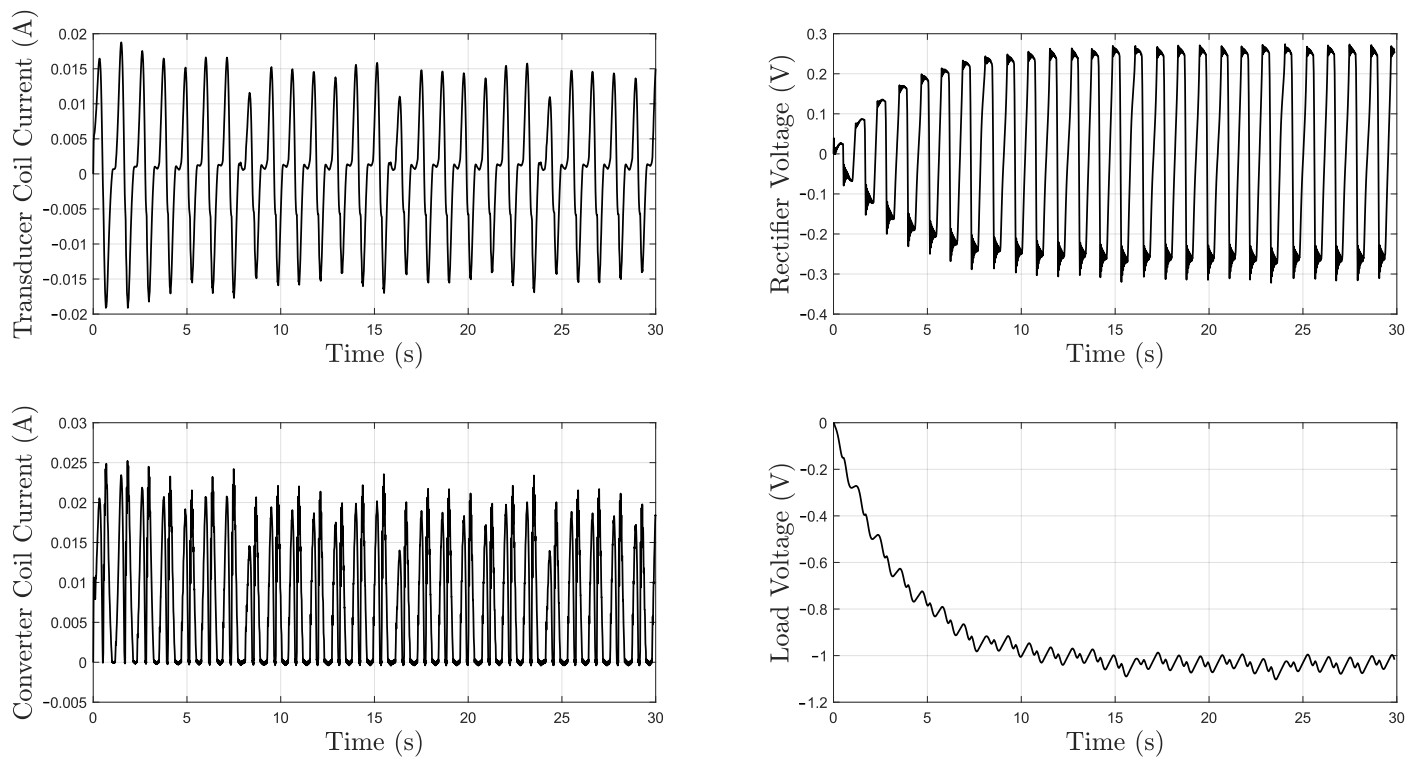


Figure 8. Time response of the state-space variables of the hip-mounted energy harvesting system.

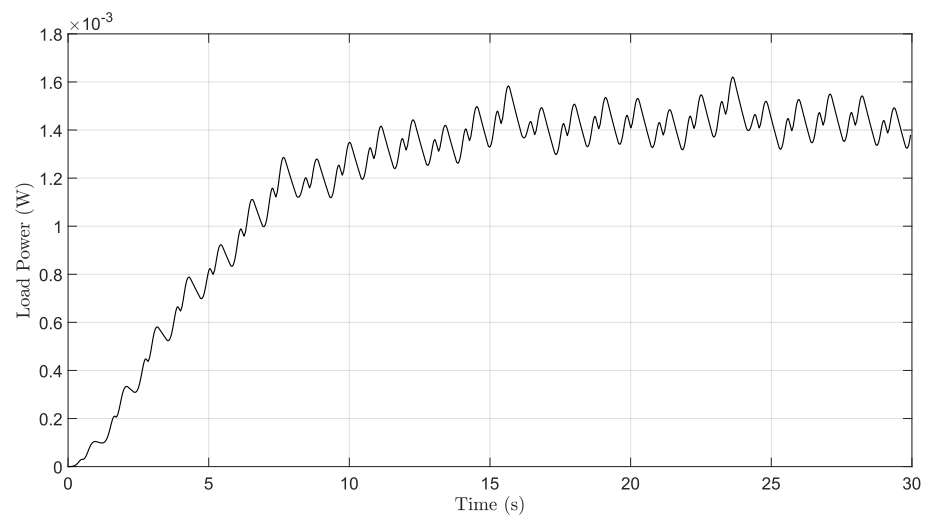


Figure 9. Estimated load power of the hip-mounted energy harvesting system when walking at a speed of 4.5 km/h.

Recurrence plots of the considered physical quantities measured and calculated for the hip joint are presented in Figure 10. The RPs were estimated for 3500 samples measured in the steady-state.

Long diagonal lines with visible disturbances on the estimated RPs indicate a regular or “almost” regular dynamic behavior of the considered system.

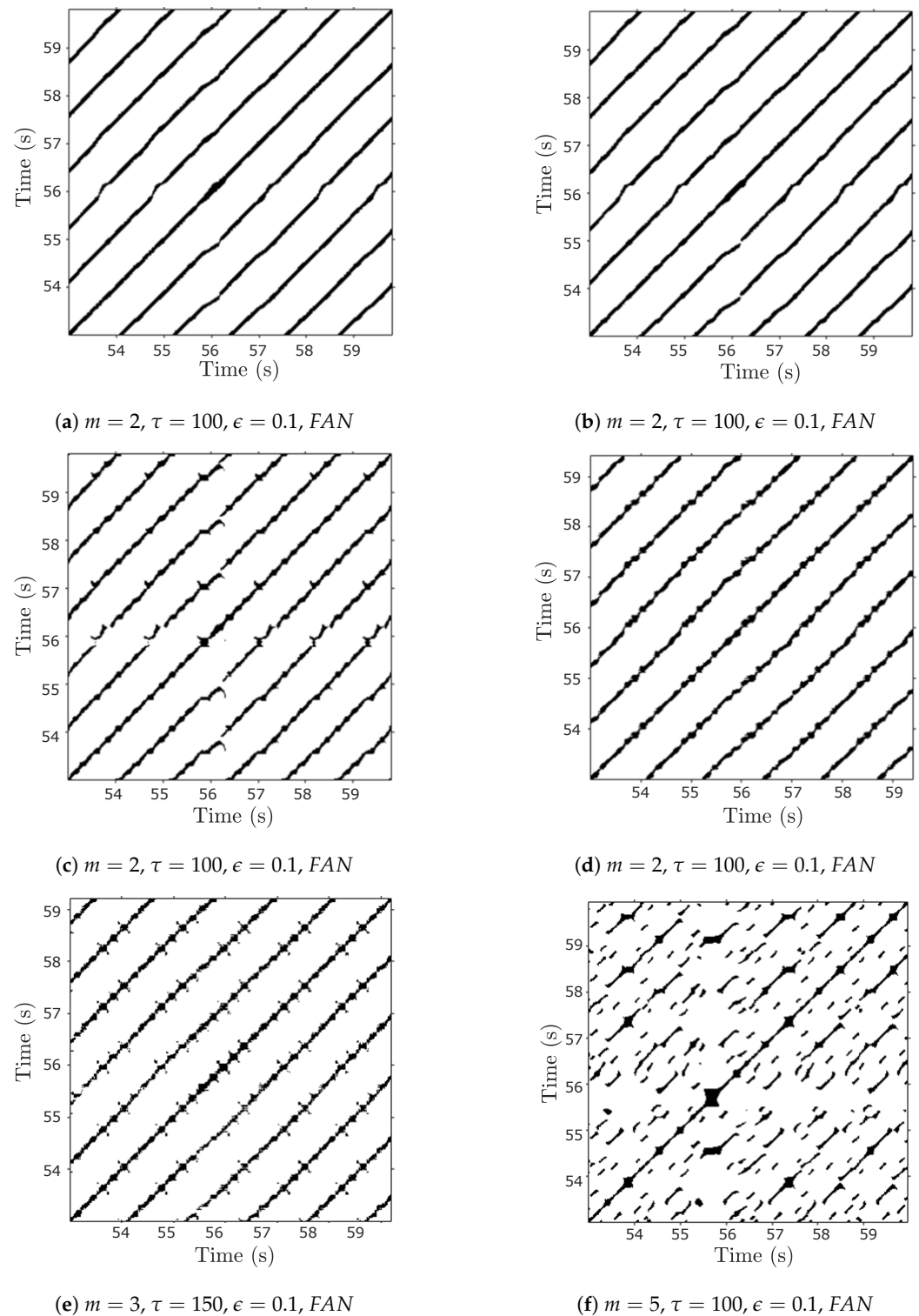


Figure 10. Recurrence plots obtained from the hip-mounted energy harvesting system quantities. (a) rotational velocity; (b) induced coil voltage; (c) transducer coil current; (d) rectifier voltage; (e) converter coil current; (f) load voltage.

4.2. Knee Joint

The knee is the joint that dissipates the most energy throughout the gait cycle, so an energy harvester based on knee movement would assist the knee muscles while generating electrical energy. Additionally, the movement of this joint is characterized by greater

values of angular velocity compared to the other joints. The motion of the electromagnetic transducer attached to the knee joint is shown in Figure 11a. The maximum velocity reached by the transducer is about 0.3 m/s, and the range of motion goes from 0.36 mm to 0.4 mm. Figure 11b shows the induced coil voltage. As expected, the voltage generated by this joint is the highest of all joints, reaching a maximum value of 20 V.

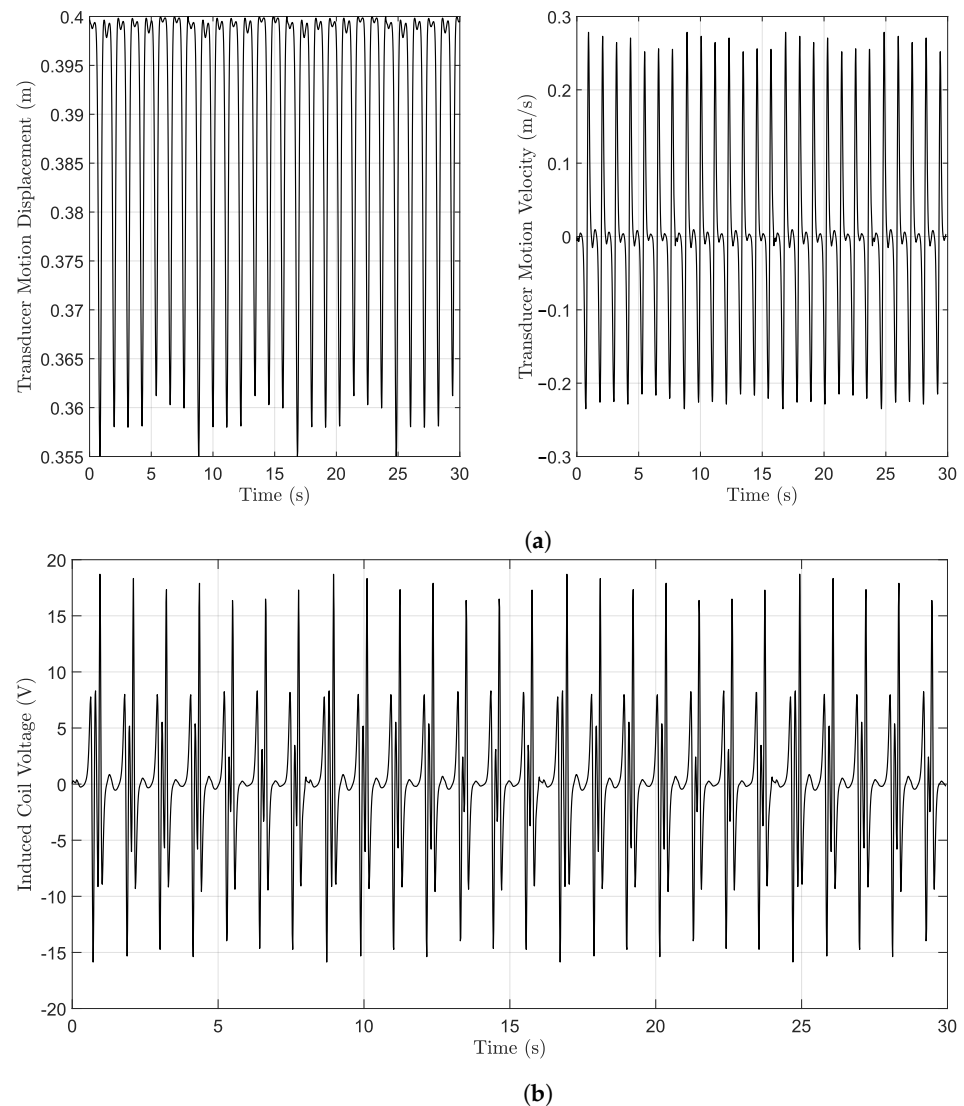


Figure 11. (a) Linear motion; and (b) Induced coil voltage of the knee-mounted electromagnetic transducer at a walking speed of 4.5 km/h.

Figure 12 illustrates the changes in the RMS voltage with respect to different PWM duty cycles and load resistance values and shows the point of maximum power. It was observed that the system's best performance occurs when the PWM duty cycle is close to 0.5, and the load resistance has a value of 120 Ω .

The dynamical system response computed using the state-space averaging model of the power conditioning circuit is presented in Figure 13. The selected PWM duty cycle and load resistance were 0.5 and 30 Ω , respectively. The obtained output power is presented in Figure 14. The stabilization time of the system is close to 20 s, and the generated power estimated is about 90 mW.

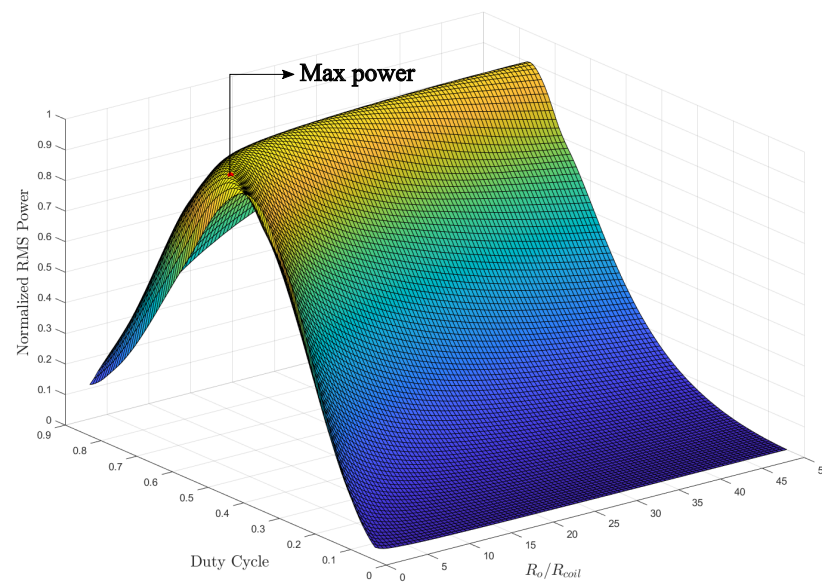


Figure 12. RMS output power of the knee-mounted energy harvesting system with respect to the duty cycle and load resistance.

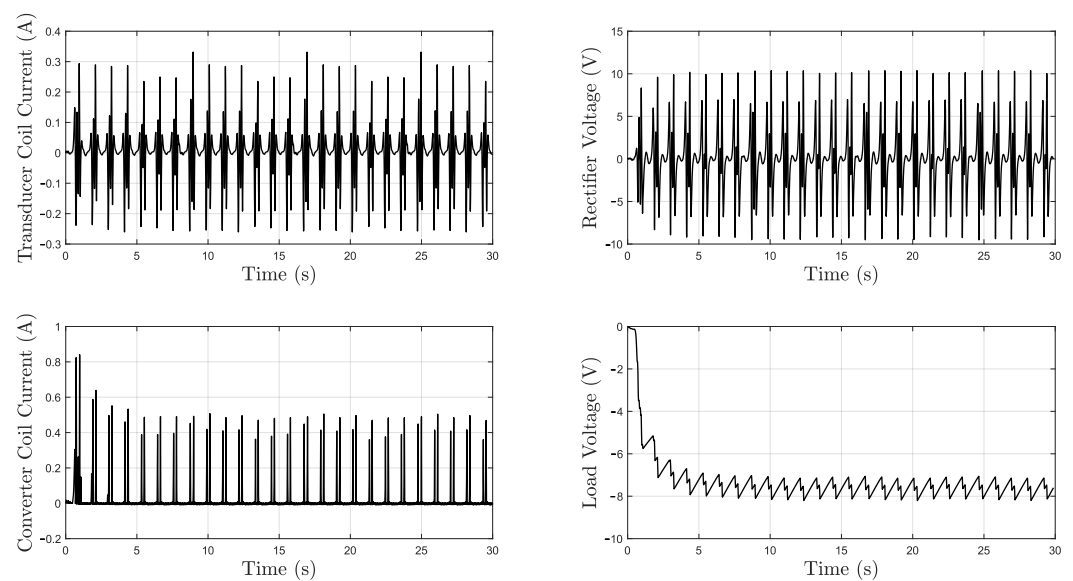


Figure 13. Time response of the state-space variables of the knee-mounted energy harvesting system.

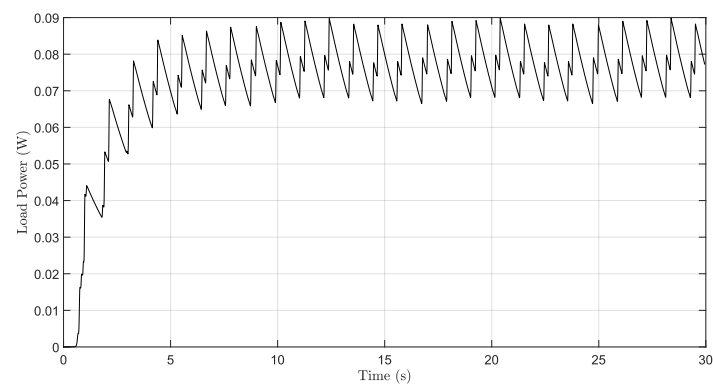


Figure 14. Estimated load power of the knee-mounted energy harvesting system when walking at a speed of 4.5 km/h.

Figure 15 shows the time histories of the considered physical quantities measured and calculated on the knee joint and the corresponding recurrence plots estimated for 3500 samples.

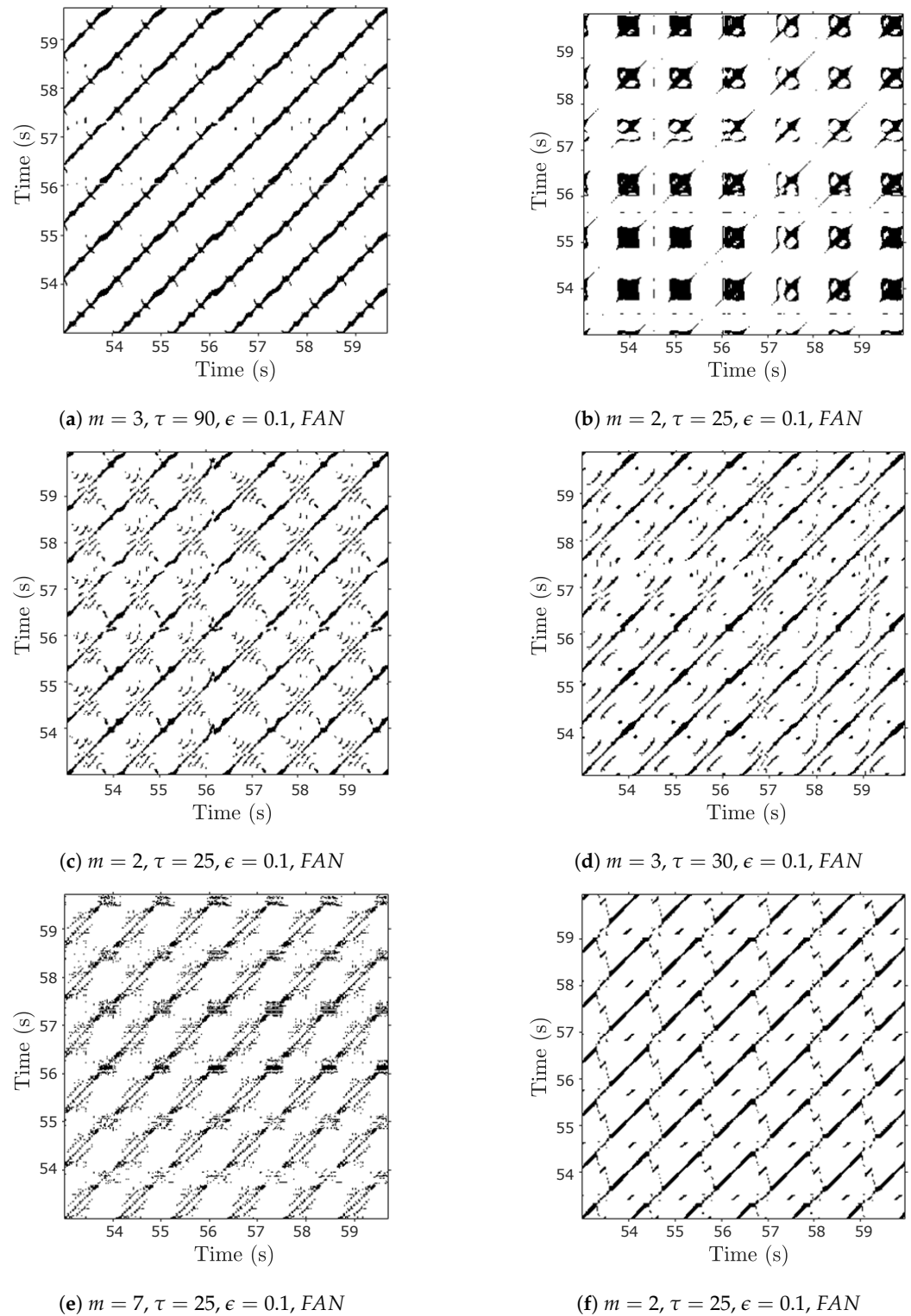


Figure 15. Recurrence plots obtained from the knee-mounted energy harvesting system quantities. (a) rotational velocity; (b) induced coil voltage; (c) transducer coil current; (d) rectifier voltage; (e) converter coil current; (f) load voltage.

On the obtained RPs, the diagonally oriented, periodic recurrent structures are visible. Long diagonal lines and checkerboard structures are characteristic of oscillating systems [29].

4.3. Ankle Joint

Figure 16a depicts the motion of the electromagnetic transducer driven by the ankle joint. The maximum velocity reached by the transducer is close to 0.25 m/s. The induced coil voltage of the transducer is shown in Figure 16b. The generated voltage contains peaks of power of around 15 V.

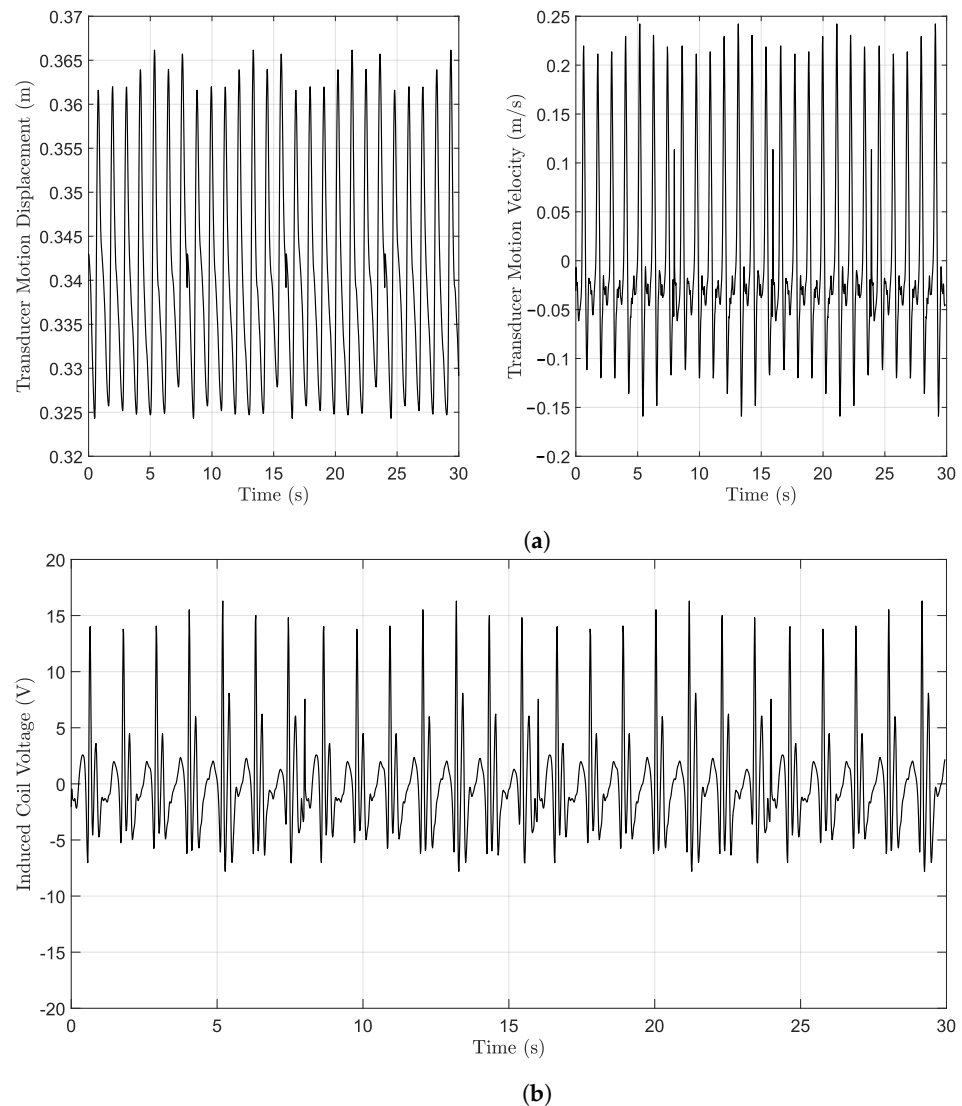


Figure 16. (a) Linear motion; and (b) Induced coil voltage of the hip-mounted electromagnetic transducer at a walking speed of 4.5 km/h.

Figure 17 shows the RMS load voltage of the implemented energy harvesting system considering different PWM duty cycles and values of load resistance. The point of maximum RMS power is found when the PWM duty cycle is close to 0.5, and the load resistance is about 34Ω .

The PWM duty cycle and load resistance selected were 0.5 and 750Ω , respectively. The time response of the state-space variables representing the modeled system is shown in Figure 18. Figure 19 shows the generated power. The load power finally has an average value of 0.045 W, and the stabilization time amounts to 12 s.

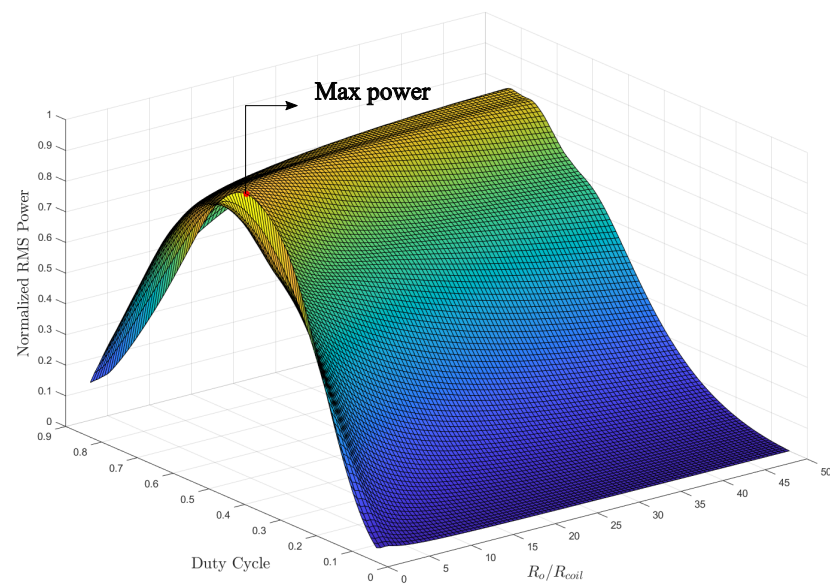


Figure 17. RMS output power of the ankle-mounted energy harvesting system with respect to the duty cycle and load resistance.

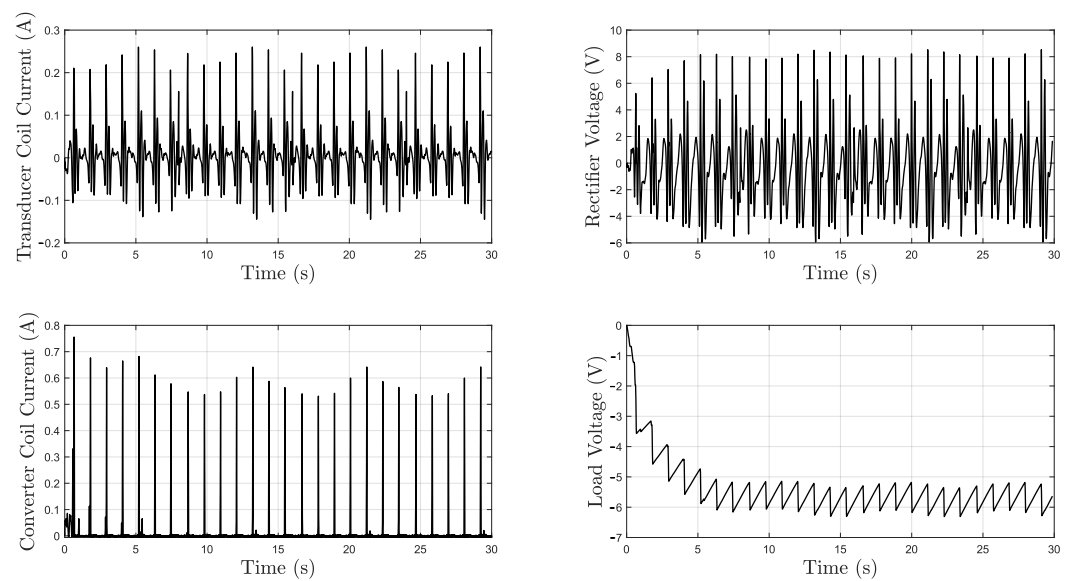


Figure 18. Time response of the state-space variables of the ankle-mounted energy harvesting system.

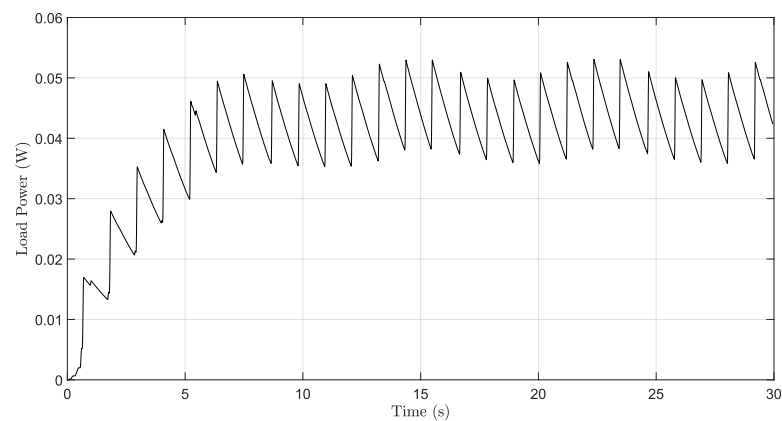


Figure 19. Load power of the energy harvesting system mounted on the ankle joint.

Recurrence plots estimated for the time histories of the considered physical quantities measured and calculated for the electromagnetic harvester attached to the ankle are depicted in Figure 20. As in the case of the other measurement points, the analysis was carried out for 3500 samples in the steady-state.

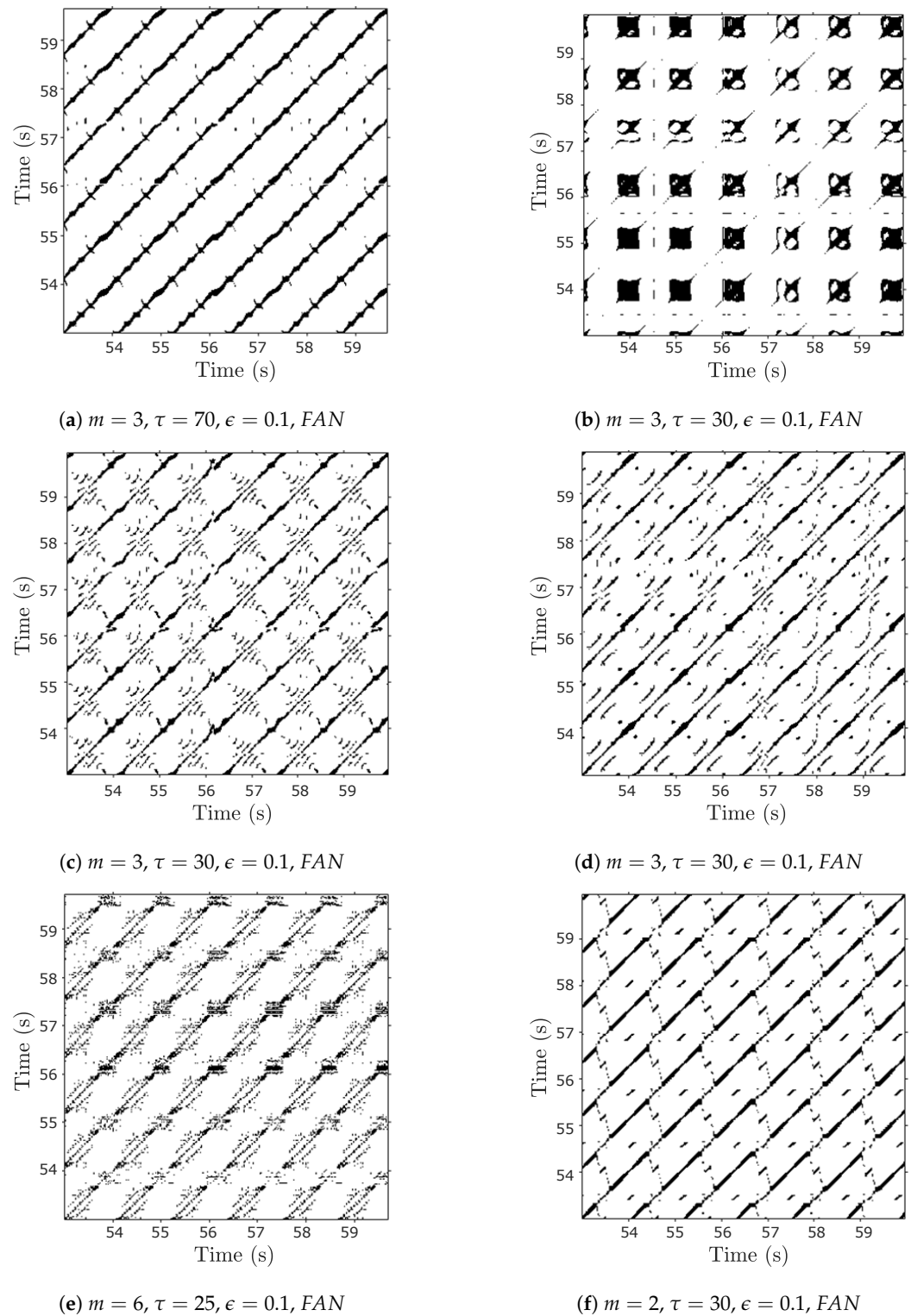


Figure 20. Recurrence plots obtained from the ankle-mounted energy harvesting system quantities; (a) rotational velocity; (b) induced coil voltage; (c) transducer coil current; (d) rectifier voltage; (e) converter coil current; (f) load voltage.

The estimated power delivered from the hip, knee, and ankle joints to the electrical load connected to the power conditioning circuit is characterized by oscillations, which were not smoothed by the circuit. However, the amplitude of the oscillations is small enough to consider the behavior of the power time history to be constant when the system reaches a steady-state.

The efficiency of the energy harvesting system is calculated by relating the load power, which is the power delivered from the energy harvester system and the power lost in the internal resistance of the transducer coils:

$$\eta = \frac{P_{load}}{P_{lost} + P_{load}} \quad (16)$$

where P_{lost} is the power dissipated in the transducer internal resistance and P_{load} is the power load.

The estimated average efficiency of the device was 0.3. However, the energy dissipated due to the friction between the parts of the electromagnetic transducer, the internal resistance of the power conditioning circuit elements, and the power lost in the wires were not considered. The most common location for electromagnetic energy harvesters is the knee joint since its movement exhibits the highest velocities compared to the other lower limb joints. Most of the methods used are based on designing and mounting the device in the human body, contrary to the approach followed in this research. Table 3 presents a comparison of different technologies encountered in the literature:

Table 3. Comparison of electromagnetic technology used for harvesting energy from the human movement.

Output Power	Location	Methods	Input	Ref.
10.4 mW	Knee joint	Measurement and simulation	8 Hz	[6]
0.2 mW/cm ³	Ankle joint	Measurement	8 km/h	[7]
1.6 mW	Shoes	Measurement		[30]
416.6 µW	Ankle joint	Measurement and simulation		[31]
0.42 mW	Leg	Measurement and simulation		[32]
0.84 mW	Hand	Measurement and simulation	5 Hz	[33]
2.46 mW	Back	Measurement and Simulation		[34]
1.4 mW	Hip joint	Simulation	4.5 km/h	
90 mW	Knee joint	Simulation	4.5 km/h	
45 mW	Ankle joint	Simulation	4.5 km/h	

It is difficult to compare the achievements of different researchers presented in the literature since they concern different locations of energy harvesting and devices of different structural parameters and operational conditions.

4.4. RQA Measures

Estimated RPs provide valuable insights into the dynamics of the considered systems. However, in various practical applications, the interpretation of the patterns and structures presented within the recurrence plot can be difficult and, moreover, depend on the researcher's intuition and experience. In order to overcome the subjectivity of interpretation, in the 1990s, Zbilut and Webber formulated five complexity measures based on diagonal structures in RPs called recurrence quantification analysis (RQA) [27]. Since not only diagonal but also vertical and horizontal elements are present in the RPs, additional measures have been proposed by Marwan et al. [35]. Contrary to the five “classical” RQA measures, the new measures are able to detect, e.g., chaos–chaos transitions [36] and chaos–order transitions [29]. In this paper, based on the computed recurrence plots, the “classical” RQA analysis (proposed by Zbilut and Webber) was carried out. Obtained results are

gathered in Table 4. Computations were performed with the application of CRP Toolbox for MATLAB [37].

Table 4. Results of the carried out recurrence quantification analysis.

	<i>RR</i>	<i>DET</i>	<i>L</i>	<i>L_{max}</i>	<i>ENTR</i>
Hip Joint					
Rotational Joint Velocity (<i>RV</i>)	0.0997	0.9999	318.8056	3400	6.2370
Transducer Induced Voltage (<i>TIV</i>)	0.0997	0.9999	251.3183	3400	6.0501
Transducer Inductance Current (<i>SV₁</i>)	0.0997	0.9998	71.1061	3400	4.9530
Rectifier Voltage (<i>SV₂</i>)	0.0997	0.9997	66.2809	3200	4.8355
Converter Inductance Current (<i>SV₃</i>)	0.0997	0.9991	27.7869	3100	3.9821
Load Voltage (<i>LV</i>)	0.0998	0.9997	53.9709	3475	4.8245
Load Power (<i>LP</i>)	0.0998	0.9997	53.9918	3475	4.8256
Knee Joint					
Rotational Joint Velocity (<i>RV</i>)	0.0997	0.9996	53.6390	3320	4.4041
Transducer Induced Voltage (<i>TIV</i>)	0.0998	0.9967	26.7134	2121	4.0428
Transducer Inductance Current (<i>SV₁</i>)	0.0998	0.9987	24.7266	2122	3.9134
Rectifier Voltage (<i>SV₂</i>)	0.0997	0.9986	31.0438	2504	4.0277
Converter Inductance Current (<i>SV₃</i>)	0.0997	0.8428	5.83173	394	2.3226
Load Voltage (<i>LV</i>)	0.0998	0.9985	35.1008	3475	3.5716
Load Power (<i>LP</i>)	0.0998	0.9986	35.0679	3475	3.5702
Ankle Joint					
Rotational Joint Velocity (<i>RV</i>)	0.0997	0.9995	49.0584	3360	4.5180
Transducer Induced Voltage (<i>TIV</i>)	0.0997	0.9989	32.5250	3440	4.1800
Transducer Inductance Current (<i>SV₁</i>)	0.0997	0.9987	25.1214	1988	3.9726
Rectifier Voltage (<i>SV₂</i>)	0.0997	0.9993	34.8633	3440	4.2629
Converter Inductance Current (<i>SV₃</i>)	0.0999	0.8853	7.27593	426	2.5351
Load Voltage (<i>LV</i>)	0.0997	0.9972	59.3336	3470	3.4533
Load Power (<i>LP</i>)	0.0997	0.9972	59.8217	3470	3.4741

In order to compare and interpret the meaning of the values of the RQA measures determined for the considered lower limb joints, the graphical representation of the results obtained for the input (*RV*) and output (*LP*) signals has been provided (Figures 21 and 22, respectively). As the result of *FAN* criterion selection, according to which all the columns of the *R* matrix have the same recurrence density [30], values of the *RR* measures obtained for the *RV* signals measured for all joints are equal (Figure 21).

The second considered measure—*DET*—describes whether the system of interest is more likely to exhibit periodic behavior or chaotic processes. In the case of periodic signals, the diagonal lines visible on the recurrence plots are long (like in the case of the *RV* signals analyzed in this paper). Moreover, the estimated values of *DET* measure for all the joints are equal up to the third decimal place. The periodic character of the analyzed *RV* signal, which is characterized by long diagonal lines on the RP, is also confirmed by the values of the *L* and *L_{max}* measures, which describe the average diagonal line length (*L*) and the length of the longest diagonal within the entire RP (*L_{max}*), respectively.

Values of the *ENTR* measure (Shannon entropy of the frequency distribution of the diagonal line lengths) reflect the complexity of the deterministic structure of the analyzed system. Since in the case of the considered *RV* signals, the *ENTR* values are small, they prove the low dynamic complexity of the considered system (periodic system behavior).

In the case of the *LP* output signal, as the result of *FAN* criterion selection, values of the *RR* measure obtained for all the joints are equal (Figure 22).

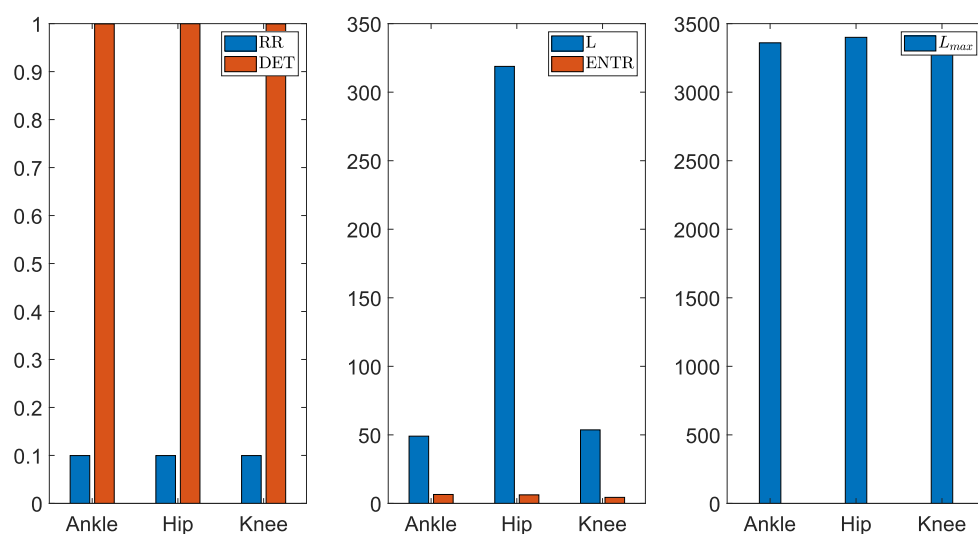


Figure 21. Graphical representation of the RQA measures estimated for the RV (input) signal.

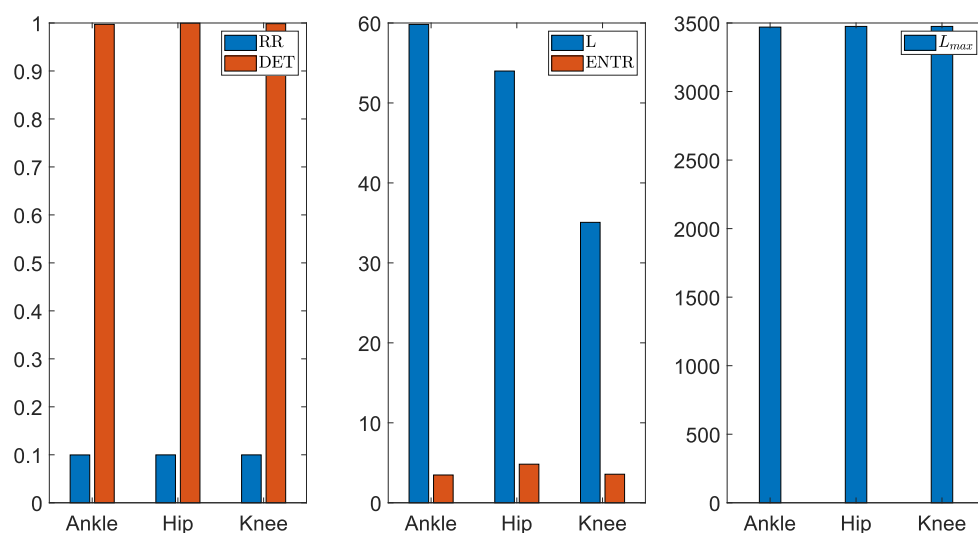


Figure 22. Graphical representation of the RQA measures estimated for the LP (output) signal.

As in the case of the input signal, the estimated values of DET measurements for all the joints, as well as the values of the L and L_{max} measures, prove the periodic character of the analyzed LP signals. Values of the $ENTR$ measure are small, proving the low dynamic complexity and periodic behavior of the considered LP signals.

To the best of our knowledge, the approach that follows in this study has been little implemented in other investigations. Real gait data from different joints were collected and used as an input mechanical variable for the energy harvesting device. A model was used to estimate the voltage induced by an electromagnetic energy harvesting device, considering each lower limb joint as a different energy source. In the paper, the authors compared the internal dynamic processes and system output quality for three different device locations: on the ankle, knee, and hip, respectively. The influence of the power conditioning circuit on the performance of the energy harvesting structure was studied by numerical simulation. Finally, a dynamic analysis of the system state variables was carried out, which allowed the detection of unwanted phenomena, such as chaos, unwanted oscillations, overshoots, and instability.

5. Conclusions

The paper presented the application of an electromagnetic transducer with its power conditioning circuit for harvesting energy from human walking. The proposed harvester structure makes it possible to transform the angular kinetic energy associated with the lower limb movement into electrical energy and deliver it to a low-power electronic device with a semi-stable output voltage level. An experimental study with a participant walking at constant speed was conducted to acquire real data of each of the lower limb joint movements. The interaction of the harvester structure and the power conditioning circuit was studied through the state-space averaging method. Its dynamic features were analyzed using recurrence plots and recurrence quantification analysis.

During the carried out research, satisfactory results have been obtained that demonstrate the viability of devices based on electromagnetic induction to collect energy from walking. The estimated harvesting power generated by the knee joint is large enough to power portable electronic devices up to 90 mW when the user is walking at a speed of 4.5 km/h. The same device mounted on a different lower limb joint generates considerably different electrical energy in the range of 1.4 mW to 90 mW without implementing multiplier gear. The stabilization time of the system is around 10 s to 15 s. Due to the sensitivity to changes in the dynamic behavior of the analyzed system, RP and RQA provide a valuable tool to quantify the analysis of different conditions and device configurations, as well as their influence on the periodic input–output waveforms, power output, and internal processes.

Further research on the control strategy of the power conditioning circuit would improve the performance of the device, which was considered to have a fixed PWM duty cycle in this study.

Author Contributions: Conceptualization, L.M.A. and M.I.; methodology, L.M.A. and J.I.; software, L.M.A. and J.I.; formal analysis, L.M.A., J.I. and M.I.; investigation, L.M.A.; data curation, L.M.A.; writing—original draft preparation, L.M.A.; writing—review and editing, L.M.A. and J.I.; visualization, L.M.A.; supervision, J.I. and M.I. All authors have read and agreed to the published version of the manuscript.

Funding: The paper publication fee was funded under subvention funds for the Faculty of Mechanical Engineering and Robotics and by the program “Excellence Initiative—Research University” for the AGH “University of Science and Technology”.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Acknowledgments: J.I. would like to thank for the financial support of the research from the POIR.04.01.04-00-0115/17 project.

Conflicts of Interest: The authors declare no conflict of interest.

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