# Triboelectric Nanogenerator Modeling and Triboelectric Nanogenerator-Based Pressure-Sensor Interface for Implantable Total Knee Replacement

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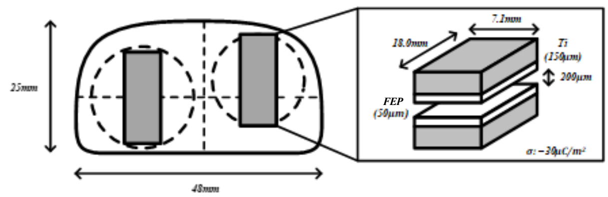
*Abstract* - **Total knee replacement (TKR) surgeries are increasing worldwide due to the aging population and the growing activity levels of middle-aged patients. Continuous monitoring of knee-joint loading is crucial for enhancing implant design, facilitating early failure detection, and informing personalized rehabilitation. Triboelectric nanogenerators (TENGs), which convert mechanical energy into electrical energy through contact electrification and electrostatic induction, are attractive for wearable and implantable electronics owing to their high energy density and mechanical flexibility. However, implantable TENGs are often limited by small surface areas and low internal capacitance, which makes energy harvesting challenging. To address this limitation, this work employs TENGs as pressure sensors rather than energy harvesters. We present a TENG model suitable for integration into TKR implants and propose a low-power sensor interface that rectifies and digitizes the signal using a dual-output rectifier (DOR) and a 10-bit SAR ADC. Under a 1-Hz gait-like excitation, the system measured force-dependent voltage responses and monotonic ADC outputs. These results show that the proposed TENG model and TENG sensor interface enable pressure/load monitoring in TKR implants.**

***Keywords*—Triboelectric nanogenerator (TENG), Total knee replacement (TKR), Implantable pressure sensor**

## I. INTRODUCTION

Total knee replacement (TKR) surgery has been steadily increasing due to an aging population and a growing number of older adults. Precise monitoring of knee joint loading is essential to ensure the long-term stability and performance of implants after surgery. Continuous monitoring offers various clinical benefits, including enhanced implant design, early detection of implant failure, and the development of patient-specific rehabilitation strategies.

Triboelectric nanogenerators (TENGs) are energy conversion devices that transform mechanical energy into electrical energy through contact electrification and electrostatic induction [1]. Thanks to their high-power density and mechanical flexibility, TENGs have shown potential for use in wearables, implantable biomedical devices, and IoT sensors. In particular, their application as self-powered pressure sensors that require no external power supply is considered a promising approach in the biomedical and implant fields. Several TENG-based pressure or load sensors have already been demonstrated in cardiovascular and orthopedic settings, such as transcatheter self-powered endocardial pressure sensors [2], bioresorbable triboelectric pressure sensors for cardiovascular postoperative care [3], and smart knee implants or TKR load-monitoring systems that employ triboelectric transducers under gait loading [4], [5]. These prior works mainly focus on transducer design, materials, and system-level feasibility, often using discrete

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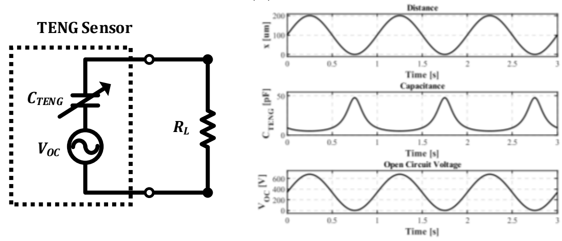


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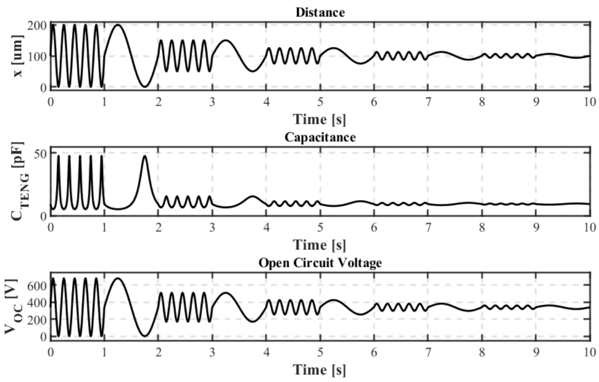


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Fig. 1. Implantable TENG sensor for TKR (a) Mechanical structure of the TENG sensor (b) Electrical model with $V_{oc}(x)$ and $C_{TENG}(x)$ driving $R_L$ (c) Modeling results for various cases according to the gait cycle and the distance

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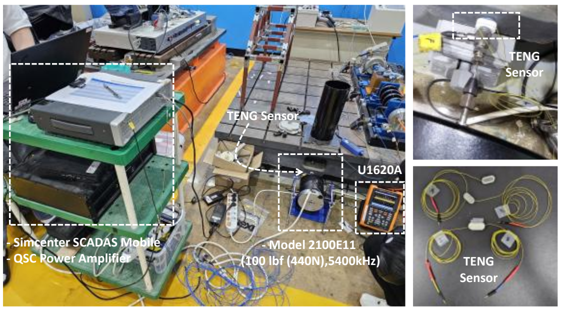


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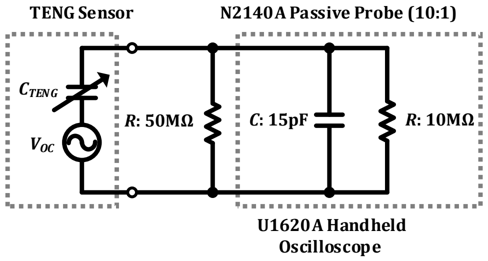


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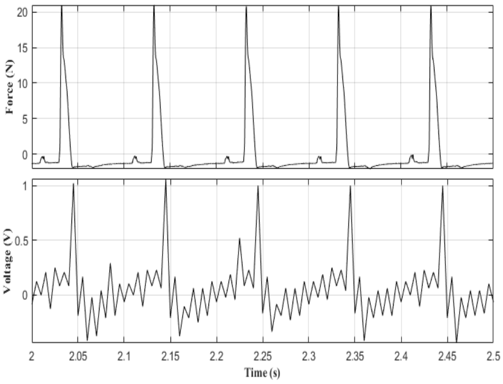


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Fig. 2. TENG sensor measurement: (a) experimental setup with electrodynamic shaker, drive electronics, and handheld oscilloscope, (b) equivalent circuit with TENG source, (c) measured shaker-applied force and TENG output voltage

or external readout electronics, with limited emphasis on a co-designed low-power integrated interface. However, implantable TENGs are often limited in size and possess low internal capacitance, which leads to challenges in energy harvesting, namely low output power and significant temporal variation. Motivated by this, this work focuses on using TENGs as pressure sensors for TKR load monitoring.

In this paper, we analyze a TENG model tailored for integration into TKR implants and propose the design of a TENG sensor interface that captures and processes the generated signal. The sensor interface is implemented and simulated using a 180 nm BCD process. In contrast to prior TENG-based pressure-sensor systems, this work focuses on the circuits-and-systems-level co-design of a TKR-oriented TENG model and a low-power dual-output rectifier plus 10-bit SAR ADC interface optimized for 1 Hz gait-rate and sub-μW operation. Section II analyses the modeling of the implantable TENG for TKR applications and presents the design of the interface circuit. Section III discusses the simulation results, and Section IV concludes this work.

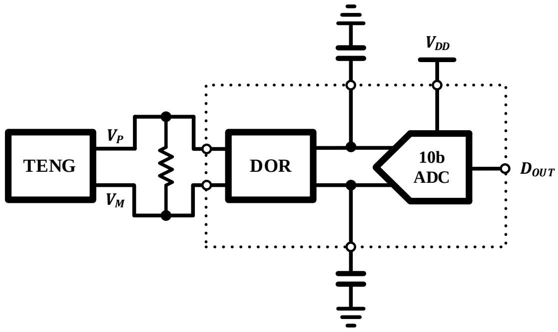


Fig. 3. TENG sensor interface with a dual-output rectifier (DOR) [6] and a conventional 10-bit charge-redistribution SAR ADC.

## II. IMPLANTABLE TENG SYSTEM FOR PRESSURE SENSOR INTERFACE

### *A. Electrical Modeling of the Implantable TENG*

Due to the mechanical constraints of the human knee joint, the dimensions of the TENG are limited by the effective intra-articular area. The TENG used in this paper employs a Ti/FEP stacked structure placed inside the implant housing, as shown in Fig. 1(a), which illustrates the most representative type of TENG, the vertical contact-separation TENG (CS-TENG). The available area is approximately 25 mm × 48 mm, as dictated by the TKR housing geometry. The fabricated prototype has an active area of 18 mm × 7.1 mm. The plate-to-plate separation is designed to vary between 0 and 0.2 mm under gait loading. FEP (Fluorinated ethylene propylene) is used as the dielectric layer, and Ti is used as the metal electrodes. The effective area and the choice of biocompatible materials yield a limited intrinsic capacitance in the implant environment; the TENG is employed as a pressure sensor that reads load-induced charge variations.

In the TKR environment, the TENG repeatedly contacts and separates the metal-polymer plates in response to human movement, generating triboelectricity during this process that charges on the plate surfaces. The plate separation distance x(t) changes over time in response to movement, and the TENG is modeled as an equivalent circuit of a voltage source connected in series with a capacitor that varies according to x(t) [7]. Fig. 1(b) shows this electrical model. Fig. 1(c) presents the modeled response to walking-like stimulation assuming a frequency of 1–5 Hz and a separation range of 0–0.2 mm. This demonstrates that the proposed TENG model can accurately model various walking conditions related to the TKR environment.

Fig. 2(a) shows the measurement setup of the TENG sensor. An electrodynamic shaker (Model 2100E11, rated at 100 lbf) driven by a Simcenter SCADAS Mobile–QSC power amplifier applied periodic forces of constant amplitude. The TENG output voltage was recorded with a U1620A handheld oscilloscope. Fig. 2(b) represents the equivalent circuit of the measurement setup. The TENG is modeled as an open-circuit voltage $V_{OC}(x)$ in series with a displacement-dependent capacitance $C_{TENG}(x)$. The passive probe and the handheld oscilloscope are modeled together as 10 MΩ in parallel with 15 pF. Fig. 2(c) shows the shaker

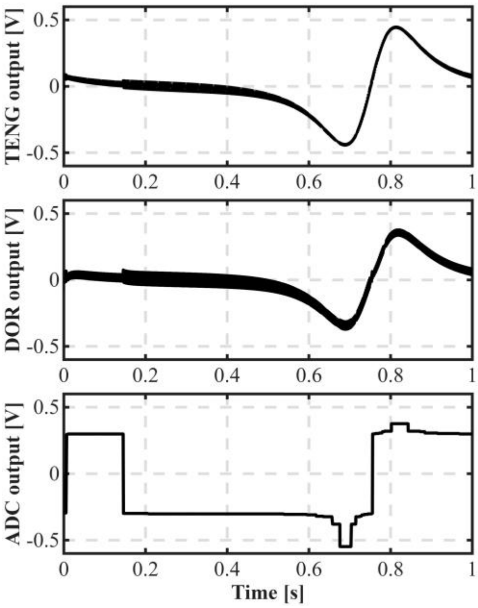


Fig. 4. Simulation results of the TENG sensor interface with the modeled TENG

force waveform and the corresponding TENG voltage. The output voltage is slightly delayed relative to the force peak, and the peak voltage is approximately 1.0 V. These measurement results indicate that the TENG output increases monotonically with the applied load and can serve as a load or pressure sensing metric under the present load conditions. In the model, the plate separation x(t) is used as the driving variable. Because the measurement applied pulses rather than a sinusoid, a waveform-level match is not expected. Nevertheless, the measured voltage consistently correlates with the magnitude and timing of the applied load; therefore, the model is suitable for sensor calibration and force–distance–voltage mapping.

### *B. TENG Sensor Interface*

In TENG-based energy-harvesting systems, rectifiers and Bennet doublers (BDs) are widely adopted. However, TENGs are characterized by different positive and negative peak output voltages, and connecting the two outputs to a conventional full-wave rectifier (FBR) significantly decreases harvesting efficiency. Therefore, we adopt a dual-output rectifier (DOR) [6], [8]–[10] to efficiently harvest the unequal peaks. The adopted DOR consists of two half-wave rectification paths that independently process the positive and negative TENG terminals. Each path is implemented with diode-connected transistors and a storage capacitor (CP, CN) that captures the corresponding peak voltage, resulting in rectified outputs VP and VN that follow the upper and lower envelopes of the TENG waveform. These two outputs are then combined through a passive resistive divider and a decoupling capacitor to generate a single-ended sensor voltage VREC within a 0–1 V range that is directly compatible with the following ADC, following the dual-output rectifier concept reported in [6]. Although the focus of this work is on pressure sensing, the DOR is retained to enable future use of the TENG′s output power to drive a low-

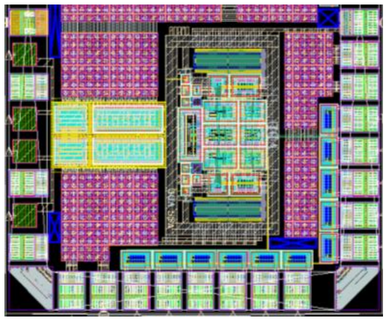

Fig. 5. Layout of the TENG sensor interface

power sensor interface. Accordingly, Fig. 3 shows the proposed TENG sensor interface. The DOR rectifies and stabilizes TENG′s differential outputs, and a 10-bit SAR ADC digitizes this signal. The SAR ADC employs a conventional charge-redistribution capacitive DAC with top-plate sampling, a dynamic comparator, and asynchronous SAR logic. It operates from a low supply voltage with a full-scale input range of approximately 0–1.0 V, providing 10-bit resolution on the order of 1 mV/LSB and duty-cycled 1 Hz operation tailored to the slow gait-induced TENG signal. Based on the measured and simulated transfer characteristic between the TENG output and the rectified sensor voltage VREC, the knee-load range of interest maps to a VREC span on the order of several hundred millivolts. For postoperative monitoring, we target resolving load changes on the order of a few percent of this span, which corresponds to a required resolution of approximately 6–7 effective bits. The adopted 10-bit resolution therefore provides sufficient margin so that one LSB corresponds to significantly less than 1% of the VREC span, making the quantization error negligible compared with the TENG and circuit noise while still keeping the ADC power consumption low. To match the slow gait-induced TENG signal, the ADC is duty-cycled and performs only one conversion per gait cycle (≈1 sample/s), so that the average power consumption of the interface remains in the sub-μW range while maintaining adequate resolution for TKR pressure/load monitoring. In this paper, we consider gait-rate operation at 1-Hz, and the rectified signal is directly sampled to obtain load-related pressure data. The complete DOR and 10-bit SAR ADC circuitry occupies approximately 740 μm × 720 μm in the 180 nm BCD process, which is compatible with the form-factor constraints of implantable TKR systems.

## III. SIMULATION RESULTS

Fig. 4 presents simulation results for the interface shown in Fig. 3, incorporating the previously designed TENG model. Under gait-rate operation at 1 Hz and an effective load of tens of MΩ, the TENG generates a spike voltage each cycle, and the DOR harvests the positive and negative signals separately. Here, the DOR output in Fig. 4 corresponds to the single-ended rectified node VREC obtained by combining the positive and negative paths of the

DOR and applied to the ADC input, rather than the raw differential signal (VP–VN). The DOR conducts only during brief intervals when pressure is applied. The ADC input becomes a unipolar waveform with suppressed low-frequency ripple, and the digital output shows increasing peak values as the load increases. In the simulations of Fig. 4, the LSB step size of the quantized digital output corresponds to significantly less than 1% of the full VREC span, confirming that the chosen 10-bit resolution is sufficient for tracking load-induced changes in the TENG signal. During the initial interval of the simulation, the applied load and the rectified voltage remain at a baseline level while the DOR storage capacitors settle, so the ADC output stays at a constant code; subsequent changes in the applied load result in the varying ADC codes shown in Fig. 4. The apparent high-frequency fluctuations at the DOR output are mainly due to the charge–discharge behavior of the storage capacitors during the short conduction intervals of the rectifier (rectification ripple), rather than additional random noise from the interface circuitry. Post-layout simulations at 1 Hz gait-rate operation indicate that the proposed TENG sensor interface consumes a total average power of approximately 1.77 μW. The 10-bit SAR ADC dominates the power consumption with about 1.75 μW, while the DOR consumes only 17.7 nW and the remaining bias and auxiliary circuits contribute a negligible portion. This power breakdown confirms that the interface operates within a very low-power budget suitable for implantable TKR systems. In separate dynamic simulations with a near full-scale sinusoidal input at a 40 kS/s conversion rate, the 10-bit SAR ADC achieves an effective number of bits (ENOB) of approximately 9.8 bits, which is slightly below the ideal quantization limit but still sufficient for the required resolution in TKR pressure/load monitoring.

## IV. CONCLUSION

This paper adopts a TENG as a pressure sensor for TKR implants and presents a TENG model and sensor interface based on a dual-output rectifier (DOR) and a 10-bit SAR ADC. Under 1-Hz walking conditions, the TENG showed periodic spikes. The DOR separated and rectified the positive and negative signals, and the ADC digitized the signals. The measured TENG voltage consistently corresponded to the magnitude and timing of the pressure, verifying the effectiveness of the proposed model for force–distance–voltage calibration.

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