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Piezoelectric Load Measurement Model in Knee Implants*

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Abstract— **This paper explores the feasibility of a new sensing platform for knee implant diagnostics. The proposed unit measures force and transmits the reading information wirelessly to an external receiving unit. This device is to be located in the tibial tray of the knee implant. The system measures force through the use of piezoelectric elements housed in the insert. At the same time, the piezoelectric material can generate enough energy to transmit the measurements without requiring batteries. Only the modeling of the piezoelectric voltage output is discussed at present. The force measurement can provide useful information about ligament balance while helping in the post-operative physical therapy.**

I. INTRODUCTION

Total knee arthroplasty (TKA) or total knee replacement (TKR) is a surgical procedure that substitutes the load-bearing surfaces of the knee joint, mostly because of osteoarthritis. This degenerative joint disease is characterized by severe pain and immobility due to the degradation of articular cartilage. Currently, more than 400,000 TKA are done worldwide each year [1], with more than 250,000 performed in the US alone [2]. Most of the surgical procedures involve adults 65 years and older (67% of the cases). Although the implants are designed to last for more than 20 years, there are premature failures. It is estimated that around 3% of them fail each year because of joint loosening or component failure, and there is 1-2% that require inspection due to complications, mostly because of infections [3]. Nowadays, revision surgery typically accounts for up to 8% of all TKA operations [2]. The revision surgeries of the TKA involve higher complication rates (are more traumatic than first-time surgeries), and implicate higher medical costs, around $74,000 [3]. By 2050 over 20% of the US population will be over 65 years old; it will account to almost 30% for Europe and near 40% for Japan (Table I). According to these demographic trends, in order to keep the associated costs controlled, improvements in implant designs and surgical techniques will be required.

TABLE I. ADULTS 65 YEARS AND OLDER [4]

Region	Population Percentage[a]		
	1950	2000	2050
USA	8.3	12.4	21.6
Europe	8.2	14.8	27.4
Japan	4.9	17.2	37.8
World	5.2	6.8	16.2

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TKA revisions are mainly associated with infection, loosening, and instability [5-7]. Although loosening can also be produced by infection, aseptic loosening is the implant loosening due to the plastic debris (produced by the wear of the plastic bearing insert) that reacts with the surrounding tissue. Instability happens when the ligament's balancing is not adequate. This is usually translated into a TKA revision with a more complex knee replacement that compensates for this imbalance. Thus, early detection of premature wear or instability failure would help to reduce trauma as well.

When analyzing wear on TKR implants, level walking is defined as the most important activity with ground reaction forces (GRF) reaching values of 1.1-1.2 times the body weight (BW). But little is known about the biomechanical information in more demanding body activities, such as climbing (GRF up to 1.4 BW) or descending stairs (GRF up to 1.8 BW) [1]. Most of this information is gathered using instrumented stair cases to analyze the transferred loads. The recordings can show if there is ambulation variability and/or asymmetry loading between limbs during gait. In addition, strain gages and thin-film pressure transducers have been applied to bone implants. This has been performed to study the load transfer mechanism from the femur to the tibia. Such systems would need to be functional for the implant duration, more than 20 years. However, a battery autonomous system is limited to a lifespan on the order of 10 years (as the case for cardiac pacemakers) [8] or even less. That is why most of the approaches to date rely on battery-less telemetry systems. This technique requires the use of two antennas, for transmission of power and another for transmission of information [9]. A recent study, using a telemetry instrumented knee implant, showed that a force of 2.5 BW acts on the joint when walking and up to 3.5 BW when descending stairs [10]. Still, the devices are limited to monitor the knee load dynamics when connected to an external receiver under controlled conditions, not for everyday use. Hence, specialized instrumentation is required to study knee implant behavior under varied circumstances.

A traditional knee implant has a metallic femoral component, a metal tibial tray, and a low friction bearing surface insert made of ultra-high molecular weight polyethylene (UHMWPE) [6], as shown in Fig. 1. The body load is transmitted from the metallic femur component to the polyethylene bearing to the metal tibial tray. The femoral and tibial components require bone resection to accommodate the implant. A round shaped implant is used for the femur (mimicking the bone shape) while a flat surface is used for the tibial insert (often a stem is used for bone implantation). As the bone removal is kept to a minimum, there is little space to insert electronics. In addition to the transmission of vertical forces (from the femur to the tibia), the force should be balanced on the tibial plate (side-to-side and front-to-

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back). Instability in TKA has been previously studied and concluded that imbalance is detrimental on long-term survival in TKR [11-13]. A former study measured the pressure distribution across the tibiofemoral joint in TKA [11]. This work categorized the pressure distribution patterns in four categories: normal, varus-valgus instability, rotational misalignment, and combination of malrotation and instability, as shown in Fig. 2. Therefore, the knowledge of force distribution on the tibial tray can be used by surgeons as a technique to evaluate early ligamentous instability.

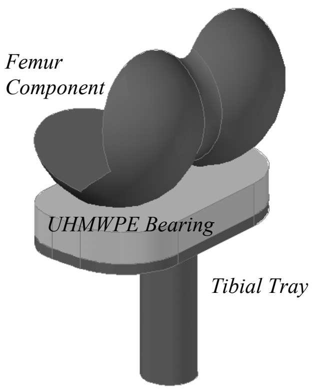

Figure 1. Schematic of a total knee replacement implant

Since telemetry systems need to be attached to the sensors in order to provide energy and data collection, usually under controlled conditions, it is desirable to use autonomous devices for this operation. The generation of energy using piezoelectric elements has been well documented for biomedical applications [14,15]. One of the advantages of using piezoelectric materials, in addition to its relatively small size, is that the voltage produced depends on the load applied. When a load is applied to a piezoelectric material, a voltage proportional to the load is generated. Attached electronics can record and/or transmit regularly the measurements gathered which is well suited for long term studies. This work proposes a grid of 56 load sensors (Fig. 3) capable of determining the contact pressure zones described in Fig. 2 due to the joint instabilities.

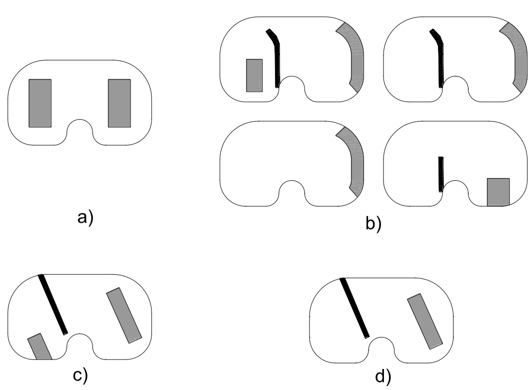

Figure 2. Schematic representation of the contact pressure at the knee joint described by [11], a) for normal pressure distribution, b) for varus-valgus instabilities, c) for malrotation, and d) for instability and malrotation. Darker shading indicates higher contact pressure.

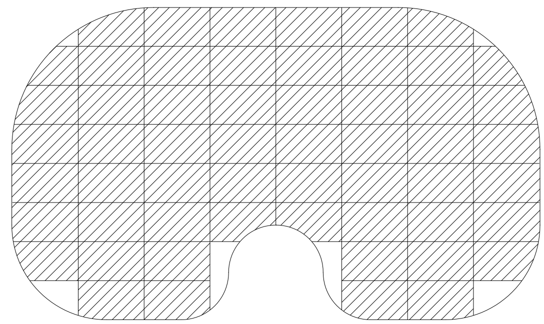

Figure 3. Proposed pressure sensor areas on the tibial tray

Although a previous study showed that energy generation from knee implants is possible [2], this research proposes piezoelectric elements (as load sensors and energy generators) for force distribution determination. The objective is to determine the characteristic loading in order to evaluate knee implant misalignment during the implant's lifetime. This can help surgeons to evaluate the evolution of TKA patients early on.

II. PIEZOELECTRICITY

Piezoelectric materials are capable of transforming mechanical energy into electrical energy when a mechanical load is applied. Conversely, strain or mechanical deformation is obtained when electrical energy is applied. The relationship between mechanical and electrical domain was standardized by the IEEE Standard on Piezoelectricity. The tensor equations that constitute piezoelectric materials are commonly presented as

$$\{S\} = [s^E]\{T\} + [d]\{E\} \quad (1)$$

$$\{D\} = [d]\{T\} + [\varepsilon^T]\{E\} \quad (2)$$

where S represents the mechanical strain, s^E is the elastic compliance (under constant electric field), D is the electrical displacement, T is the mechanical strain, E is the electric field, d is the piezoelectric strain constant, and ε^T is the dielectric constant (under constant stress). Thus, generated charge is proportional to the external stress and to the piezoelectric material properties. Noting that $S = \Delta l/l$, $D = Q/A$, $T = F/A$, and $E = V/l$, where Δl is the change in thickness, l represents the material thickness, Q the electrical charge, A the cross sectional area, F is the applied force, and V the voltage, (1) and (2) can be rearranged into

$$\{\Delta l/l\} = [s^E]\{F/A\} + [d]\{V/l\} \quad (3)$$

$$\{Q/A\} = [d]\{F/A\} + [\varepsilon^T]\{V/l\} \quad (4)$$

If a sinusoidal input force is assumed (3) and (4) can be transformed to the Laplace domain leading to

$$v = j\omega C_m F + j\omega dV \quad (3)$$

$$i = j\omega Cp\, V + j\omega dF \quad (4)$$

where v is the velocity ($d\Delta l/dt$), i is the current (dQ/dt), C_m is the short circuit compliance ($s^E l/A$), and C_p is the free capacitance ($\varepsilon^T A/l$). This is typically represented as the piezoelectric coupling diagram shown in Fig. 4 [15]. The mechanical domain is represented by the mass of the system (M_m), the stiffness ($1/C_m$), and the damping (B_m). The coupling is modeled as an ideal transformer, where the transformer ratio is $\phi = -C_m/d$ (Fig. 4a). The electrical model including the equivalent mechanical elements is presented in Fig. 4b, where $R_{em} = \phi^2 B_m$, $L_{em} = \phi^2 M_m$, $C_{em} = C_m/\phi^2$, $V_{in}=\phi F_{in}$, and $C_p' = (1-d^2/(s^E\varepsilon^T))\varepsilon^T A/l$. The system can be further modeled as containing impedances (for the equivalent mechanical elements, the piezoelectric element, and the external load. The system can be solved for V_{out} (open-circuit voltage) or for V_{Load} (adding a resistive load). As commented previously by [16], the piezoelectric properties are usually measured at frequencies on the order of 1 kHz (much higher than gait frequency). Since these parameters change with the external loading conditions, they must be found experimentally.

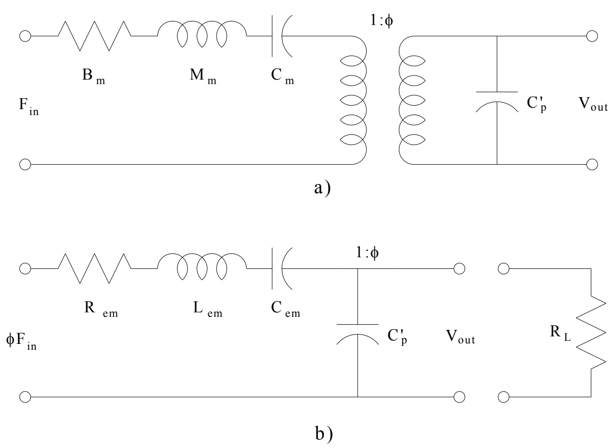

Figure 4. Representation of the piezoelectric circuit, a) Mechanical and electrical domain representation, b) Equivalent electrical representation with external load

III. Modeling

Equations (3) and (4) were solved using the input force profile according to the ISO 14243-2, shown in Fig. 5. The force profile is modeled as a polynomial whose form is $a_0 + a_1 t + a_2 t^2 + \ldots + a_n t^n$. The piezoelectric material used for the modeling is PZT type 5H. Considering that some of the parameters depend on the external loading conditions at frequencies around 1 Hz, then the experimental data is derived from [16]. Under this assumption, the open-circuit voltage for the active part of the gait cycle is modeled in Fig. 6 (A PZT 5H with dimensions of 10x10mm and 18mm thick). This model also assumes that the entire body load is transferred to one piezoelectric. The proposed model suggests up to 56 load sensors (56 piezoelectric thin blocks), then the transferred load will be much lower. It is assumed that a maximum of 8 piezoelectric sensors will be active under normal pressure load patterns. The open-circuit voltage is modeled for this condition, as shown in Fig. 7, for PZT 5H with dimensions of 10x10mm and 5mm thick. The simulated voltage output with a resistive load is shown in Fig. 8, using a matching load of 15 kΩ. Average power output is calculated as the squared RMS voltage output divided by the resistive load (V^2_{rms}/R). Power output was then calculated as 0.7 µW.

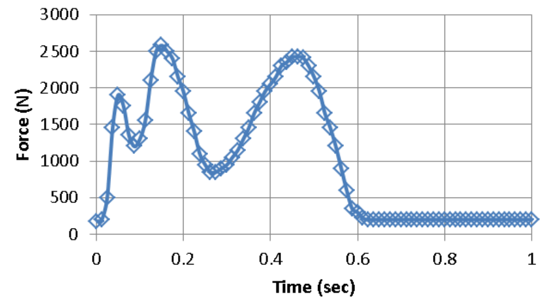

Figure 5. Axial force profile as describe by ISO 14243-2

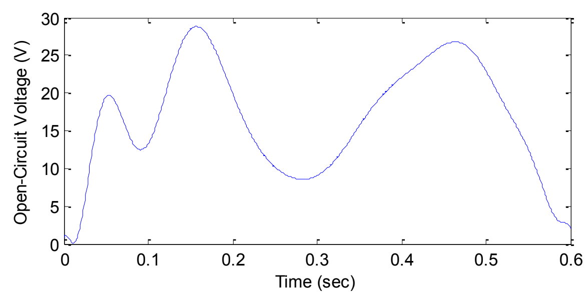

Figure 6. Mathematical model of the open-circuit voltage for one piezoelectric element under full load (V_{rms}=18V, 18mm thick)

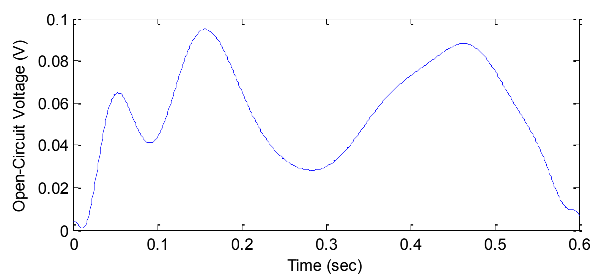

Figure 7. Mathematical model of the open-circuit voltage for one out of eight piezoelectric elements (V_{rms}=60mV, 5mm thick)

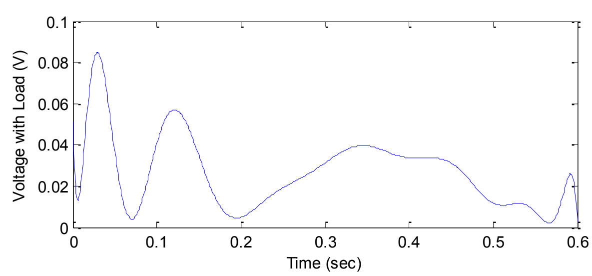

Figure 8. Mathematical model of the voltage for one out of eight piezoelectric elements for a resistive load of 15 kΩ. (V_{rms}=32mV)

The voltage output is drastically reduced when using several short piezoelectric blocks instead of one tall element. This can be observed when comparing the results shown in Fig. 6 and 7 for the open-circuit voltage. Additionally, since the voltage output of the model is lower than 100mV, rather than considering a traditional stacked piezoelectric, a monolithic design can produce a higher voltage output (at the expense of lower current and requiring a much higher matching load). Thinner piezoelectric materials generate smaller voltages than taller arrangements, but are adequate to fit inside the tibial tray. Taller designs require a thicker tibial tray, but this requires also more bone removal [16].

Energy harvesting depends on the actual system requirements. Fig. 9 presents a typical power profile for an energy harvesting system with wireless communication (transmitting and receiving). The wireless communication usually consumes the most power (a few mW) but it is used only for a fraction of the total time. Using the information presented in Table II [17], a few micro joules could be sufficient. The present system needs to account for the wireless communication power requirements (duration or duty cycle) and wireless need (on demand or transmitting regularly). Minimizing the power envelope can enhance the practicality of this sensing platform. One way to accomplish this is by using traditional telemetry for wireless interrogation and using the energy harvesting solely for powering the electronics that enable data recording for long term studies (more than 10 years).

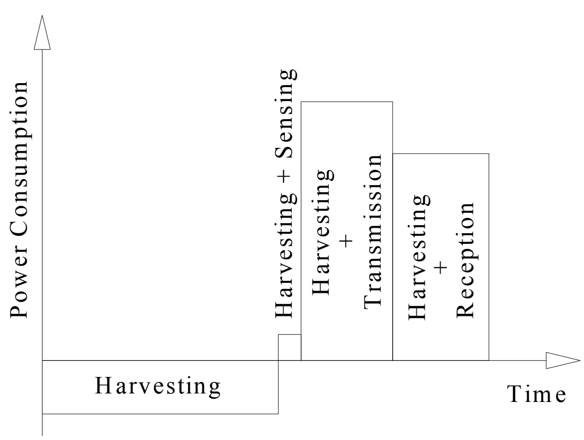

Figure 9. Typical power profile for a harvesting system [17] (not at scale)

TABLE II. ESTIMATION OF SYSTEM REQUIREMENT [17]

System Tasks	Duration (ms)	Power (µW)	Energy (µJ)
Transmission	5	5000	25
Reception	5	3750	18.75
Sensing	1	10	10
Total (500ms cycle)	500	88	44
Requirement	>440	100	44

IV. CONCLUSION

This work presented a new diagnostic technique to evaluate load distribution on knee joint implants. This information can be used as a way to evaluate early ligamentous instability on TKA patients. In addition, surgeons have also related imbalance as a source of aseptic loosening. Hence, early detection of instability can help to manage TKA revisions and trauma as well.

This paper elaborates on the modeling of a piezoelectric load transducer as well as a piezoelectric energy generator. Taller generator designs produce a higher power output but require more bone removal. Thinner designs, although providing less power, can fit better inside the thin tibial plate. On the other hand, experimental evaluation needs be performed in future studies to compare against theoretical results. Additionally, stacked and monolithic piezoelectric designs can be evaluated.

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