Proceedings of the 8th International Conference on Energy Harvesting, Storage, and Transfer (EHST 2025)
July 15, 2025 - July 17, 2025 | Imperial College London Conference, London, United Kingdom
Paper No.138
DOI: 10.11159/ehst25.138

Hip Implant with Embedded Piezoelectric Sensors for Load Monitoring

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Abstract - This work presents the design, integration, and experimental validation of a smart total hip replacement (THR) implant with embedded piezoelectric sensors for multidirectional load sensing, energy harvesting, and wireless data transmission. Finite element analysis (FEA) guided the placement of seven piezoelectric modules within the femoral head, targeting regions of peak stress under simulated gait loading. A custom cam-driven testbed replicated walking motion at ~2 Hz, allowing controlled performance evaluation. Sensor S4, located in a high-load zone, consistently produced dominant voltage responses across three trials, validating sensor placement and confirming high spatial resolution and signal repeatability. RMS voltage outputs showed strong correlation with applied forces, enabling voltage-to-load calibration. The harvested energy supported wireless data transmission, confirming the feasibility of battery-free operation. These findings establish a robust foundation for autonomous orthopaedic implants capable of continuous biomechanical monitoring, individualized rehabilitation, and early detection of implant-related complications.

***Keywords*:** Hip, Smart Implant, Energy Harvesting, Health Monitoring
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1. Introduction

Total hip replacements (THRs) are among the most successful surgical procedures worldwide [1], with improved durability over recent decades [2]. Between 2009 and 2019, THRs increased by 22% in OECD countries [3], a trend expected to rise with global aging and population growth [2–4]. However, implant loosening remains the leading cause of revision surgeries [3]. Conventional hip implants cannot monitor internal load transfer, making it difficult to detect issues before symptoms arise and often leading to delayed interventions [5]. Since implant longevity is influenced by joint stress and activity [6], there is growing demand for technologies that monitor post-operative load patterns to guide rehabilitation.

Integrating sensors within implants can enable real-time biomechanical monitoring, enhancing prosthesis performance and informing both patient care and design improvements [7]. These smart systems also help assess rehabilitation progress and determine the need for mobility aids [10], while early prototypes have aided in defining load inputs for in vitro testing [9]. Moreover, energy harvesters that respond proportionally to joint loading offer a dual function as power sources and load sensors [9, 10].

Instrumented implants with embedded sensors and actuators show great promise for improving orthopedic outcomes [11–14]. Beyond sensing, they can monitor osseointegration [15] and even promote bone healing through electrical stimulation [15–18]. Despite their potential, prior systems have depended on batteries or external power, limiting continuous measurement [19–25]. Early designs used strain gauges with wired telemetry [23], while later models integrated strain sensors and circuits inside prostheses but faced lifespan and data limitations. Recent advancements achieved multi-directional sensing, longer operation times, and measurements of force and temperature [24-27], though continuous monitoring remains constrained.

This study presents a novel smart THR system that combines embedded piezoelectric sensors, wireless communication, and energy harvesting for real-time in vivo load monitoring. Based on FEA-informed sensor placement, the implant captures joint forces through electrical signals without external power. While not yet diagnostic, the prototype establishes a foundational platform for self-powered orthopedic implants, enabling personalized care, early detection of abnormal loading, and reduced revision rates.

2. Method

2.1. FEA for Locating Critical Contact Points

A representative hip implant assembly, comprising the femoral head, polyethylene liner, and acetabular shell, was modeled in SolidWorks and imported into ANSYS Mechanical for structural analysis. All components were assigned the material properties of polylactic acid (PLA), matching the material used in experimental prototypes. Two primary contact interfaces were defined to simulate joint articulation: between the liner and the acetabular shell, and between the liner and the femoral head. Both interfaces were modeled as frictionless with asymmetric contact behavior to allow sliding motion without penetration. The liner–shell interface incorporated a 0.599 mm clearance using the Pure Penalty method, while the liner–head interface included a 0.251 mm clearance, reflecting manufacturing tolerances and functional motion.

Meshing produced 2,225 elements and 4,673 nodes, enabling accurate simulation of localized stress and deformation. Modal analysis was first conducted to determine the natural frequencies and mode shapes, followed by a harmonic response analysis under physiologically relevant loading. As shown in Figure 1, total deformation contours reveal the highest displacement concentrated beneath the femoral head, along the principal load transfer path during walking. This region also corresponded to areas of elevated stress intensity, identified in red, indicating zones of mechanical strain ideal for sensor integration. Based on this analysis, seven piezoelectric energy harvesters were strategically positioned in the sub-femoral region to maximize electromechanical response and capture localized loading behavior during gait cycles.

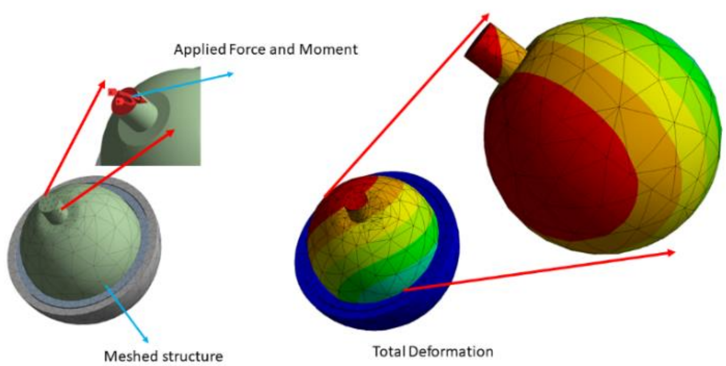

Fig. 1: The meshed structure of the implant and total deformation profile under simulated gait loading. Regions of critical stress concentration and maximum deformation are highlighted in red. The highest deformation occurs beneath the femoral head, guiding the placement of piezoelectric energy harvesters in this load-intensive region.

2.2. Smart Implant Design

The 3D-printed smart total hip replacement (THR) system, illustrated in Figure 2, introduces a novel implant architecture that integrates sensing capabilities directly into its structure. The system consists of three main components: the femoral stem and head, the acetabular cup, and seven embedded piezoelectric energy harvesters. The femoral head is structurally separated into two parts, a femoral head cover and a femoral head base, to house internal sensing modules.

Each sensing module is radially positioned based on high-stress regions identified through finite element analysis (FEA) and consists of a roller interface, a spring-loaded connecting rod, and a base-mounted piezoelectric transducer. The roller is partially exposed through openings in the femoral head cover, maintaining direct contact with the acetabular surface. As mechanical loads are applied during gait, the rollers transfer force through the rods to the piezoelectric elements, converting localized strain into electrical signals.

The seven sensors are distributed circumferentially to capture multidirectional loading with high spatial accuracy. This configuration enables the implant to monitor joint biomechanics in real time, detecting variations in load distribution that may indicate changes in patient activity or early signs of implant degradation. A wireless data acquisition system is used to collect and transmit signals for further analysis.

This design transforms the femoral head into an active sensing platform that not only restores joint function but also provides continuous feedback on implant performance. It supports future applications in personalized rehabilitation, early complication detection, and long-term orthopedic care.

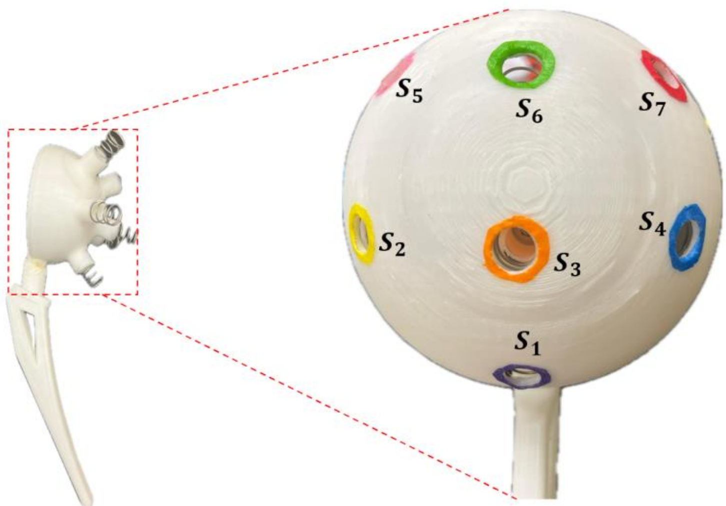

Fig. 2: A 3D printed hip replacement (THR) design with integrated piezoelectric sensing at seven different locations.

The smart THR system demonstrates the structural integration of piezoelectric energy harvesters embedded at contact zones identified through finite element analysis. These sensors are positioned in mechanically strategic regions of the femoral head to convert joint-loading forces into electrical signals through localized deformation. This arrangement enables real-time, in vivo load monitoring and supports data-driven orthopedic evaluation.

Each piezoelectric module is situated beneath an opening in the femoral head cover, where a roller element remains partially exposed. As physiological loads are applied during movement, contact forces are transmitted through the roller and spring-loaded rod to the underlying piezoelectric transducer. This mechanical chain produces proportional voltage signals that reflect localized joint forces during daily activities.

To capture and visualize these signals, the system includes a wireless ESP32-based data acquisition module, an oscilloscope for real-time signal observation, and supporting electronics. This setup validates the implant's sensing functionality and forms the basis for future wireless communication and automated health monitoring applications.

2.3. Experimental Testing

The experimental evaluation of the smart hip implant was carried out using a custom-designed benchtop testbed that simulated cyclic joint motion under controlled laboratory conditions. This setup was developed to characterize the performance of the implant's embedded piezoelectric energy harvesters during simulated walking activities. The central component of the system is a 3D-printed cam-follower mechanism, driven by a NEMA Frame 56C three-phase AC motor. The cam was engineered to produce sinusoidal reciprocating motion in the follower, replicating the dynamic force patterns typically experienced in the hip joint during locomotion. Motor speed and loading frequency were controlled through an external interface, allowing fine-tuned adjustments to simulate different levels of physiological activity. This enabled the reproduction of realistic gait cycles to assess the implant's ability to generate voltage responses in relation to mechanical loading.

Tests were conducted at a loading frequency of 2 Hz to represent typical walking conditions. Each trial was repeated three times to ensure repeatability and reliability of the measurements. During these experiments, both force inputs and voltage outputs were captured in real time from the seven piezoelectric sensors (S1 through S7) embedded within the femoral head. This setup allowed for detailed evaluation of how varying loading conditions influence electrical signal generation. By analyzing multi-trial data, the sensing behavior of the implant was characterized, and its consistency and responsiveness were confirmed. The results demonstrate the implant's capability to monitor biomechanical loads associated with routine daily activities.

2. Results

Figure 3 presents the root-mean-square (RMS) voltage (a–c) and RMS load (d–f) responses collected from the seven piezoelectric sensors (S1 to S7) embedded within the femoral head of the smart hip implant during three independent trials at a walking frequency of 2 Hz. Each column in the subplots represents the magnitude of electrical or mechanical output for a specific sensor, enabling a direct comparison of sensor behavior across repeated experiments.

In all three voltage trials (Fig. 3a–c), Sensor S4 consistently exhibits the highest RMS voltage output, with values reaching approximately 20–25 mV. This indicates that S4 is located in a region of concentrated mechanical stress, which aligns with the finite element analysis (FEA) predictions used to guide sensor placement. Sensors S3, S5, and S6 also show moderate responses across all trials, suggesting that these positions experience intermediate load transfer. In contrast, Sensor S7 consistently produces the lowest voltage, typically below 5 mV, indicating minimal mechanical excitation at that location.

The corresponding RMS load plots (Fig. 3d–f) confirm these trends, with Sensor S4 again registering the highest mechanical load across all three trials. The close agreement between RMS voltage and load distributions validates the electromechanical coupling behavior of the piezoelectric elements and demonstrates that sensor outputs scale proportionally with applied mechanical input. Notably, the voltage-to-load trend remains consistent across all repetitions, highlighting the system's repeatability and measurement reliability.

This trial-to-trial consistency reinforces the reliability of the sensor configuration and mechanical design. The high sensitivity and signal clarity at specific locations (especially S4) underscore the effectiveness of the FEA-informed design approach in targeting biomechanically relevant regions. Furthermore, the reproducibility of the measurements across all sensors indicates robust mechanical-electrical transduction under dynamic gait simulation.

Overall, the data in Figure 3 confirms that the smart hip implant is capable of spatially resolved, repeatable sensing of joint loads, and supports the feasibility of using embedded piezoelectric elements for real-time, self-powered biomechanical monitoring during daily activities.

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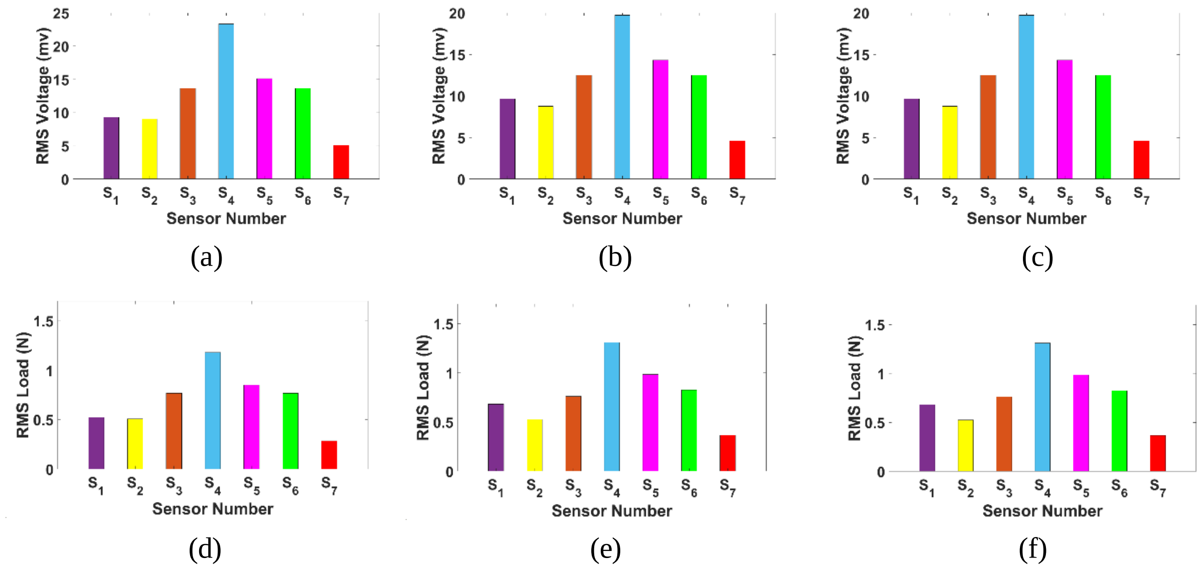

Fig. 3: The RMS voltage and load measurements at 2 Hz for three trials (a-c); and the corresponding RMS loads (d-f).

Figure 4 presents the average RMS voltage output (Fig. 4a) and average RMS load (Fig. 4b) recorded from the seven piezoelectric sensors (S1 to S7) during gait simulation at 2 Hz. Error bars indicate the standard deviation for each sensor, providing insight into signal variability and repeatability across multiple trials.

Sensor S4 stands out with the highest average voltage (~22 mV) and load (~1.3 N), confirming its location in a region of maximum mechanical stress, as predicted by the FEA-based design. This strong electromechanical response reinforces the strategic placement of S4 and its suitability for primary load monitoring. Sensors S5 and S6 also exhibit elevated outputs, supporting their positions near secondary high-strain regions.

Sensor S7 consistently shows the lowest average voltage and force, suggesting minimal mechanical excitation and confirming its position outside major load-bearing zones. Meanwhile, sensors S1–S3 show moderate voltage and load responses, indicating intermediate mechanical interaction.

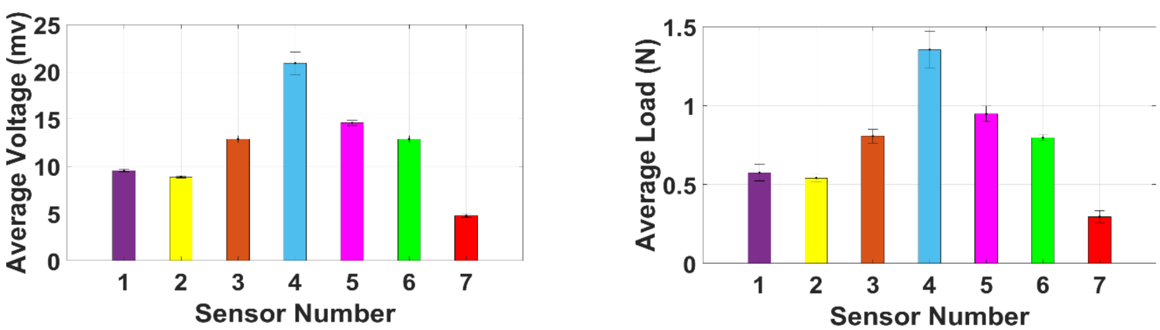

Fig. 4: (a) Voltage output per sensor; (b) Load measurement. Error bars represent standard deviation.

Table 1 quantitatively supports these findings by reporting the standard deviation (σ) and standard error (SE) for voltage and force signals at each sensor location. Although S4 displays the highest variability (σV = 20.91 mV, σF = 1.35 N), its standard error remains relatively controlled (SEV = 1.20 mV, SEF = 0.11 N), demonstrating consistent output despite the larger dynamic range. In contrast, sensors with lower outputs such as S7 exhibit smaller deviations, aligning with their limited exposure to mechanical stress.

These results validate the functional robustness of the smart hip implant and highlight its ability to distinguish localized loading patterns with spatial resolution and statistical reliability. The alignment between voltage and force distributions, as well as the consistent trial-to-trial behavior, confirm the implant's effectiveness in capturing biomechanical loads during cyclic motion. Collectively, this performance establishes a solid foundation for in vivo load monitoring and supports the feasibility of translating piezoelectric voltage signals into clinically relevant mechanical metrics.

Table 1: Standard deviation and standard error of voltage and load signals for all sensors at 2 Hz.

Sensor	$\sigma_V(mV)$	$SE_V(mV)$	$\sigma_F(N)$	$SE_F(N)$
S_1	9.53	0.12	0.58	0.05
S_2	8.85	0.11	0.54	0.03
S_3	12.88	0.38	0.81	0.04
S_4	20.91	1.20	1.35	0.11
S_5	14.59	0.26	0.95	0.05
S_6	12.88	0.38	0.80	0.02
S_7	4.74	0.16	0.30	0.04

The experimental results presented in this study demonstrate the feasibility, repeatability, and sensitivity of a fully integrated smart hip implant capable of real-time biomechanical load monitoring. By leveraging finite element analysis for optimal sensor placement and validating the design through controlled gait simulations, the system achieved reliable spatial resolution across multiple load-bearing zones. The consistent alignment between mechanical loading and electrical output across trials confirms the robustness of the sensing mechanism and supports its application for autonomous joint force tracking. Importantly, the dual functionality of the piezoelectric modules, serving both as sensors and energy harvesters, lays the groundwork for battery-free operation and wireless data transmission. These findings represent a critical step toward developing intelligent orthopaedic implants that actively contribute to postoperative care, patient-specific rehabilitation, and early detection of implant-related complications.

3. Conclusion

This study presents the successful development and validation of a smart total hip replacement (THR) implant that integrates piezoelectric sensing, energy harvesting, and wireless monitoring into a unified system. By embedding seven strategically placed piezoelectric modules within the femoral head, the implant effectively captured localized joint loading patterns under simulated walking conditions. Experimental trials at 2 Hz confirmed high spatial resolution, repeatable voltage–load responses, and strong agreement with finite element predictions, demonstrating the system's mechanical integrity and sensing accuracy. In addition to reliable biomechanical monitoring, the implant harvested sufficient energy under dynamic loading to support wireless data transmission, highlighting its potential as a self-powered orthopedic device. The generated voltage signals scaled proportionally with mechanical input and were used to derive robust calibration curves for quantifying internal joint forces. This transforms the implant from a passive structural component into an active diagnostic tool capable of delivering real-time physiological insights. The dual-functionality of sensing and power harvesting positions this system as a foundational platform for battery-free, autonomous orthopedic implants. Its ability to track load variations over time opens new avenues for early detection of implant loosening, gait abnormalities, or patient non-compliance, well before clinical symptoms emerge. Overall, the integration of electromechanical sensing and energy harvesting into a smart THR framework marks a significant advancement in orthopedic technology. With further refinement, this platform has the potential to enhance patient-specific rehabilitation, reduce revision surgeries, and establish a new paradigm for intelligent, connected joint prostheses.

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