MULTI-SOURCE ENERGY HARVESTING POWER GENERATORS FOR INSTRUMENTED IMPLANTS

Towards the Development of a Smart Hip Prosthesis

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Abstract: Very few developments have been done to provide electric power supply of instrumented hip prosthesis. Actually, vibration-powered generators are the most appropriate mechanisms for this kind of application's environment. This paper describes the first attempt to develop the concept of energy harvesting from multiple energy sources applied in the same hip implant. Exploiting the potential of the three angular movements over the femoral component, namely in the abduction-adduction, flexion-extension and inward-outward rotation axes, three inboard vibration-based mechanisms were developed in order to ensure electric power supply from multiple energy sources. A total of 53.7 μJ/s was harvested by a translation movement-based electromagnetic energy generator when a sinusoidal function with an amplitude of 40 mm and a frequency of 4 Hz was applied. A rotation movement-based electromagnetic energy generator has harvested 0.77 μJ/s when a sinusoidal function with an amplitude of 60° and a frequency of 2.5 Hz was used. The piezoelectric energy harvester has achieved 0.6 μJ/s with the application of a sinusoidal function with an amplitude of 200 N and a frequency of 4 Hz. Besides, its ability of being fully autonomous, operating without expiry and maintenance, while offering safety during its entire lifetime are relevant features. This paper should provide the basis for the development of smart hip prosthesis with the ability to fix the aseptic implant loosening problem.

1 INTRODUCTION

Loosening of the prosthetic stem and cup is a serious complication of the Total Hip Replacement Arthroplasty (THR), being referred that more than 80% of the non-success surgical procedures are due to implant loosening (Alpuim et al., 2008). Generally, the revision rate is about 10% in the case of prosthesis implanted 10 years before. However, a growth of about 100% is estimated in the revision procedures in the EUA by 2030 (Kurtz et al., 2007). The progressive bone loss surrounding the implant is considered the main cause of the THR failure. The revision surgeries are more complex, more expensive, more painful and present a non-success rate higher than primary THRs. Taking into account the increase of the average life expectancy and the number of THRs applied in young patients, the development of durable hip prosthesis is imperative. The current instrumented prosthesis proposals have only been designed to collect forces and kinematics data acting *in vivo*, in order to promote the continuous optimization of such implants (Damm et al., 2010; Heinlein et al., 2009; Westerhoff et al., 2009; Rohlmann et al., 2008; Heinlein et al., 2007; Graichen et al., 1999). The expertise of these implants does not allow continuous real-time problem solving, but only provides data to support new research. To avoid the need of revision surgeries, a new concept of prosthesis is emerging to diagnose and contribute to fix the loosening problem: methodology based on the use of mechanical micro-stimulation to promote the remodelling of the bone surrounding the implant, considering that bone resorption and deposition are strongly related to mechanical stimuli (Frias et al.,

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2010). Therefore, the smart hip prosthesis should allow the osteointegration monitoring in the critical regions of the bone-implant interface (self-diagnosis function) and mechanically micro-stimulate the local region under loosening, in order to remodel the bone surrounding the hip prosthesis (adaptive function). The failure detection in hip implants and the regions of the implant where it occurs with time are currently being studied (Marschner et al., 2009; Rowlands et al., 2008; Alpuim et al., 2008; Puers et al., 2000). To yield an architecture to accommodate energy harvesting systems, activation circuits to wake up deep sleep electronics, who relies on batteries to operate, have been developed to instrument hip prosthesis (Morais et al., 2009), but they have been powered inductively by external coils (Morais et al., 2009; Marcelli et al., 2007). The detection/micro-stimulation system's operation demands for an autonomous bio-generation system that electrically must supply not only the telemetry but also the mechanical bio-stimulation systems. Only a vibration bio-generator, designed using the electromagnetic principle, was proposed to supply smart hip prosthesis (Morais et al., 2011; Morais et al., 2010), but the multi-source methodology of the vibration-based energy harvesting system in the same hip implant was not approached. When the availability of the electric power supply is jeopardized, the reliability of the power supply mechanism decreases. This paper reports an electric vibration-based bio-generator from multiple energy sources for smart hip prosthesis. It is composed of a piezoelectric and two electromagnetic generation mechanisms in a same hip joint prosthesis. This methodology should serve as a reference for future work on smart hip prosthesis with the purpose of avoiding revision procedures.

This paper is organized as follows: after this introductory section, the three generators that make up the prototype are described, from the theoretical background to the characterization of the practical design. The simulated and experimental generation results are presented and discussed in section 3. Finally, in section 4 conclusions and final remarks of this work are given.

2 MULTI-SOURCE ELECTRIC POWER BIO-GENERATORS

2.1 Hip Prosthesis Prototype

To validate the multi-source self-powered electrical supplying methodology, the commercially available *Metabloc*^{TM} straight stem system (*Zimmer* Corporate, Warsaw, Indiana, EUA) was used as a model to design a passive hip prosthesis prototype. The size 10 of this stem system was modified to obtain a hollow hip prosthesis prototype. The fatigue resistance of instrumented hollow bone implants has already been guaranteed by fatigue tests (Westerhoff et al., 2009; Heinlein et al., 2007). Figure 1 focuses on the full active prototype of the hip prosthesis with vibration-based electric power bio-generators. The electromagnetic-based transduction mechanisms were positioned respectively in the body and in the upper half of the head, whereas the piezoelectric-based transducer was mounted in the lower half of the femoral head.

Figure 1: Electric power bio-generators from multiple energy sources for a hip prosthesis prototype.

2.2 Energy Harvesting Systems

There are many possibilities to harvest electric energy from the surrounding environment. Biofuel Cells, magnetic induction, thermoelectric and vibration are some of the main sources used to harvest energy. High-quality articles and books have been published about this subject and highlight how important such mechanisms can be in the development of smart bone implants (Lu et al., 2011; Kaźmierski and Beeby, 2011; Carmo et al., 2010; Zhu et al., 2010; Beeby and White, 2010; Westerhoff et al., 2009; Priya and Inman, 2009; Kerzenmacher et al., 2008; Wei and Liu, 2008). Vibration-based generation is currently the most appropriate solution to convert mechanical vibrations into electrical energy in order to electrically supply the active elements of the smart hip prosthesis (Morais et al., 2011; von Büren et al., 2006).

2.3 Translation Movement-based Electromagnetic Energy Harvester

Using mechanical accelerations, obtained from human gait activities, as the energy source for energy scavengers, an electromagnetic power transducer (TEEH) was designed in the body of the hip prosthesis to take advantage of the movements in the abduction-adduction and flexion-extension axes through the hip joint (Winter, 2009; Whittle, 2007).

2.3.1 Theory Background

The principle of the electromagnetic generation of electric energy is based on Faraday's law, who formulated that the relative movement of a coil within a constant magnetic field, generated by a permanent magnet, induces an electromotive force in that coil through the change in the magnetic flux (Ida, 2004). The theory of the linear behaviour of the generality of the vibration-based generators, is already well developed (Kaźmierski and Beeby, 2011; Priya and Inman, 2009; Cook-Chennault et al., 2008; Gilbert and Balouchi, 2008; Beeby et al., 2006). As with inertial resonant generators, they use mechanical movement as the physical condition to harvest electric energy. Linearly, they can be modelled as a single degree-of-freedom mechanical damping system represented by a second-order mass-spring-damper system, because the damping mechanism is proportional to the kinetic energy. The general resonant generator theory states that:

(i) The mechanical input is the external mechanical vibration (represented below by $y(t)$, as in figure 2). Generally, the human gait analysis has shown frequency movements between 0.5 Hz and 2 Hz. The international ISO 14242 standard specifies, for a frequency of 1 Hz, a pattern of the relative angular movement between articulating components and a pattern of the applied force for orbital bearing type wear testing machines of hip prosthesis. However, the real loading and displacement parameters are much more complex than the standardized ones, involving highly nonlinear functions with several parameters, such as the frequency of movements, weight, age, bone structure, health conditions, type of activity, muscle acceleration imposed by the patient's activity, among others;

(ii) The mechanical structure can be modelled as an inertial frame (fixed referential) where a suspended seismic mass is attached, representing a magnet, coupled to a spring, which in turn is coupled to a damping element, representing the sum of the comprising parasitic losses and the electrical energy extracted by the transducer (Beeby et al., 2006). External movements are transmitted by the inertial frame, producing a relative displacement $z(t)$ between the mass and the frame (as represented in figure 2), which is the amount of mechanical vibration to be converted into electric energy. The differential equation of this second order system is described as:

$$m\ddot{z}(t) + c\dot{z}(t) + kz(t) = -m\ddot{y}(t) \tag{1}$$

in which m is the seismic mass, k the stiffness of the spring and c is the damping coefficient. When this damping system is excited by an external sinusoidal vibration $y(t) = Y\sin(\omega t)$, the solution of (1) is given by:

$$z(t) = \frac{\omega^2}{\sqrt{\left(\omega_n^2 - \omega^2\right)^2 + \left(2\zeta\omega_n\omega\right)^2}}\, Y sin\left(\omega t - arctg\left(\frac{2\zeta\omega_n\omega}{\omega_n^2 - \omega^2}\right)\right) \tag{2}$$

in which $\omega_n = \sqrt{k/m}$ is the natural frequency and $\zeta = c/2m\omega_n$ is the total damping ratio of the resonant generator system. The damping coefficient resulting from electromagnetic transduction c_e can be approximately achieved (considering only movements from high to zero magnetic fields (Beeby et al., 2006)) by:

$$c_e = \frac{\left(NlB\right)^2}{R_{load} + R_{coil} + j\omega L_{coil}} \tag{3}$$

l is the perimeter of one turn of the coil, N is the number of turns of the coil, B is the flux density to which the coil is subjected, and R_{load}, R_{coil} and L_{coil} are respectively the load resistance, coil resistance and coil inductance;

(iii) The average power output, applying $y(t) = Y\sin(\omega t)$, is defined as:

$$P(t) = \frac{m\zeta Y^2\omega^3\Omega^3}{\left(1-\Omega^2\right)^2 + \left(2\zeta\Omega\right)^2} \tag{4}$$

in which $\Omega = \omega/\omega_n$ is a dimensionless parameter that denotes the difference between the real frequency and the natural frequency of the generator system. Considering $V = \sqrt{2PR}$, the average voltage output can be estimated by:

$$V(t) = \frac{BlY\omega^3}{\sqrt{\left(\omega_n^2 - \omega^2\right)^2 + \left(2\zeta\omega_n\omega\right)^2}} \tag{5}$$

(iv) In order to optimize the generation of electric power, the frequency of the hip kinematics must match the resonant frequency of the generator. Taking into account that the external vibration, which is the input of the bio-generator of smart hip prosthesis, cannot be controlled by the generator, the matching must be performed by tuning the resonant frequency of the generator. Although the vibration-based transducers are currently considered the best methodology to develop bio-generators from human gait at hip localization, a continuous matching of the frequency range of the hip kinematics of patients with the resonant frequency of the generator is a difficult task to do, because the duration and frequency of every-day human activities and the frequency of the activity itself are unpredictable (Morlock et al., 2001). With constant resonant frequency, the best result is obtained when the human being controls the duration and frequency of the activity. Even so, a *perfect* match is not achievable.

This linear model does not take into account the real mechanical input data (translational and rotational movements of the hip joint), and several other forces acting in the system, such as friction and gravity forces. However, it is a solid basis to start the study of the dynamic behaviour of this kind of system.

2.3.2 Permanent Magnet Vibration Power Generator Prototype

The generator prototype is composed of an extension coil spring (K = 2.45 N/m, 5 mm of diameter, 10 mm of steady-state length and 0.2 mm^2 of wire section) and two neodymium disc magnets N35 (6 mm of diameter, 6 mm of height, 1.21 g of weight and 1.22 T of magnetic field), which are suspended inside a Teflon tube ($c_m = 0.04$) where enamelled copper wire (0.1 mm of diameter, 27 mm of length and 1.72×10^{-8} Ωm of electrical resistivity) was wound (N = 2000 turns, 124.4 Ω of total wire resistance), which in turn was attached to the hip prosthesis fixture. The coil and the prosthesis make up the inertial frame. Two magnets were used to make larger the separation between the poles of the magnet, in order to ensure that the magnetic field lines were nearly perpendicular to the wiring direction of the coil, which leads to better results, according to Morais at al. (2011). Figure 2 shows a 2-D representation of this bio-generator. The coil was located as close as possible to the magnetic field lines in order to maximize the change in magnetic flux and reduce friction between the tube and the magnet. Taking into account the volume restrictions inside the prosthesis, the coil was lengthened to maximize the number of coil turns. The spring was chosen to be nonferrous to avoid the induction of a current into the spring from the magnetic field generated by the magnet, preventing magnetic attraction between them that would stop the relative movement between the magnet and the coil during the human gait. With this design, the natural frequency of the electromagnetic transducer is 4.98 Hz and the total damping ratio is 0.2556.

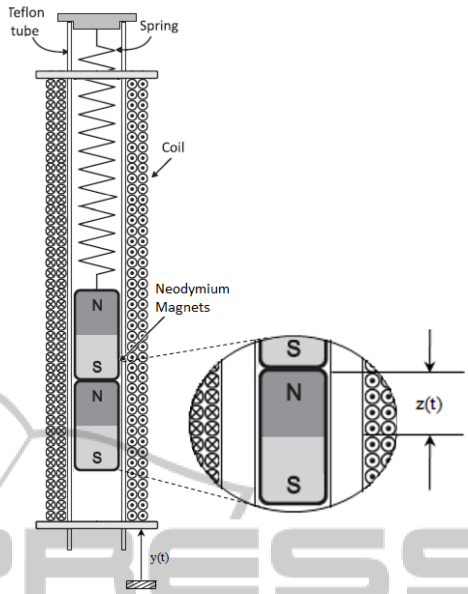

Figure 2: Scheme of the TEEH transducer.

2.4 Rotation Movement-based Electromagnetic Energy Harvester

Another electromagnetic transducer was designed using the modular ball head of the hip prosthesis and an acetabular component, in order to exploit the potential of the rotation movement through the hip joint (REEH transducer).

2.4.1 Theory Background

According the Faraday's law, the total induced electromotive force (V_{emf}) in a circuit due to motion is given by the integral of the electric field intensity along the desired contour for the electromotive force, as given by equation 6 (Ida, 2004).

$$V_{emf} = \oint_C (\overrightarrow{v} \times \overrightarrow{B}) \cdot d\overrightarrow{l} \qquad (6)$$

in which $\overrightarrow{v} \times \overrightarrow{B}$ is the induced electric field intensity, C is the desired contour (in this case a circle of R = 4 mm of radius). The electromagnetic energy harvester based on the rotation movement of the hip prosthesis uses this same principle, which is also used to design alternating current generators. The total harvested energy is the total sum of the energy that can be harvested from the rotation around the flexion-extension axis and the energy acquired from the rotation around the inward-outward or the abduction-adduction axes, according to the following expression of the total induced electromotive force:

$$V_{emf}^{\hat{x}\hat{z}} = -\pi R^2 NB \frac{d\alpha_{\hat{z}}}{dt} sin(\alpha_{\hat{z}}) - \pi R^2 NB \frac{d\alpha_{\hat{x}}}{dt} sin(\alpha_{\hat{x}}) \qquad (7)$$

Equation 7 demonstrates that the voltage generation is maximized with the increase of the rotation change, which means that the higher the frequency the higher the output voltage. Because the amplitude of rotation around the flexion-extension is greater than the other rotations, the induced electromotive force harvested due to this rotation ($V^{\hat{x}}_{emf}$) is predominant.

2.4.2 Permanent Magnet Vibration Power Generator Prototype

The ball head was hollowed to allow the installation of a circular winding of enamelled copper wire (AWG 42, 0.063 mm of diameter), which was coiled ($N =$ 4710 turns, 682 Ω of total wire resistance, 117.1 m of total length of the coil, 7.92 mm of average diameter) around a Teflon tube (5.8 mm of diameter, 12 mm of length) whose core was designed to be a steel cylinder (4 mm of diameter, 14 mm of length, 100 of relative permeability). Twenty-four neodymium disc magnets N52 (6 mm of diameter, 2 mm of height, 0.43 g of weight and 1.48 T of magnetic field) were put inside the structure of an acetabular component of high density polyethylene to set the magnetic field lines over the volume of the upper half of the ball head of the hip prosthesis, according to figure 3. Six groups of two magnets, positioned equidistantly, were settled symmetrically in the acetabulum with six other groups of two magnets, also positioned equidistantly. Therefore, the rotation around the flexion-extension axis and around the inward-outward axis or the abduction-adduction axis (depending on the location of the magnets) are used as the vibration source to harvest electric energy. Figure 4 presents the electromagnetic-based generator to be applied to the human hip implant.

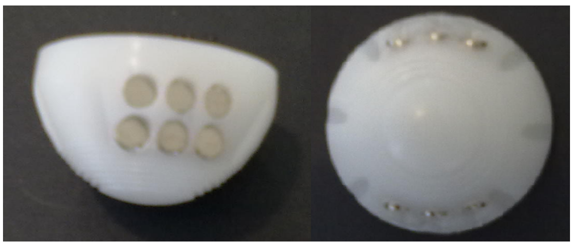

Figure 3: Acetabular component.

2.5 Piezoelectric Energy Harvester

A piezoelectric power generator (PEH) was designed to exploit the potential of the axial load over the hip joint in the harvester process. Figure 5 provides a representation of the piezoelectric-based generator applied to the human hip implant.

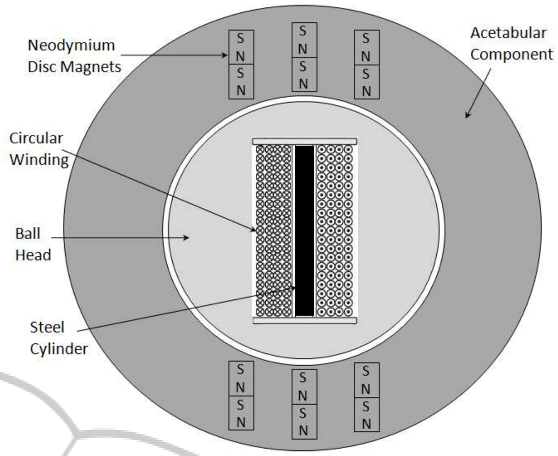

Figure 4: Scheme of the REEH transducer.

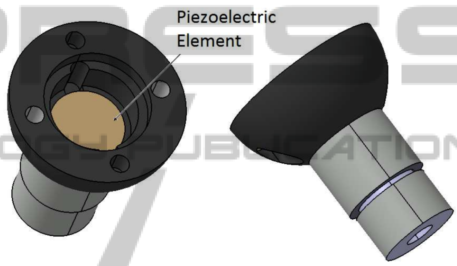

Figure 5: PEH system.

2.5.1 Piezoelectric Power Generator Prototype

A piezoelectric ceramic diaphragm (ref. 7BB-12-9, *muRata* Corporate, Kyoto, Japan) with 9 mm of diameter and 0.22 mm of thickness (12 mm of plate size, 0.1 mm of plate thickness and 9.0 ± 1.0 kHz of resonant frequency) was put in the lower half of ball head of the hip prosthesis, in order to transduce the large axial load changes during the gait cycle over it into electric energy (Priya and Inman, 2009). The maximization of the electric power harvested requires the matching of the frequency range of the axial load over the hip joint of patients with the resonant frequency of the transducer. However, the unpredictability of the frequency of the axial load makes this task hard to implement.

2.5.2 Theory Background

General 1-D piezoelectric vibration energy harvesters can also be modelled as a single degree-of-freedom mechanical damping system, represented by a second-order mass-spring-damper system (Renno et al., 2009; duToit et al., 2005). These standard models are inaccurate for our purpose since the total mechanical damping ratio is not equal to the mechanical damping ratio of the second-order mass-spring-damper system, because the piezoelectric element is attached to the hip prosthesis structure, which settles a new mechanical damping ratio and a proof mass very difficult to find due to the geometry of the prosthesis. An artificial neural network model (Kalogirou, 2000) was used to overcome this ill-defined problem, offering an alternative way to predict the power and energy conversion of this transducer mechanism. A multilayer 'feed-forward' neural network (ANN) was trained to perform the matching between the input data (a series of pairs of the frequency and amplitude of sinusoidal axial forces over the head of the hip prosthesis) and the target data (average power and peak-to-peak voltage), acquired from experimental tests. The ANN consists of one input layer, with two neurons, two hidden layers, with seven neurons each, and one output layer, with two neurons, as shown in figure 6 and equation 8. The Levenberg-Marquardt's algorithm was used as the training algorithm and the mean square error of 1.0×10^{-20} as the convergence criteria for the network training. Sigmoid functions (Tansig) for the hidden layers and linear function (Purelin) for the output layer were used as the transfer functions.

$$\mathbf{y}_N = f_L(\mathbf{LW}_2 f_S(\mathbf{LW}_1 f_S(\mathbf{IW}_1 \mathbf{i}_N + \mathbf{b}_1) + \mathbf{b}_2) + \mathbf{b}_3) \quad (8)$$

in which $\mathbf{y}_N$ is the output 2×1 matrix, $\mathbf{i}_N$ is the 2×1 input matrix, $\mathbf{IW}_1$ is a input weight 7×2 matrix, $\mathbf{LW}_1$ and $\mathbf{LW}_2$ are respectively layer weight 7×7 and 2×7 matrices, and $\mathbf{b}_1$, $\mathbf{b}_2$ and $\mathbf{b}_3$ are respectively bias 7×1, 7×1 and 2×1 matrices. f_L and f_S are respectively linear and sigmoid functions.

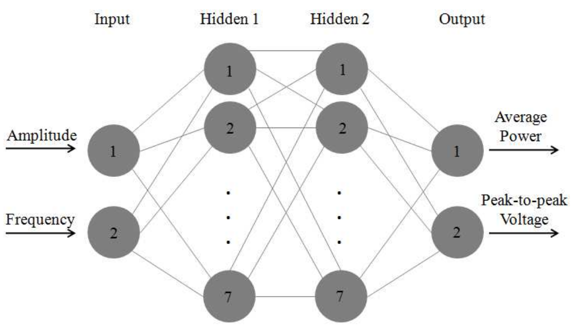

Figure 6: Architecture of the ANN used in modelling for the average power and peak-to-peak voltage of the PEH transducer.

3 RESULTS AND DISCUSSION

All experimental procedures were performed with a mechanical testing machine used to study the tribological behaviour of materials for hip joint prosthesis (Santos et al., 2011). Each generator was independently tested. The generated instantaneous voltage signal was acquired from the combination of the amplitude of several rotational and translational movements and the associated frequency. For each harvesting element and for each combination amplitude/frequency, the experimental generated average and peak power, energy and peak-to-peak voltage were analysed. These experimental results were compared with the models reported in sections 2.3.1, 2.4.1 and 2.5.2.

3.1 TEEH Results

A load resistance of 979 Ω was used to enable the energy transfer of this bio-generator when sinusoidal input vibrations with amplitudes in the range 10 mm to 40 mm and frequencies in the range 0.5 Hz to 4 Hz were applied to the generator. Figures 7 and 8 show respectively the results of the experimental and simulated average power, whereas figure 9 highlights respectively the results of the experimental and simulated peak-to-peak voltage. The maximum energy harvested was 53.7 μJ/s when the sinusoidal function has an amplitude of 40 mm and a frequency of 4 Hz. With the same amplitude but with a frequency of 2.5 Hz, 12.7 μJ/s can still be harvested. It is clear that energy production is increased by increasing amplitude and frequency. This harvester is able to provide 567.4 μW of instantaneous peak power when the input is excited with an amplitude of 40 mm and a frequency of 3 Hz.

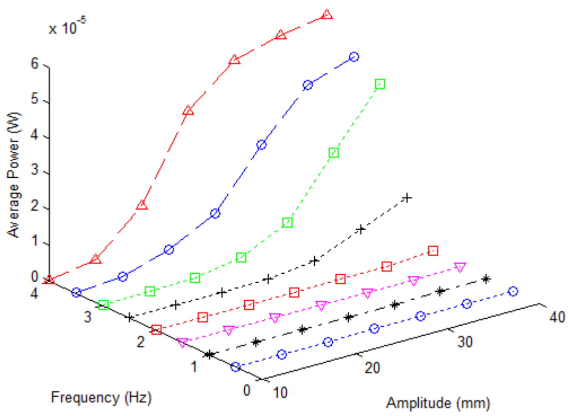

Figure 7: Experimental average power harvested from the TEEH transducer.

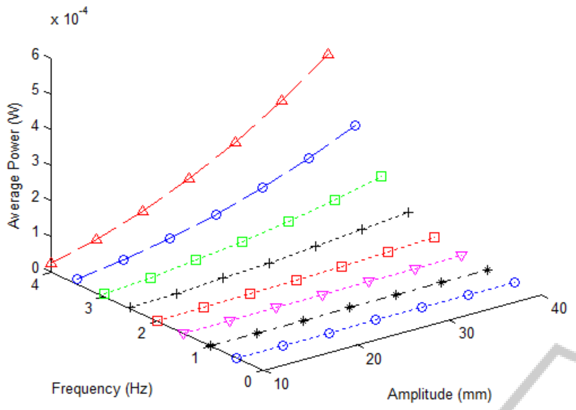

Figure 8: Simulated average power harvested from the TEEH transducer.

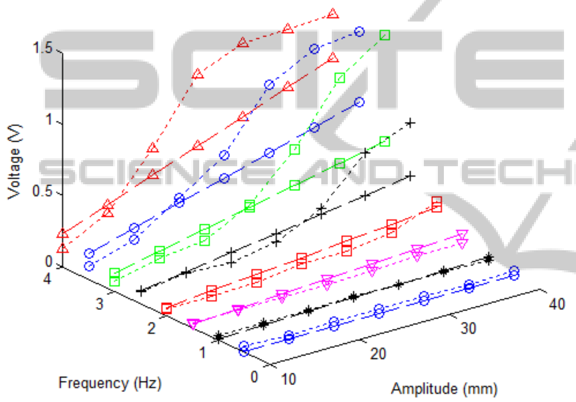

Figure 9: Simulated (dashed line) and experimental (dotted line) voltage harvested from the TEEH transducer.

3.2 REEH Results

A load resistance of 8.98 kΩ was used to enable energy transfer of this bio-generator when sinusoidal rotations in the flexion-extension axis with amplitudes in the range 50° to 70° and frequencies in the range 0.5 Hz to 2.5 Hz, were applied to the generator. Figures 10 and 11 show the experimental results. Figures 12 and 13 highlight the simulated results using 80 mT as the magnetic field in the winding (measured at the ends of the winding). The maximum energy harvested was 0.77 μJ/s when a sinusoidal function with an amplitude of 60° and a frequency of 2.5 Hz was applied. With an amplitude of 70° and a frequency of 1.5 Hz, 0.39 μJ/s can still be harvested. The increased energy production with increasing amplitude/frequency is also verified. This harvester provides 3.1 μW of instantaneous peak power when the input is excited with an amplitude of 60° and a frequency of 2.5 Hz.

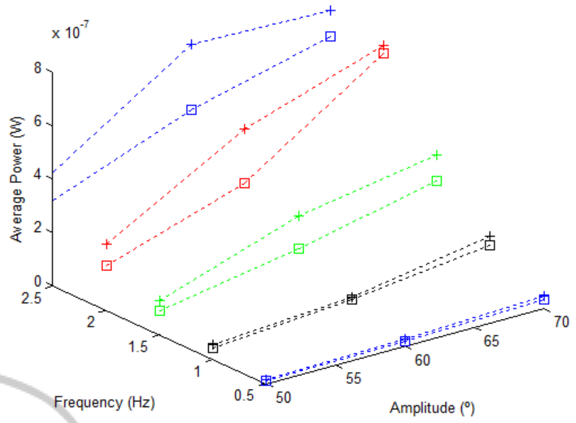

Figure 10: Experimental average power harvested from the REEH transducer (the plus sign refers to peak-to-peak amplitudes in the range −10 mm to 60 mm, −10 mm to 50 mm and −10 mm to 40 mm; the square refers to peak-to-peak amplitudes in the range −20 mm to 50 mm, −20 mm to 40 mm and −20 mm to 30 mm).

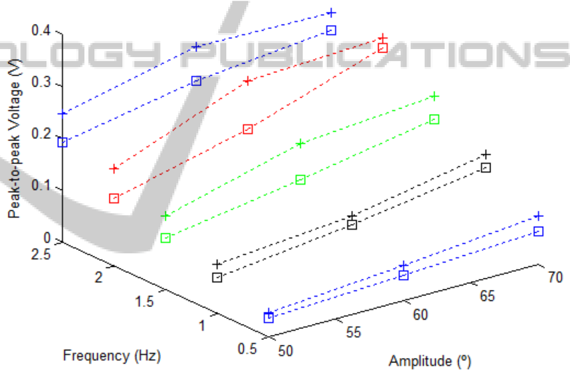

Figure 11: Experimental voltage harvested from the REEH transducer (the plus sign refers to peak-to-peak amplitudes in the range −10 mm to 60 mm, −10 mm to 50 mm and −10 mm to 40 mm; the square refers to peak-to-peak amplitudes in the range −20 mm to 50 mm, −20 mm to 40 mm and −20 mm to 30 mm).

3.3 PEH Results

External sinusoidal forces with amplitudes in the range 100 N to 250 N and frequencies in the range 0.5 Hz to 4 Hz were applied to the generator. A load of 1 MΩ was used to enable the energy transfer. Figures 14 and 15 show the experimental results, whereas figures 16 and 17 highlight the validation results of the 'feed-forward' neural network using only data not used in the training process. The maximum energy harvested was 0.6 μ J/s when the sinusoidal function has an amplitude of 200 N and a frequency of 4 Hz. With an amplitude of 100 N and a frequency of 2.5 Hz, 0.2 μ J/s can still be harvested. Regarding the instantaneous peak power, this generator can harvest

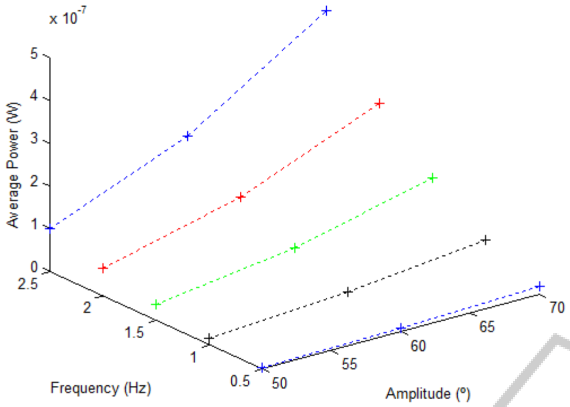

Figure 12: Simulated average power harvested from the REEH transducer.

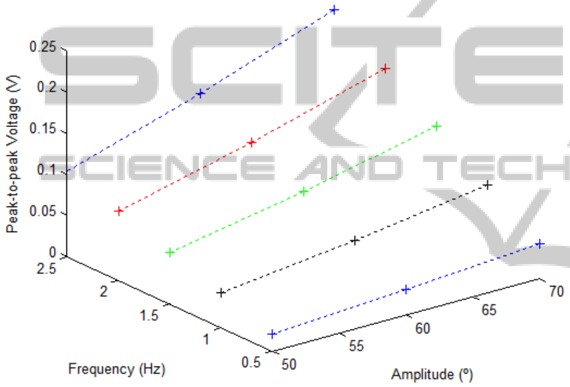

Figure 13: Simulated voltage harvested from the REEH transducer.

9.1 μW for frequencies of 3.5 Hz and 4 Hz.

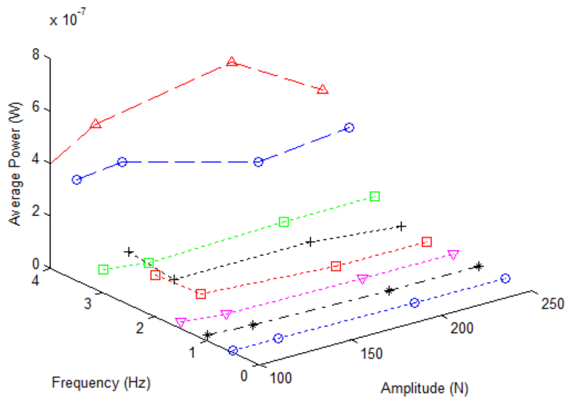

Figure 14: Experimental average power harvested from the PEH transducer.

3.4 Discussion

The concept of energy harvesting from multiple energy sources was proved in this study as a reliable

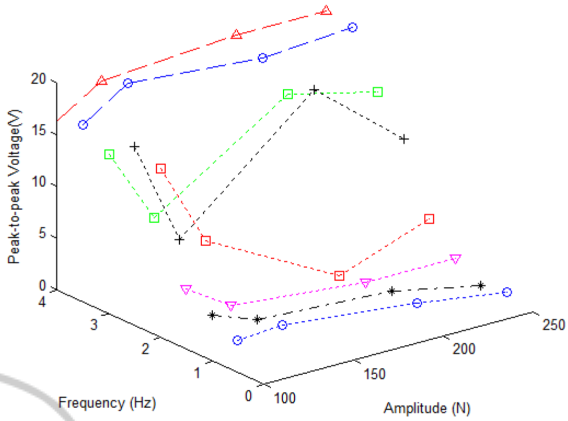

Figure 15: Experimental voltage harvested from the PEH transducer.

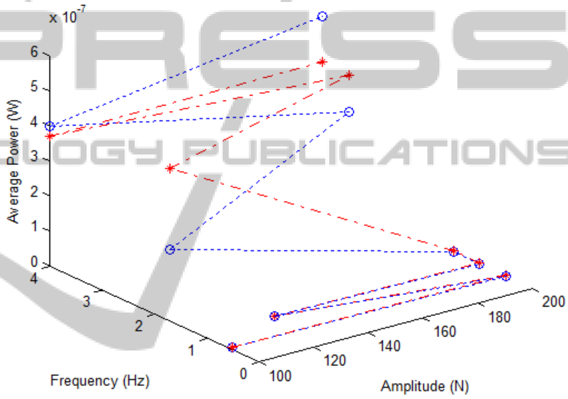

Figure 16: Validation of the average power harvested from the PEH transducer (dash-dot line refers to the network output).

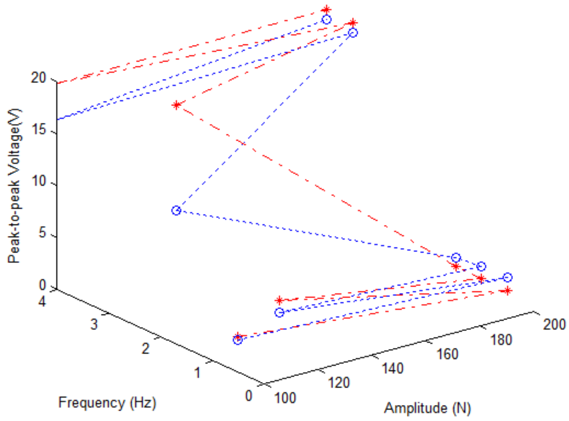

Figure 17: Validation of the voltage harvested from the PEH transducer (dash-dot line refers to the network output).

methodology to suffice the electrical power needs of smart hip prosthesis. According to Morais et al. (2011), a total energy consumption of about 360 μJ with an average power of 1.21 μW is required to power a telemetric system of a hip prosthesis for a working period of 300 seconds. Three transducers provide electric energy to supply a telemetry system, but they also ensure the availability of the electric supply, underlining the development of optimized electric power harvesting elements from multiple energy sources, towards the design of a new concept of smart hip prosthesis based on its lifetime extension. However, experimental results show that each transducer must be optimized in order to maximize electric generation during typical walking speeds, namely in the range between 0.5 Hz and 2 Hz, and to allow the osteointegration monitoring as well as mechanical micro-stimulation. Due to the tracking performance of the control operations of the testing machine, a small loosening between the acetabular component and the femoral head occurs when the current force is near to zero in the tracking of sinusoidal trajectories. This explains the higher values of the voltage harvested from the PEH transducer for 100 N of amplitude over higher amplitudes for the same frequency. The developed models for the electromagnetic transducers do not perfectly represent all possible dynamics of the electric power generation process. More accurate models are being designed to carry out optimization programs. The piezoelectric transducer must be redesigned to remain attached to the hip prosthesis but its dynamic behaviour should not be significantly affected by the mechanical properties of the implant. Also note that the energy profiles must be simulated and measured under *in-vitro* and *in-vivo* realistic conditions.

Although the power harvested from the TEEH transducer is dominant over the other transducers, all the three bio-generators are being optimized in order to maximize its ability to harvest energy from the human motion. The development of efficient power management modules is outside the scope of this study.

3.4.1 Optimization of the TEEH Generator

The major problem of this transducer is the matching between the frequency range of the hip kinematics of patients and the resonant frequency of this bio-generator. A possible solution to this problem is the development of a broadband energy harvesting that must carry out the power maximization over all the frequency range of the hip joint kinematics. Another problem of this transducer is the use of a coil spring, because the spring constant decreases over time during operation, which can jeopardize the autonomy of the smart hip prosthesis. Magnetically levitated generators are a potential solution for this specific situation, which must however be designed for a broadband application.

3.4.2 Optimization of the REEH Generator

A constant magnetic field and an average radius for the coils were assumed in the model presented in section 2.4.1. However, the magnetic field, produced by the several magnets put in the acetabular component, is neither constant nor uniform, which makes expression 7 for the voltage generation a highly nonlinear function. On the other hand, the magnets are at a distance from the winding such that the magnetic field over the winding is very low.

Several issues must be considered in order to maximize the generation of electric power by this transducer: (1) minimize the distance between the magnets and the winding; (2) maximize the radius of the winding and the number of wire turns; (3) setup concave magnets in order to ensure a uniform magnetic field; (4) setup a core of a material with very high relative permeability; (5) development of a transducer design based on a broadband approach.

3.4.3 Optimization of the PEH Generator

The piezoelectric transducer was designed with only a single piezoelectric element, which resonant frequency is much higher than the frequency of the hip joint kinematics. The presented piezoelectric harvesting is not based on a cantilevered broadband vibro-impacting power transducer methodology, which performs high vibration frequencies after mechanical impacts. Besides, the installation of a stack of piezoelectric elements with much lower resonant frequency and performing as a broadband energy harvesting must be considered in order to multiply the generation of electric energy.

4 CONCLUSIONS AND FINAL REMARKS

The development of smart prosthesis is a rising trend of the concept of instrumented prosthesis. In the case of the hip prosthesis, expertise methodologies are claimed to be developed in order to preventively fix the loosening problem during the lifetime of the implant in order to avoid revision procedures. The first demand to achieve this goal is the design of energy harvesting elements to electrically supply the telemetric systems and the design of active mechanisms that can preventively fix the loosening problem. This paper reports the first study about the development of an energy harvesting system from multiple sources for smart hip prosthesis. Considering the energy obtained from the movement as the most abundant in the human body, three energy harvesting power bio-generators, namely a piezoelectric-based and two electromagnetic-based harvesting elements, were designed to harvest energy from several movements over the femoral component. They were able to produce energy to supply the power needs of a telemetric system. This approach ensures the availability of the electric power supply and operates autonomously, safely and without maintenance during the lifetime of the hip prosthesis. An ongoing optimization of the harvesting elements is being conducted in order to improve the electric power bio-generation up to levels required by the active actuators that would prevent the aseptic loosening.

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REFERENCES

Alpuim, P., Filonovich, S., Costa, C., Rocha, P., Vasilevskiy, M., Lanceros-Mendez, S., Frias, C., Marques, A., Soares, R., and Costa, C. (2008). Fabrication of a strain sensor for bone implant failure detection based on piezoresistive doped nanocrystalline silicon. *Journal of Non-Crystalline Solids*, 354:2585–2589.

Beeby, S., Tudor, M., and White, N. (2006). Energy harvesting vibration sources for microsystems applications. *Measurement Science and Technology*, 17:R175–R195.

Beeby, S. and White, N. (2010). *Energy Harvesting for Autonomous Systems*. Artech House, Norwood, MA, EUA.

Carmo, J., Ribeiro, J., Silva, M., Goncalves, L., and Correia, J. (2010). Thermoelectric generator and solid-state battery for stand-alone microsystems. *Journal of Micromechanics and Microengineering*, 20:1–8.

Cook-Chennault, K., Thambi, N., and Sastry, A. (2008). Powering mems portable devices a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems. *Smart Materials and Structures*, 17:1–33.

Damm, P., Graichen, F., Rohlmann, A., Bender, A., and Bergmann, G. (2010). Total hip joint prosthesis for in vivo measurement of forces and moments. *Medical Engineering & Physics*, 32:95–100.

duToit, N., Wardle, B., and Kim, S. (2005). Design considerations for mems-scale piezoelectric mechanical vibration energy harvesters. *Integrated Ferroelectrics*, 71:121–160.

Frias, C., Reis, J., e Silva, F. C., Potes, J., Simões, J., and Marques, A. (2010). Polymeric piezoelectric actuator substrate for osteoblast mechanical stimulation. *Journal of Biomechanics*, 43:1061–1066.

Gilbert, J. and Balouchi, F. (2008). Comparison of energy harvesting systems for wireless sensor networks. *International Journal of Automation and Computing*, 5(4):334–347.

Graichen, F., Bergmann, G., and Rohlmann, A. (1999). Hip endoprosthesis for in vivo measurement of joint force and temperature. *Journal of Biomechanics*, 32:1113–1117.

Heinlein, B., Graichen, F., Bender, A., Rohlmann, A., and Bergmann, G. (2007). Design, calibration and pre-clinical testing of an instrumented tibial tray. *Journal of Biomechanics*, 40:S4–S10.

Heinlein, B., Kutzner, I., Graichen, F., Bender, A., Rohlmann, A., Halder, A., Beier, A., and Bergmann, G. (2009). ESB clinical biomechanics award 2008: Complete data of total knee replacement loading for level walking and stair climbing measured in vivo with a follow-up of 610 months. *Clinical Biomechanics*, 24:315–326.

Ida, N. (2004). *Engineering Electromagnetics*. Springer, New York, 2nd edition.

Kalogirou, S. (2000). Applications of artificial neural-networks for energy systems. *Applied Energy*, 67:17–35.

Kaźmierski, T. and Beeby, S. (2011). *Energy Harvesting Systems - Principles, Modeling and Applications*. Springer, New York, EUA.

Kerzenmacher, S., Ducrée, J., Zengerle, R., and von Stetten, F. (2008). Energy harvesting by implantable abiotically catalyzed glucose fuel cells. *Journal of Power Sources*, 182:1–17.

Kurtz, S., Ong, K., Lau, E., Mowat, F., and Halpern, M. (2007). Projections of primary and revision hip and knee arthroplasty in the united states from 2005 to 2030. *The Journal of Bone and Joint Surgery (American)*, 89(4):780–785.

Lu, M., Zhang, G., Fu, K., Yu, G., Su, D., and Hu, J. (2011). Gallium nitride schottky betavoltaic nuclear batteries. *Energy Conversion and Management*, 52:1955–1958.

Marcelli, E., Scalambraa, F., Cercenelli, L., and Plicchi, G. (2007). A new hermetic antenna for wireless transmission systems of implantable medical devices. *Medical Engineering & Physics*, 29:140–147.

Marschner, U., Grtz, H., Jettkant, B., Ruwischa, D., Woldt, G., Fischer, W., and Clasbrummel, B. (2009). Integration of a wireless lock-in measurement of hip prosthesis vibrations for loosening detection. *Sensors and Actuators A: Physical*, 156:145–154.

Morais, R., Frias, C., Silva, N., Azevedo, J., Serôdio, C., Silva, P., Ferreira, J., Simões, J., and Reis, M. (2009). An activation circuit for battery-powered biomedical implantable systems. *Sensors and Actuators A: Physical*, 156:229–236.

Morais, R., Silva, N., Santos, P., Frias, C., Ferreira, J., Ramos, A., Simões, J., Baptista, J., and Reis, M. (2010). Permanent magnet vibration power generator as an embedded mechanism for smart hip prosthesis. *Procedia Engineering*, 5:766–769.

Morais, R., Silva, N., Santos, P., Frias, C., Ferreira, J., Ramos, A., Simões, J., Baptista, J., and Reis, M. (2011). Double permanent magnet vibration power generator for smart hip prosthesis. *Sensors andActuatorsA: Physical*, In Press, Corrected Proof.

Morlock, M., Schneider, E., Bluhm, A., Vollmer, M., Bergmann, G., Müller, V., and Honl, M. (2001). Duration and frequency of every day activities in total hip patients. *Journal of Biomechanics*, 34:873–881.

Priya, S. and Inman, D. (2009). *Energy Harvesting Technologies*. Springer, New York, USA.

Puers, R., Catrysse, M., Vandevoorde, G., Collier, R., Louridas, E., Burny, F., Donkerwolcke, M., and Moulart, F. (2000). A telemetry system for the detection of hip prosthesis loosening by vibration analysis. *Sensors and Actuators A: Physical*, 85:42–47.

Renno, J., Daqaq, M., and Inman, D. (2009). On the optimal energy harvesting from a vibration source. *Journal of Sound and Vibration*, 320:386–405.

Rohlmann, A., Graichen, F., Bender, A., Kayser, R., and Bergmann, G. (2008). Loads on a telemeterized vertebral body replacement measured in three patients within the first postoperative month. *Clinical Biomechanics*, 23:147–158.

Rowlands, A., Duck, F., and Cunningham, J. (2008). Bone vibration measurement using ultrasound: Application to detection of hip prosthesis loosening. *Medical Engineering & Physics*, 30:278–284.

Santos, M., Rolo, D., Ferreira, J., Ramos, A., and Boeri, C. (2011). Fuzzy control of a servopneumatic wear simulator of acetabular components of hip prosthesis - implementing nonlinear controllers for the angular movement of three coupled. In *Proceedings of the 8th International Conference on Informatics in Control, Automation and Robotics*, pages 155–160.

von Büren, T., Mitcheson, P., Green, T., Yeatman, E., Holmes, A., and Tröster, G. (2006). Optimization of inertial micropower generators for human walking motion. *IEEE Sensors Journal*, 6(1):28–38.

Wei, X. and Liu, J. (2008). Power sources and electrical recharging strategies for implantable medical devices. *Frontiers of Energy and Power Engineering in China*, 2(1):1–13.

Westerhoff, P., Graichen, F., Bender, A., Rohlmann, A., and Bergmann, G. (2009). An instrumented implant for in vivo measurement of contact forces and contact moments in the shoulder joint. *Medical Engineering & Physics*, 31:207–213.

Whittle, M. (2007). *Gait analysis - An introduction*. Butterworth Heinemann Elsevier, 4th edition.

Winter, D. (2009). *Biomechanics and motor control of human movement*. John Wiley & Sons, 4th edition.

Zhu, D., Tudor, M., and Beeby, S. (2010). Strategies for increasing the operating frequency range of vibration energy harvesters: a review. *Measurement Science and Technology*, 21:1–29.