

Analysis of an Electromechanical Generator Implanted in a Human Total Knee Prosthesis

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Abstract—This paper describes a miniaturized electromechanical generator, integrable in a human total knee prosthesis, in which the mechanical energy, related to the knee joint movement, is converted into electrical energy. This device has been conceived in order to power an autonomous sensor system, integrated into the prosthesis, able to monitor the loads on the articular surfaces and to transmit those outside the body.

Keywords—*electromechanical generator; human energy harvesting; knee prosthesis; biomedical devices; system health; biomechatronics.*

I. INTRODUCTION

The world of medical devices is rapidly expanding with the aim of improving the life-style of people. Now the orthopedic replacement of the joint knee by total knee prosthesis is considered common practice, and the increasing of the life, the monitoring of its components and the complete recovery of articular mobility are important requirements. Several complications are connected with the perfect replacement of the knee joint, especially, in order to adapt the prosthesis to patient allowing the correct articular mobility. In fact, the kinematic characteristics of implant-articular surfaces are not constant due to wear of the components, and in addition, the reduction of anchorage of the prosthesis inserts in the bones can reduce the functionality and can cause patient's grief. This brings to replacement of the implant with a new one, but its performances will be inferior and the rehabilitation of the patient longer. The prosthesis design has to improve in order to reduce the consequences of the system alteration. A possible improvement is to allow the doctor to monitor in-vivo the working condition of a prosthesis, with more benefits: a reduction of the wear due to an incorrect use, a better patient rehabilitation and a data collection to improve the future design of the prosthesis. It is evident that this goal requires the correct understanding of the distribution of the forces on the articular surfaces. The research group valued the possibility to measure the forces on the tibial plate with an electronically instrumented prosthesis, in which the forces are measured and transmitted in wireless modality. In order to make completely autonomous and free from external power supply this device, at the moment, our research is interested to insert within the knee prosthesis an autonomous system able to generate and store

electrical energy using mechanical energy disposable in the human knee joint.

II. ENERGY SCAVENGING FROM THE HUMAN KNEE MOVEMENT

A. System description

The kinetic energy of the human movement has an average value, theoretically, more than sufficient in order to allow the operational requirements of the electronic device (a few mwatts). The discontinuity of the human movement and the small value of the principal frequency of its energetic spectrum do not allow an efficient harvesting of the mechanical energy. Many devices have been conceived with the aim of scavenging mechanical energy of the human movement. Mechanical energy conversion into electrical energy is obtained, predominantly, by piezoelectric and electromagnetic devices. The disadvantage of the first one is a small value of energy generated for unity of volume, while the second one has an important difficulty connected with the physical conversion principle. This solution has a limit just in these circumstances: the resonance working conditions are limited by difficulty of obtaining a small natural frequency for a small mechanical device, in which, in the hypothesis of a linear model, the resonant frequency reduction requires an increase in mass and softness of the spring. Whereas, the physical dimension reduction of the devices brings to the stiffening of elastic linkage and to the mobile component reduction in mass. In the literature, several solutions have been reported to overcome this problem. For example, a multi-resonance system can be employed in order to optimize the operational requirements. Alternatively, the use, for the linkage suspension, of a material with non-linear elastic characteristics can be adopted in order to introduce more parameters in the design. A typical electromagnetic solution is the design of a mechanical system, in which there is a magnet oscillating inside a coil (or vice), in resonance conditions. In this paper, a novel knee-implanted electromechanical generator will be shown. It is completely different, in our opinion, by the devices that are in the literature. The proposed device has the advantage of converting the relative motion of the tibial and femur inserts of the total knee prosthesis directly into electrical energy without the

movement of any device. The basis of the idea is very simple: in the thickness of the titanium surfaces of each condyle, a series of prismatic magnets is placed with the magnetic axis parallel to surface of tibial plate. Between the two condyles, in a prominence of tibial plate, is realized a cavity in which two cylindrical coils of copper wire with their axis parallel to the magnetic axis are inserted. In this way, the relative motion between femur and tibia, correspondent to the relative motion of magnets and coils, induces on the coils a potential difference according to Faraday- Neumann-Lenz's law. In order to obtain a first estimate of the capabilities of the device it was decided to perform a finite element electromagnetic simulation and a tridimensional CAD model of the total knee prosthesis was designed (Fig. 1). After a discussion of the parameters that affect the relative movement of the tibial and femoral inserts, a linkage was created with the aim to play a motion, as more as possible, corresponding to the real one. The design of this solution, then, will be used to make a prototype to obtain experimental results.

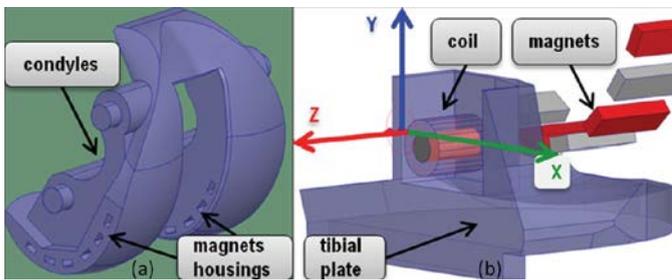


Figure 1. Femoral insert (condyles) of the knee prosthesis and a section, in the x-y plane, with the component of the electromagnetic generator.

B. Design of the tridimensional model and qualitative synthesis of the kinematic chain to simulate the motion of the prosthesis

Before simulating the electromotive force induced in the coils, a 3D-model of the system is required. The femoral component is designed first, and then the polyethylene insert of tibial component is obtained. In order to obtain the geometry of the prosthesis, a series of measures was measured manually using a gauge. Afterwards, the shape of the prosthesis was obtained, using a 2D-CAD, using the following method [1]. An appropriate sequence of photos of the different views of the prosthesis was edited in the software with the aim to obtain a correspondence with the measured dimensions. Once the exact correspondence was obtained, the images were used to reconstruct 3D model geometry. In the thickness of the contact zone of each condyle, six prismatic housings contain six magnets of the same shape. In Fig. 2, a stage of the reverse engineering of the system is reported: the two circles on the left enwrap the articular surfaces of the condyles in the sagittal plane, and the two circles on the right enwrap the articular surfaces in the frontal plane. At the moment, the changes to model of the real prosthesis are limited only to the housings of the coils and the magnets. The magnets inserted in the thickness of each condyle are positioned in threes along the arcs of those circles. In the element of the tibial plate, prominent respect to its contact surface with the condyles, the coils' housing is realized, whose dimensions are reported in

Table I. The exact reproduction of the movement of the knee prosthesis is a complex project that would take into account the constraints due to residual ligaments, but, at least at this stage of research; this approach is not justified. The proposed device consists of a crank-rocker arm four bar linkage. The crank-rocker arm is the easiest mechanism that allows making a roto-translation similar to that occurring in the real prosthesis during the same angle of relative rotation between the femoral and tibia parts. In Fig. 3, it is shown the centre of rotation "O" of the crank, directly connected to the drive axle, the connecting rod "AB", i.e. the femoral portion of the prosthesis, the centre "O¹" of the rocker arm and the frame of the four bars linkage "OO¹".



Figure 2. A stage of the reverse engineering of the prosthesis.

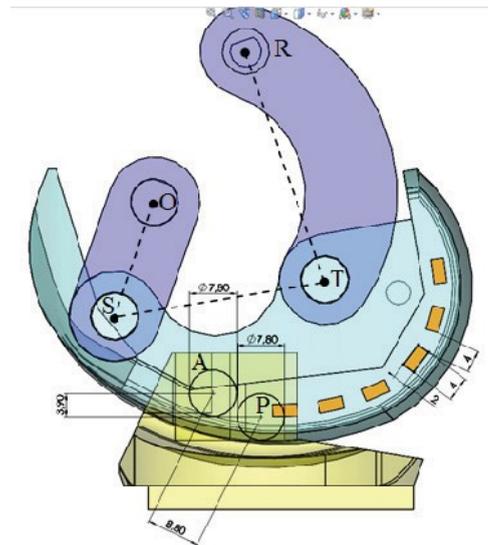


Figure 3. Motion system of the knee prosthesis.

TABLE I. GEOMETRICAL DIMENSIONS OF THE ELECTROMECHANICAL SYSTEM

Component	Dimensions	
	Parameter [units]	Value
Magnet	(length,height,width); [mm]	(4,2,13)
Coil A	(diameter,length); [mm]	(7.80,13.6)
Coil P	(diameter, length); [mm]	(7.80,17.9)

III. FINITE ELEMENTS ELECTROMAGNETIC SIMULATION (FEES). RESULTS AND CONSIDERATIONS

The simulation has been conducted considering a flexion of approximately sixty degrees during the swing phase of the gait

cycle. This rotation is possible also in normal activity of people with TKA [2-3-4]. The biomechanical analysis of the relative movement of the tibial and femoral inserts [5-6] shows that the relative motion of the inserts is too difficult. In particular, during the rotation, also a translational movement exists. In order to obtain a dynamical analysis to evaluate the rate of change of magnetic flux induced on the coils, a selection of the most popular software for FEES has been examined. We concluded that is possible to simulate the relative motion of a magnet respect to a coil only if their relative motion is purely rotatory or translational. Therefore, in order to recreate a situation, as more as possible, corresponding to the real one, an alternative path was decided. Using the possibility of movement animation offered by the 3D CAD software, the motion of the system, reproduced by the kinematic chain described before, was discretized. Full rotation has been divided into small steps of 5 degrees each. Subsequently, in each configuration that the system occupies at the end of each step, a magnetostatic simulation of the induction field linked with each solenoid has been carried out. In this initial phase, the analysis regarded the evaluation of the electromotive force induced during the passage of the magnet only in a single coil (coil A of Table I). The permeability of the magnetic circuit has been augmented using two coils with a ferromagnetic core. The copper coil used in this simulation has five hundred turns, and the diameter of the wire is 0.1 mm. The magnets have the characteristics reported in the Table II.

TABLE II. PHYSICAL CHARACTERISTICS OF THE MAGNETS

Material	Dimensions	
	Parameter [units]	Value
NdFeB (Neodymium N45)	Residual Induction B_r ; [mT]	1320-1380
	Coercive force; [kAm^{-1}]	923
	Intrinsic coercive force; [kAm^{-1}]	955
	Energy product $(BH)_{max}$; [kJm^{-3}]	342-366
	Max operating Temperature; [$^{\circ}C$]	80

Their positioning in the condyles is realized with the magnetic axis parallel to the z-axis of the Fig. 1. In particular, the magnets, whose housing are aligned in the two condyles, have the same polarity, while the two adjoining magnets, on the single condyle, have reverse polarity. This positioning was selected for a bigger variation of the magnetic induction field on the coil. Supposing possible a variation of the magnetic induction field in all the turns of the coil, it was necessary to try a method for the determination of the total flux in the solenoid. This problem was approached in two steps. A first calculation was executed evaluating the flow produced on three particular sections of the solenoid. Fig. 4 shows, in particular, the diagram of the magnetic flux induced in such a single section, in each single angular step. The different curves are referred to three particular sections of the solenoid, showed in the little box: $S_{(versor\ k)}$ is the surface of the solenoid whose normal versor is the versor k (similarly for $S_{(versor\ -k)}$), and $S_{(x-y)}$ is the section in the sagittal plane, which is a symmetry plane for the solenoid.

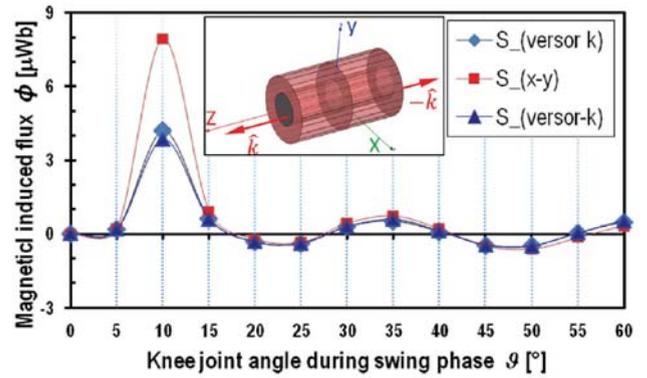


Figure 4. Function trend of magnetic flux, induced on three sections of the solenoid, indicated in Figure, in different angular positions of the magnets respect to coil A.

A preliminary diagram analysis confirms the oscillating variation of the flux, due to reverse polarity of the couples of magnets. This figure shows, also, that the stray flux on the solenoid is very little, in fact, the values of the flux on the two $S_{(versor\pm k)}$ sections are practically coincident, but if the analysis had been limited to the two $S_{(versor\pm k)}$ sections, the interpretation of the situation would have been incomplete. In fact, a particular situation was observed in the configuration relative to the position 10° (Fig. 4): in this configuration, the flux induced in the $S_{(x-y)}$ section is twice respect to flux on the $S_{(versor\ k)}$ and $S_{(versor\ -k)}$ surfaces.

An analysis of this situation, using a 3D representation of the magnetostatic induction field is reported in Fig. 5.

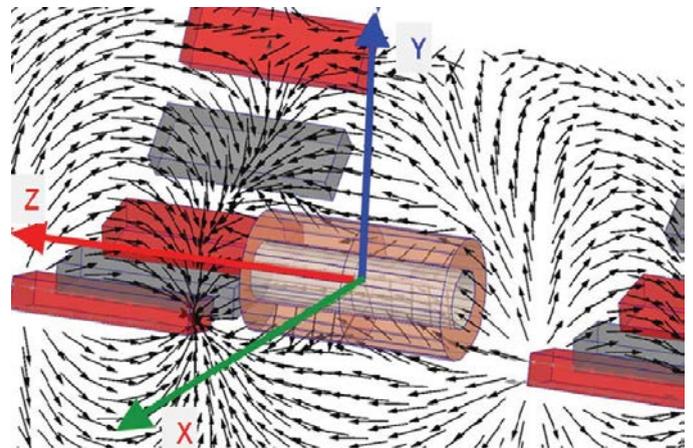


Figure 5. Flow map of the magnetic induction field in the axial plane $y-z$, related to a rotation of 10° of the magnets. It has been pointed out a bigger density of the flow lines in proximity of the $x-y$ plane of the solenoid. The red magnets have the magnetic axis with the same sense and direction of z -axis while the gray magnets are opposite in sense.

Observing Fig. 5, it has been pointed out that the flow lines are addensed in the $S_{(x-y)}$ section; a possible interpretation of this situation was that, on the proximity of the right-hand side of the solenoid, the lines of force of the red magnet on the right, part make for the core of the solenoid, part make for the outside. Going to the middle plane ($x-y$) the second red magnet

on the left, aligned with the first one, attracts the lines, which become thicker in the (x-y)-section of the coil, so and the flux on this section increase. Carrying on the left-hand side of the solenoid, the effect of the magnet on the left is reduced by the effect of the gray magnet near this one, and the lines of force thin out, reducing the flux on the $S_{(versor k)}$ section. The second step, used to evaluate the total flow was to calculate the trend of the component B_{z_a} (of the magnetic induction field, perpendicular to the sections of the solenoid) as a function of the z-coordinate valued on its axis. This value should provide a good fraction of the total flux induced on each section. The values of this component along the z-axis of the solenoid, referred to the 10° configuration, are reported in Fig. 6. In particular, in this figure, in order to evaluate the variation of B_z along the diameter of the sections, there are three diagrams that are referred to the three following segments: $g1$ and $g2$ that are two generatrices of the ferromagnetic core of the solenoid, and the axis a of the solenoid. The analysis of these diagrams confirms, first of all, the symmetry of the problem and, observing the different scale of the B_{z_g1} and B_{z_g2} respect to B_{z_a} , it is evident the strong variation of the B_z component in the radial direction. In addition, the peak of the absolute value of the B_z component, in correspondence of the middle section (Fig. 6, $z=0$ mm), explains the result of Fig. 4, obtained in the first step of the computation, where the flux on the middle section is bigger than it on the $S_{(versor \pm k)}$ sections, i.e. at the coordinates z_1 and z_2 , in which the absolute value of B_z shows always the minimum value on the z-axis.

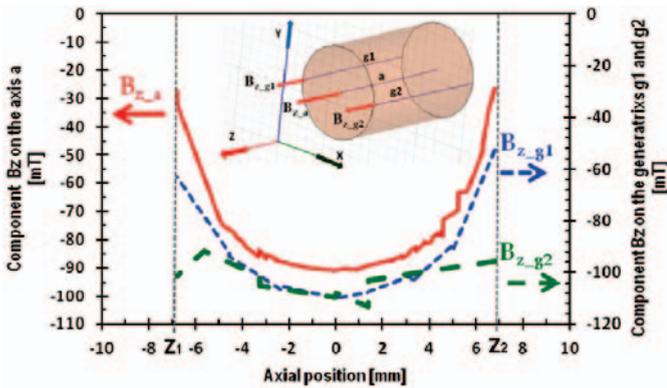


Figure 6. Function trend of z-component of the magnetic induction field on the coil A in the 10° configuration. The solenoid is positioned along z-axis between the coordinates z_1 and z_2 .

A next study will be conducted in order to obtain a method able to calculate the total flux induced in the different turns of the coil. In fact, the total flux, in each single angular configuration, could be evaluated, proximately, using the following expression,

$$\phi(\theta) = \frac{N \cdot A}{L} \cdot \int_{z_1}^{z_2} B_z dz \quad (1)$$

where $\phi(\theta)$ is the total linked flux induced in the solenoid, in the generic θ configuration, N is the total turns number, A is

the surface of each section (supposed constant), L is the length of the solenoid along z-axis, between the z_1 and z_2 positions (Fig. 6). In the expression (1), using the previous considerations, the B_z components will be the B_{z_a} values related to the θ configuration, in particular in the 10° configuration the values are those of Fig. 6. The next step will be the evaluation of the electromotive force expressed, theoretically, by the equation of *Faraday-Newmann-Lenz's law* of electromagnetic induction,

$$V = -\frac{\partial \phi}{\partial t} \quad (2)$$

where V is the electromotive force. In order to obtain a relationship of the flux as a function of the time t , it is necessary to know the variation of the knee joint angle θ during the considered rotation. In Fig. 7, the knee joint flexion is represented during the gait cycle.

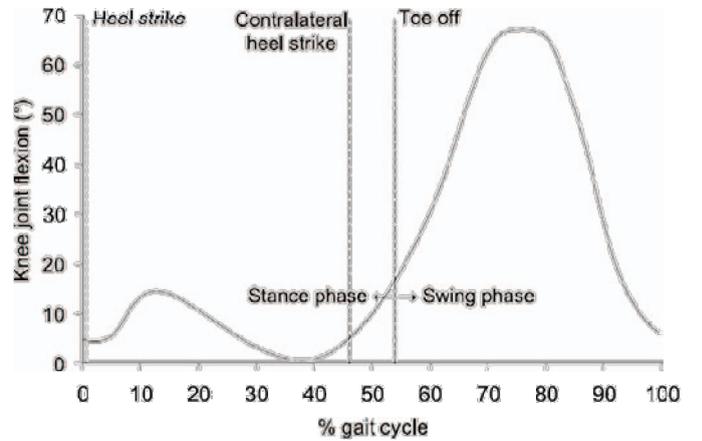


Figure 7. Knee joint flexion during gait cycle (reported in [2]).

Limiting the rotation near to swing phase, one can observe that, proximately, the complete rotation of sixty degrees occurs in the 25% of the gait cycle. Assuming the duration of the gait cycle of about 1.5 s, an average angular velocity of 160 degrees per second can be obtained. Using these results the equation (2) can be rewritten as follows,

$$V = -\frac{\partial \phi}{\partial t} = -\frac{\partial \phi}{\partial \theta} \cdot \frac{d\theta}{dt} \approx -\frac{\partial \phi}{\partial \theta} \cdot \omega_{avg} \quad (3)$$

where $\omega_{avg}=160^\circ/s$ and $\partial \phi / \partial \theta$ can be deduced by a diagram, similar to those in Fig. 4, but obtained using the relation (1) for the computation of the value of $\phi(\theta)$ in each angular position.

IV. CONCLUSIONS

The presented results will be the subject of a forthcoming analysis in order to complete the evaluation of the electromotive force, in particular, in order to determine both the best positioning of the magnets and the coils; a parametric

analysis will be necessary. Furthermore, in order to obtain a validation of the simulation, a prototype of the system and a series of measures will be conducted. Contemporaneously, a study concerning the electronic system of storage and management of the power produced is in progress.

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REFERENCES

- [1] P. Conti, "Disegno di un dispositivo per la generazione di energia elettrica dal movimento del corpo umano", Brescia: Tesi di Laurea specialistica, 2010.
- [2] S. D. Masouros, A. M. J. Bull, A. A. Amis, "Biomechanics of the knee joint", Orthopaedics and Trauma Elsevier, pp. 84-91, 2010.
- [3] C. M. Powers, S. Rao, J. Perry, "Knee kinetics in trans-tibial amputee gait", Gait and Posture Elsevier, vol. 8, pp. 1-7, 1998.
- [4] K. M. Lee, J. Guo, "Kinematic and dynamic analysis of an anatomically based knee joint", Journal of Biomechanics, vol. 43, pp. 1231-1236, 2010.
- [5] B. C. Carr, T. Goswami, "Knee implants – Review of models and biomechanics", Material and Design, vol. 30, pp. 398-413, 2009.
- [6] G. L. Hatfield, C. L. H. Kozey, J. L. A. Wilson, M. J. Dunbar, "The effect of total knee Arthroplasty on knee joint kinematics and kinetics during gait", The Journal of Arthroplasty, vol. 00, 2010.