

Study of a Pendulum in Vivo Electromechanical Generator to be Used in a Knee Prosthesis

Sylvie Turri¹, Mohamed Benbouzid¹, Abdeslam Mamoune¹ and Sylvie Breton¹

Abstract—This paper presents the principle and the energy potential of an original electromechanical generator that uses human body natural motions during walking, in order to create an autonomous generator. This in vivo and noninvasive system is intended to be used in intelligent knee prosthesis. As the combined human, mechanical, and electrical phenomena are very significant, a mechanical and an electrical study are then carried to evaluate the recoverable power. *Copyright © 2012 Praise Worthy Prize S.r.l. - All rights reserved.*

Keywords: Human motion, human-powered systems, direct drive generator, knee prosthesis.

Nomenclature

UHMWPE	= UltraHigh Molecular Weight PolyEthylene;
TKA	= Total Knee Arthroplasty;
FFT	= Fast Fourier Transform;
F	= Effort;
E	= Energy;
L	= Lagrangian;
D	= Dissipation potential;
P	= Power;
ϕ	= Generator flux;
T	= Torque;
f	= Frequency;
k	= average stiffness;
lg	= Rest length;
Δl	= Average deformation (%)
R	= Rotor radius;
M	= Rotor mass;
m	= Mass point;
λ	= Viscous damping coefficient;
g	= Gravity acceleration;
θ	= Position.

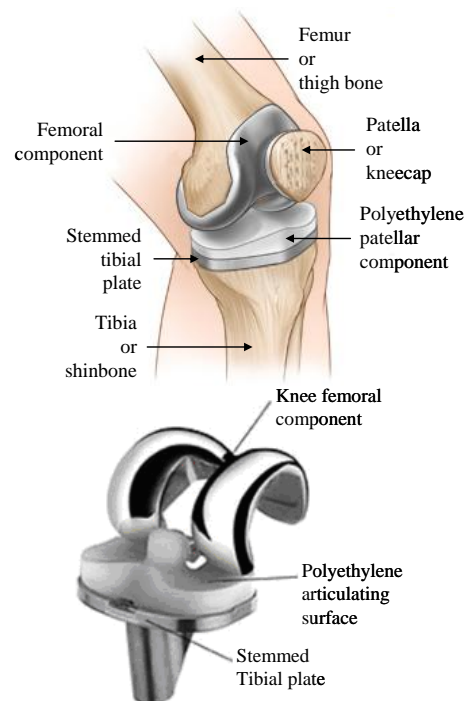


Fig. 1. Total Knee Arthroplasty.

I. Introduction

Each year, 250 thousand peoples in the USA undergo total knee implant orthopedic replacement operations [1]. Currently, total or partial orthopedic implant replacement does not replace the knee articulation but only the function: for the internal ligament, a substitution is used and for the total knee prosthesis, the articulation is replaced by a connection pivot.

The prosthesis operating conditions change over time: wear due to friction, the patient body mass changes, and morpho-functional variations such as the prosthesis deformation by the patient gait and his activities (sports, work injuries, falls, etc.). In vivo modifications can produce discomfort but can also cause dislocation of the prosthesis.

Implant failure requires revision surgery that is generally more complex and traumatic than first-time knee replacement. Such surgery accounts for over 8% of all total knee replacement operations [2-4]. If there is no osteolysis (bone degradation) or implant component dislocation, only the polyethylene material UHMWPE, as shown in Fig. 1, requires replacement. However, the most frequent cause of failure is due to a dislocation, in which case a new TKA must be carried out. Tibial and femoral bones are further reduced and a new, larger TKA is necessary. Bone-graft transplantation is then carried out, leading to a prolonged hospitalization. The impact of this operation is a diminution of knee motion and patient greater suffering. An early diagnosis is necessary if these extreme surgical revisions are to be avoided.

At present, in orthopedics in vivo microsystems do not go beyond measuring [5-10]. However the real challenge is to use in-vivo microsystems to make real-time corrections to internal dysfunctions [11]. In view of the hard constraints to which the prosthesis is subject, auto-adaptive systems would be necessary. They would allow the prosthesis to be time-adaptive to the patient morphotype, to correct faults such as implant replacement none optimization, or to rebalance the ligaments stress to restore the knee function.

In [12] are listed experimental studies on knee ligaments, each one compared to a spring. From these studies are deduced the average stiffness k , the rest length l_g , the average deformation Δl (%) and the average deformation energy (Table 1). The power is deduced for a walking frequency of 1-Hz which is considered to be the average human walking frequency [13]. The power for simple or usual deformation is close to 10% of the maximum power which is between 0.5-W and 1-W (Fig. 2) [14-15]. The ideal solution for these systems is to be autonomous. Over the past few years, autonomy of portable electronic systems has aroused many questions in the medical field. The implanted orthopedic device needs electric energy to power itself. But very few or no independent industrial systems currently operate. The power supply problem is always solved by batteries or an external supply.

An internal generator would avoid a cumbersome external device, such as the induction coils fixed on the patient leg. [7], [15-17]. Thus, to secure a necessary and useful power source to the electromechanical device, the generator should be able to produce sufficient power. As shown by Fig. 2, human body displacements represent an interesting renewable energy resource. This is why the old idea of human energy harvesting has been considered in our case as it was done by some researchers [16-20]. Recovering a modest part would allow the generation of useful energy to create adaptive and self-supplied orthopedic prostheses.

In the orthopedic domain, few systems have been studied. Only one in-vivo system has been proposed [21-22]. Mechanical energy was used to compress a piezoelectric ceramic element within knee prosthesis to produce electrical power. Therefore, this paper proposes a power recovery concept based on a flyweight located in the hollow prosthesis shaft [23]. The flyweight motion is generated by the knee displacement.

Table 1. Maximum useful power for each ligament.

Ligament	Stiffness k (N/mm)	l_g (mm)	Δl (%)	Power (W)
Anterior Cruciate Ligament (ACL)	80	30	24	2.9
Posterior Cruciate Ligament (PCL)	80	40	20	3.2
Medial Collateral Ligament (MCL)	73	60	14	3
Lateral Collateral Ligament (LCL)	40	50	11	1.1

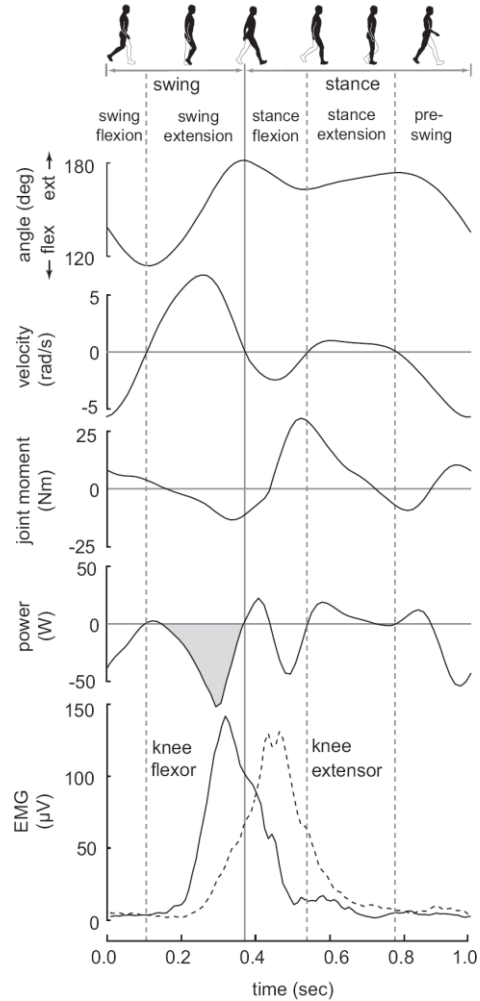


Fig. 2. Typical gait stages [14-15].

The balance wheel makes rotational motions that are transmitted to an electromagnetic generator, which recovers part of the mechanical energy. In the following, it will be presented the design of a direct-drive generator with an advanced static converter aimed to increase the recovered output.

II. Operating Principle

II.1. Mechanical System

Figure 3, illustrates the closed system which is moved by the knee through excitation forces. A mechanical pendulum system is inserted inside the hollow prosthesis shaft. The pendulum motion drives then electromagnetic generator rotor. This generator is electrically coupled to a load by a static converter.

II.2. Human Walk: A Natural Motion

As shown by Fig. 4, the x and y components of Fig. 3 correspond to the 2D knee motion with a normal walking speed of 5-km/h. These components are used to excite the system (Figs. 5 and 6).

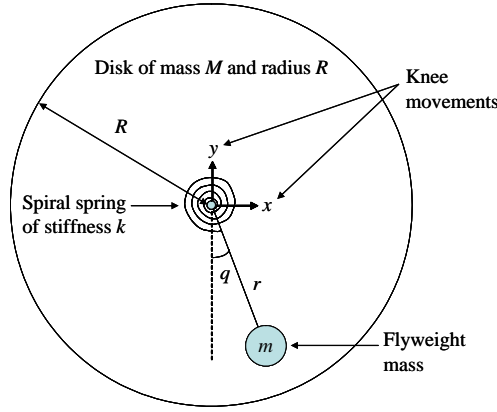


Fig. 3. Energy recovery operating diagram at the knee level.

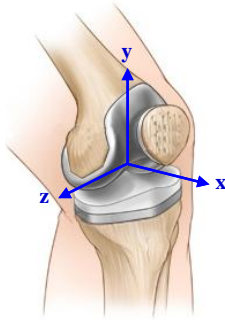


Fig. 4. The knee components.

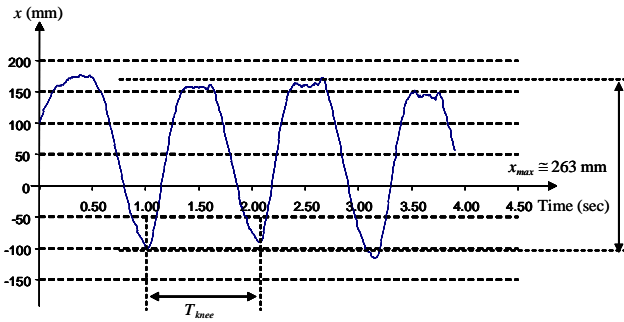


Fig. 5. The knee longitudinal motion.

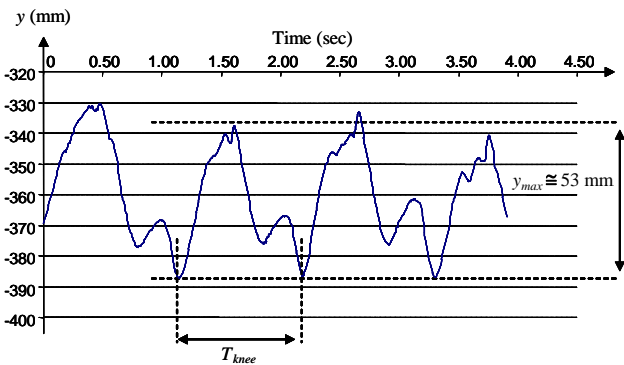


Fig. 6. The knee vertical motion.

From these figures, it is obvious that vertical and longitudinal knee motions are around a frequency of 1-Hz. This frequency corresponds to one human step. It very slightly varies from a step to the next one during normal walking [13].

In this study, we are dealing with normal walking conditions (i.e. a walk at 5 km/h) that correspond to a patient regular activity. It should be noted that ascending stairs or running will allow the patient to recover more power.

III. System Mechanical Modeling

To estimate the recovered electrical power, there is a need to evaluate the system motions coupled with the knee and the pendulum. For that purpose, the proposed study is based on the mechanical model shown by Fig. 7.

The system consists of a rotor of radius R and mass M , attached to a mass point m . This mass is placed at a distance r from the rotor rotation axis A . This rotor includes all the generator inertial parts without the mobile mass. A spiral spring of stiffness k (not represented) brings back the disc to an initial angle $\theta = 0^\circ$ when the flyweight is in the low position (of steady balance).

F_x and F_y are unknown efforts but they are closely related to x and y imposed displacements which characterize the knee trajectory (point A). These efforts represent mechanical actions generated by muscles during walking.

In the case of a Galilean reference frame and if the knee trajectory is imposed (Figs. 6 and 7), then the system is expressed with only one parameter θ .

Lagrange equations are used to characterize the system motion. In this case, the system total kinetic energy is given by

$$E_k = \frac{1}{2} M_1 \dot{x}^2 + \frac{1}{2} M_2 (\dot{x}^2 + \dot{y}^2) + \frac{1}{2} M (\dot{x}^2 + \dot{y}^2) + \frac{1}{4} M R^2 \dot{\theta}^2 + \frac{1}{2} m \left[(\dot{x} + r \dot{\theta} \cos \theta)^2 + (\dot{y} + r \dot{\theta} \sin \theta)^2 \right] \quad (1)$$

where M_1 is part 1 mass, M_2 is part 2 mass. Moreover, the system potential energy is given by

$$E_p = \frac{1}{2} M g y + m g (y - r \cos \theta) + \frac{1}{2} k \theta^2 \quad (2)$$

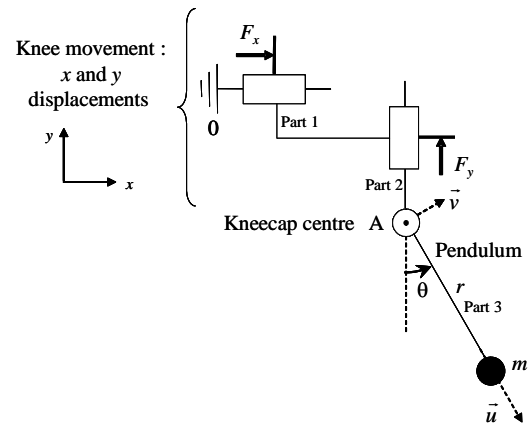


Fig. 7. Mechanical model.

The kinetic and potential electrical energies will be represented by a dissipation potential D which is only θ -dependant. The load torque corresponds to the energy transfer and the converter type.

In [24], it is shown that it is advantageous to consider the Laplace force is equivalent to a viscous friction, i.e.; both the converter and the load behave like a resistance that could be adapted to achieve optimal operation.

Therefore, if the converter-load system behaves like a resistance, the electrical power could be expressed as

$$P_e(t) = \frac{\beta^2}{R} \left(\frac{d\theta}{dt} \right)^2 \quad (3)$$

$$\text{where } \beta = \frac{d\phi}{d\theta}.$$

Moreover, the mechanical power could be simply expressed using the torque T .

$$P_{mech}(t) = T \frac{d\theta}{dt} \quad (4)$$

Neglecting the electrical losses, will lead to a practical expression of the mechanical power:

$$P_{mech}(t) = \lambda \left(\frac{d\theta}{dt} \right)^2 \quad (5)$$

$$\text{where } \lambda = \frac{\beta^2}{R}.$$

The control mode will therefore consist in optimizing the recovery coefficient or the viscous damping coefficient λ of the in order to maximize the average recovered power.

For a given excitation, there is an optimal λ value. For λ low value, the motion amplitude is very significant but the recovered energy is very poor whereas for an infinite value of λ , the pendulum system is slowed down to such an extent that motions and recovered energy are very weak.

The dissipation D is defined as the half of the dissipated power. Therefore, if a resistive load is imposed, D could be expressed by

$$D(\dot{\theta}) = \frac{1}{2} \lambda \left(\frac{d\theta}{dt} \right)^2 \quad (6)$$

Using the Lagrangian $L(\theta) = E_k - E_p$, one can derive the system dynamics

$$-\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{\theta}} \right) + \frac{\partial L}{\partial \theta} - \frac{\partial D}{\partial \dot{\theta}} = 0 \quad (7)$$

leading to the following motion equation.

$$\left(\frac{1}{2} MR + mr \right) \ddot{\theta} + \lambda \dot{\theta} + mr (\ddot{x} \cos \theta + \ddot{y} \sin \theta) + mgr \sin \theta + k\theta = 0 \quad (8)$$

This equation allows the computation of θ and therefore the estimation of the average power to be recovered.

It should be recalled that x and y are imposed. If they have been considered as unknown parameters, the system would have been characterized by three parameters: x , y and θ . In this case, the following two additional equations should have been used.

$$\begin{cases} F_x = (M_1 + M_2 + m + M) \ddot{x} + mr (\ddot{\theta} \cos \theta - \dot{\theta}^2 \sin \theta) \\ F_y = (M_2 + m + M) (\ddot{y} + g) + mr (\ddot{\theta} \sin \theta + \dot{\theta}^2 \cos \theta) \end{cases} \quad (9)$$

The above equations are not used as the muscle generated efforts F_x and F_y are unknown.

IV. Potential of an Electromechanical Resonant Generator

IV.1. The Spring

The spring is used to achieve the system resonance allowing then the maximum power recovery. For that purpose, the system is supposed to work as a simple pendulum without inertia ($M = 0$) and without energy recovering ($\lambda = 0$). In this case, the following equation is obtained.

$$\frac{1}{2} mr^2 \dot{\theta}^2 + mgr(1 - \cos \theta) = \underbrace{mgr(1 - \cos \theta_0)}_{f_0 = \text{constant}} \quad (10)$$

To operate at resonance, the system frequency f_0 must be synchronized with the knee frequency f_{knee} , i.e. 1-Hz. Thus, the spring has to be removed ($k = 0$) as the system will obviously not be able to operate at resonance with this synchronization condition.

IV.2. System Behavior without Excitation (No Knee Motion)

For a given system frequency, the recovered power continuously increases with the walking frequency [23]. However, this power will always remain below than that recovered with a walking frequency synchronized system.

Without excitation (no knee motion) and without spring, the following equation is obtained for an unloaded system.

$$\left(\frac{1}{2} MR^2 + mr^2 \right) \ddot{\theta} + mgr \sin \theta = 0 \quad (11)$$

The system theoretical frequency in the case of small oscillations is given by

$$\omega_0 = \sqrt{\frac{mgr}{\frac{1}{2}MR^2 + mr^2}} \quad (12)$$

For a system synchronized with the 1-Hz walking frequency, the following condition must be fulfilled. This is true only for small variations of θ as the system is nonlinear.

$$\frac{mgr}{\frac{1}{2}MR^2 + mr^2} = 4\pi^2$$

In order to understand how the system behaves in the above case, the device geometrical parameters will be determined so as to obtain 1-Hz. The objective in this case is that real oscillation frequencies should be synchronized with the walking frequency to recover maximum power.

For each theoretical frequency f_0 , the mobile mass is moved to its initial angle and then it is released. Furthermore, the system real oscillation frequency is determined using a Fast Fourier Transform (FFT) of $\theta(t)$.

The theoretical frequency is calculated using the following equation.

$$mgr = \omega_0^2 \left(\frac{1}{2}MR^2 + mr^2 \right) \quad (13)$$

The obtained curves for each theoretical frequency are summarized by Fig. 8. When analyzing the obtained results, the main derived conclusion is that the bigger the difference between the theoretical frequency and the knee frequency is, the more it is difficult to synchronize the two frequencies on a given angle θ .

IV.3. System Behavior with Simple Excitations

With simple excitations such as symmetrical or asymmetrical sinusoidal ones, the model validity can be

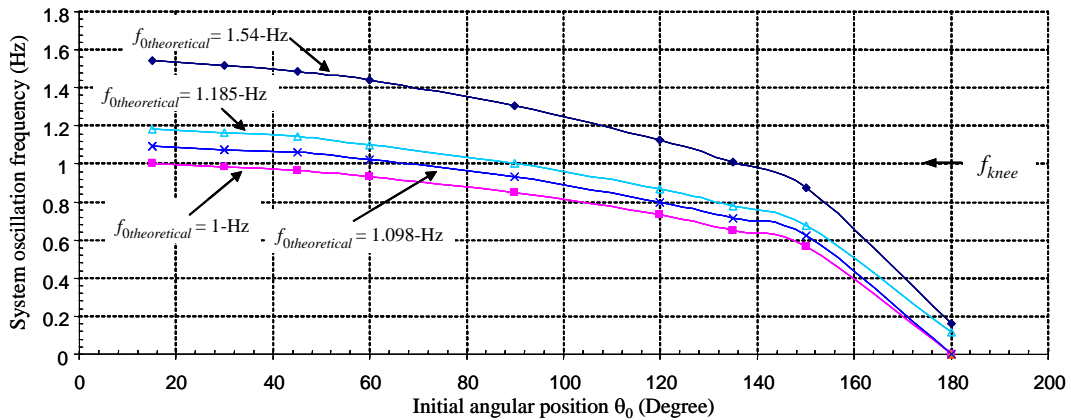


Fig. 8. System oscillation frequency versus the flyweight initial angular position.

checked. In this case, to recover the maximum power, the following results are derived:

- The system frequency must be synchronized with the excitation frequency.
- Angle θ must be near 90° , thus the need for position control.
- The term mr must be as large as possible.

IV.4. System Behavior with Walking Excitation

Figure 9 illustrates the knee 2D motion and therefore the system excitation waveform for a walking speed of 5 km/h. Table 2 summarizes simulation results for three cases selected among the several carried out ones. In this table, $P_{average}$ is the maximum average recovered power.

As case 1 is not synchronized with the walking frequency at 90° , mr ratio is different from power ratio for cases 1 and 2.

$$\frac{mr_{case1}}{mr_{case1}} = 7.14 \quad \text{and} \quad \frac{P_{average_{Case1}}}{P_{average_{Case2}}} = 5.32$$

If cases 2 and 3 are compared, same results are obtained as with simple excitations.

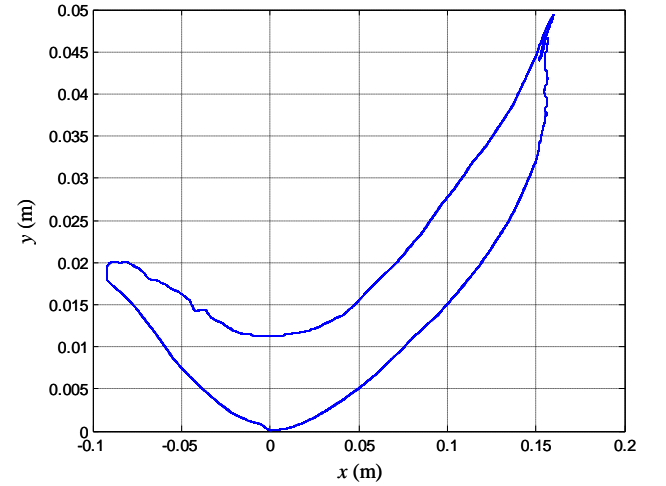


Fig. 9. Knee 2D motion for a walking speed of 5 km/h.

Table 2. Simulation results.

Case 1	
$M = 201.2\text{-g}, R = 10\text{-mm}$	$f_{0\text{theoretical}} = 1\text{-Hz}$
$m = 10\text{-g}, r = 5\text{-mm} (mr = 5 \times 10^{-5})$	$P_{\text{average}} = 630.42\text{-}\mu\text{W}$
$\lambda = 1.9167 \times 10^{-6}$	$\theta_{\text{max}} = 65^\circ$
Case 2	
$M = 50\text{-g}, R = 7\text{-mm}$	$f_{0\text{theoretical}} = 1.185\text{-Hz}$
$m = 3.5\text{-g}, r = 2\text{-mm} (mr = 7 \times 10^{-6})$	$P_{\text{average}} = 118.42\text{-}\mu\text{W}$
$\lambda = 1.9167 \times 10^{-6}$	$\theta_{\text{max}} = 103^\circ$
Case 3	
$M = 100\text{-g}, R = 13.1\text{-mm}$	$f_{0\text{theoretical}} = 1.185\text{-Hz}$
$m = 10\text{-g}, r = 5\text{-mm} (mr = 5 \times 10^{-5})$	$P_{\text{average}} = 849.40\text{-}\mu\text{W}$
$\lambda = 1.3667 \times 10^{-6}$	$\theta_{\text{max}} = 103^\circ$

Indeed, the maximum recovered power is obtained for θ close to 90° , with the largest possible mr , and with device dimensions allowing synchronization with the walking frequency for $\theta = 90^\circ$. In this case, flyweight position control at 90° is necessary using energy recovery λ . Furthermore, mr ratio is equal to power ratio.

$$\frac{mr_{\text{case3}}}{mr_{\text{case2}}} = \frac{P_{\text{averageCase3}}}{P_{\text{averageCase2}}} = 7.14$$

Figures 10 and 11 respectively show the recovered average power versus λ and the flyweight trajectory for case 3. Figure 12 illustrates the recovered electrical power in the case 3, where the peak power is 2.5-mW and the average recovered power is about 849.40- μW .

IV.5. Conclusion

The mechanical power which can be recovered from a system operating at a frequency close to its excitation depends not only on the mass m , but also on the potential distance r . The recovery is maximized when θ reaches 90° .

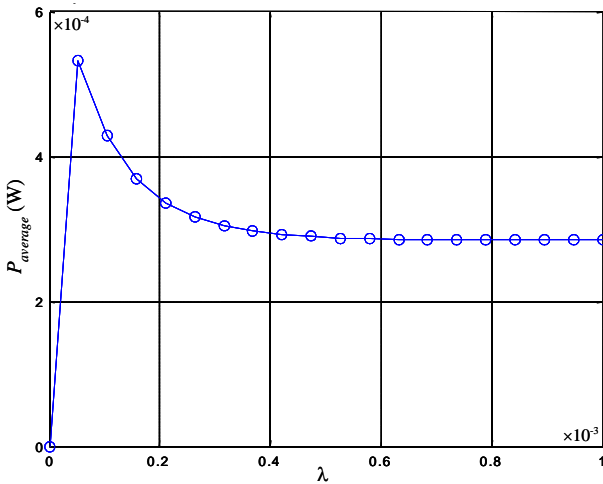


Fig. 10. Average electrical power versus the recovery coefficient (case 3).

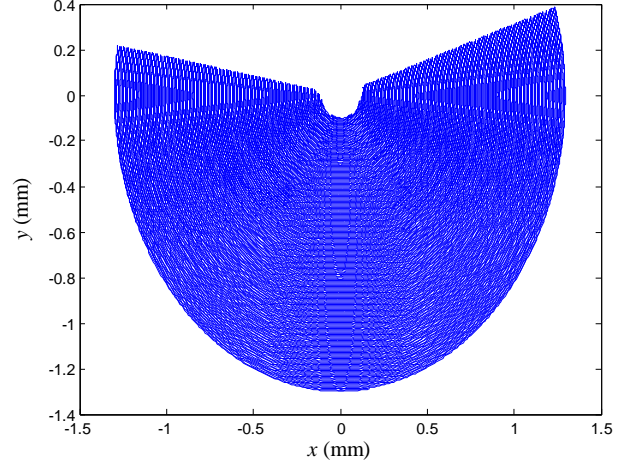


Fig. 11. Flyweight displacements (case 3).

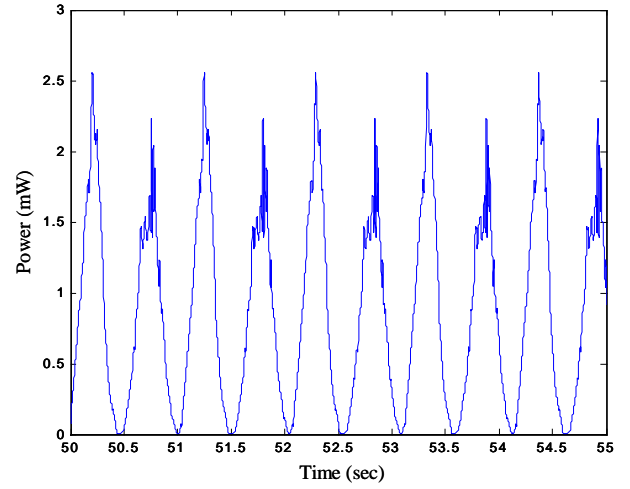


Fig. 12. The recovered electrical power (case 3).

V. On the Generator Design

The system is subjected to a fluctuating excitation according to the patient walking attitude. In order to recover the maximum energy, different elements must be optimized, among them the electromagnetic generator and the control strategy. Furthermore, medical constraints are to be accounted for: biocompatibility, reliability, and safety.

The schematic view of the proposed original permanent magnet generator topology is shown in Fig. 13. This is a direct-drive solution as the generator is integrated into the pendulum system and therefore constitutes a part of the flyweight mass. The proposed generator uses radial magnetized permanent magnets so as to exhibit a low detent torque [25].

When designing the permanent magnet generator, it will be necessary to take into account (13) which links ω_0 , r , R , m , and M . For example, if the maximum value of r and m are a priori fixed, one can deduce the maximum power that the system is able to recover. But care should be taken so that M and R values are not absurd. It is therefore necessary to make a compromise between the design characteristics and the recovered power.

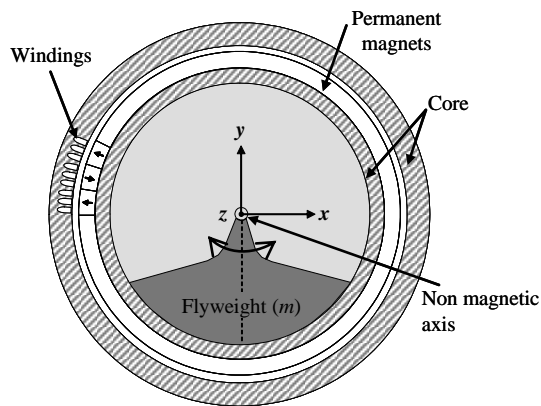


Fig. 13. Schematic view of the proposed generator.

VI. Conclusions

This paper has presented the principle and the energy potential of an original electromechanical generator that uses human body natural motions during walking, in order to create an autonomous generator. This in vivo and noninvasive system is intended to be used in knee prosthesis. In the proposed innovative but quite simple solution, the objective of recovering several tens of mW could be achieved if imposing to the load a V/I scalar control that is adaptive to the patient walking conditions. Recovering the maximum power proves relatively straightforward. Indeed, it is achieved when the flyweight reaches 90° on each side.

In this preliminary study, purely-mechanical frictions have not been taken into account. Viscous frictions will remove a portion of the available power. However, due to the low speed displacements, these frictions should not attain very high levels.

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