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# Piezoelectric effects on bone modeling for enhanced sustainability

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## HIGHLIGHTS

- To optimise the modelling of piezoelectric effects in the bone modelling analysis.
- Examined the connection between loads on bones and electrical charges generated by the piezoelectric effect.
- To significantly benefits bone biomedical engineering, in remodelling, healing, and repair.
- To Observed that electrically stimulated boneb generated charges during activities.

## ARTICLE INFO

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## ABSTRACT

Bone tissue possesses piezoelectric properties, allowing mechanical forces to be converted into electrical potentials. Piezoelectricity has been demonstrated to play a crucial role in bone remodelling and adaptability. Bone remodelling models that consider strain adaptation, both with and without piezoelectric effects, were simulated and validated in this study. This simulation help to better comprehend the interplay between mechanical and electrical stimulations during these processes. This study aimed to optimise the modelling of piezoelectric effects in bone modelling analysis. The connection between mechanical loads applied to bones and the resulting electrical charges generated by the piezoelectric effect was examined. Furthermore, mathematical modelling and simulation techniques were employed to enhance the piezoelectric effect and promote bone tissue growth and repair. The findings from this research have substantial implications for developing novel therapies for bone-related diseases and injuries. It was observed that electrically stimulated bone surfaces increased bone deposition. In some instances of physical disability or osteoporosis, therapeutic electrical stimulation can supplement the mechanical stresses of regular exercise to prevent bone loss. Consequently, the bone remodelling method on the software platform enables easy application and repetition of finite element analysis. This study significantly benefits bone tissue/biomedical engineering, particularly in bone remodelling, healing, and repair.

## 1. Introduction

The piezoelectric effect refers to generating electrical charges in specific materials when they undergo mechanical stress or deformation. Bone, as a biological material, demonstrates this effect and is sensitive to mechanical loading. Research into the piezoelectric effect on bone holds promise for enhancing bone tissue growth and repair [1,2]. Scientists aim to develop novel therapies for bone-related diseases and injuries by optimising this effect. In comparison, mathematical modelling and simulation techniques are widely employed to study the piezoelectric effect in bone. A more comprehensive understanding of the relationship between mechanical loads and the resulting electrical charges generated by the effect is still needed [3,4] (see Table 3).

Piezoelectric materials can generate an electrical charge in response to applied mechanical stress or strain. Conversely, they can deform or change shape when subjected to an electric field. The underlying principle is that deforming a crystalline material causes the displacement of electric charges within the material's structure [5–7]. Piezoelectric materials have numerous applications in sensors, actuators, transducers, and electronic devices, including microphones, speakers, and ultrasonic

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transducers. Common examples of piezoelectric materials are quartz, specific ceramics, and certain crystals like tourmaline and topaz [8,9]. Bone plays a crucial role in the body, providing structural support, protecting vital organs, storing minerals and lipids, connecting muscles to the skeleton, and enabling movement. Living tissue can alter its shape in response to mechanical stress through bone remodelling, a process involving the bone formation and resorption. Research in this area is essential, given the importance of bone remodelling in human health [7,10,11].

Past research has demonstrated that human bone's electric and dielectric properties change according to frequency. These properties are significant because they participate in the feedback process of bone remodelling and are employed in therapeutic electrical stimulation for bone healing and repair. Both mechanical and electrical stimulations can alter the influence of an electromagnetic field on bone remodelling and healing. A few studies on bone remodelling have also incorporated heat load [12,13]. A material is considered piezoelectric if it generates an electric potential when subjected to mechanical stress and exhibits a mechanical response when exposed to an electric field. Notably, bone piezoelectricity supports the idea of matrix piezoelectricity as a possible mechanism for osteocytes to detect high-stress areas. This concept can explain the differences in bone adaptability between wet bone streaming potential and dry bone matrix piezoelectricity [4,14–16]. However, the piezoelectric properties of bone tissue remain inadequately understood, with only a few mathematical and computational models of bone remodelling accounting for the piezoelectric aspects of bone. Cells initiate localised changes in bone in response to mechanical stress [17–19].

This research aims to address the gap in bone modelling by utilising optimisation modelling to analyse the piezoelectric effect on bone and explore its potential applications in bone tissue engineering. This study has the potential to significantly contribute to the development of novel therapies for bone-related diseases and injuries, ultimately improving many people's quality of life. The simulation results were validated by predicting bone density and comparing the predictions to computed tomography scan data. The present study sought to use the Ansys software platform to simulate strain-adaptive bone remodelling in a human femur. This research could contribute to developing a therapeutic electrical stimulation program for bone damage prevention in patients with physical disabilities and osteoporosis. This leads to a more comprehensive understanding of bone responses to electromechanical loadings. The parametric investigation examined the effect of initial bone density uniformity on the ultimate dispersion of bone density.

## 2. Material and methods

In the analysis of the femur bone (Fig. 1), the piezoelectric effect can be factored in as an essential element for determining the mechanical properties of the bone. For instance, the electric charge generated by the piezoelectric effect can be employed to assess strain and stress within the bone under varying loading conditions. This data can then be utilised to create more precise models of the mechanical behaviour of the femur bone. Additionally, the piezoelectric effect in the femur bone can be applied in medical applications, such as developing bone implants or prostheses. Designing materials with piezoelectric properties, akin to the femur bone, can result in implants that better integrate with the existing bone structure and enhance overall bone health. Therefore, comprehending and modelling the piezoelectric effect in the femur bone can significantly impact medical research and clinical practice [20–23]. The piezoelectric effect in the femur bone can be modelled using the piezoelectric equation, which links the electric charge generated by the material to the applied mechanical stress. This equation is given as:

$$\varepsilon = d * \sigma + d_{ij} * E_j$$

Here, ε represents the electric charge density, d denotes the piezoelectric coefficient tensor, σ symbolises the mechanical stress tensor, $d_{ij}$ refers to the piezoelectric strain tensor, and $E_j$ is the electric field tensor (Fig. 1).

In the case of the femur bone, both the piezoelectric coefficient tensor and the piezoelectric strain tensor depend on the bone's direction and orientation. This is because collagen fibres in the bone are not uniformly oriented and have a preferred direction. The electric charge generated by the piezoelectric effect in the femur bone can be measured

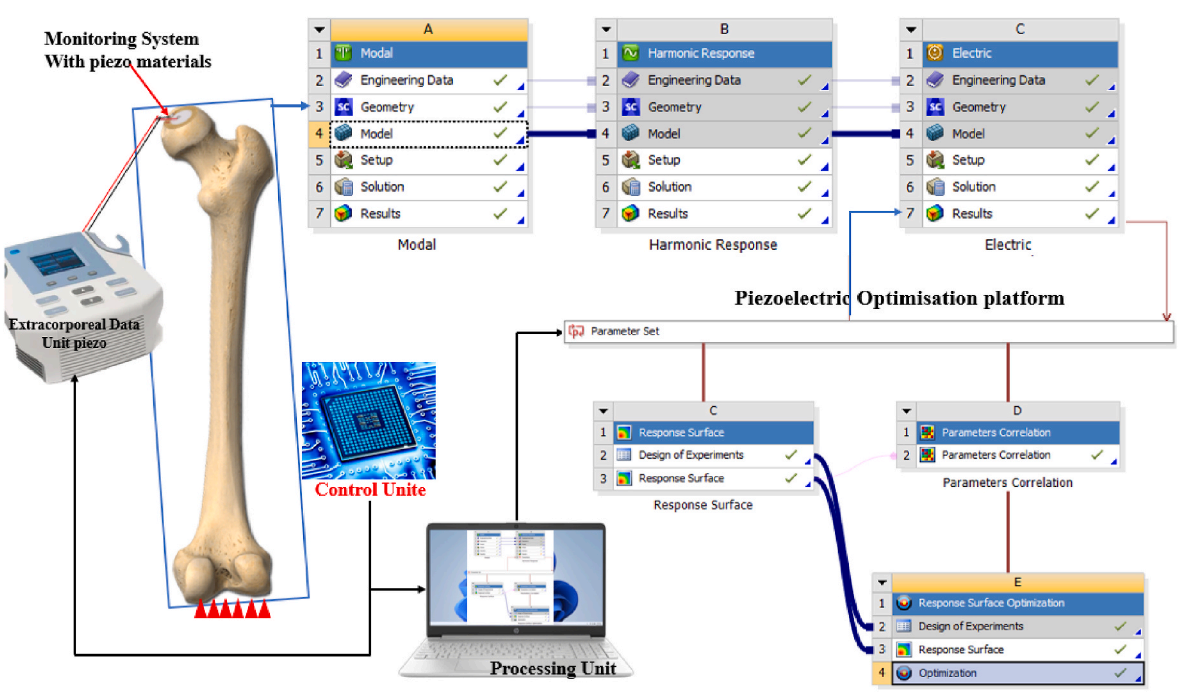


**Fig. 1.** Schematic representation of the boundary conditions applied in the optimisation process of the experiment and data acquisition of the piezoelectric effect for improved energy generation.

using various techniques, such as piezoelectric sensors or electrical impedance measurements. These measurements can then be employed to determine the mechanical properties of the bone and develop more accurate models for bone analysis [24–27]. Ultimately, the piezoelectric effect plays a crucial role in the mechanical behaviour of the femur bone and can offer valuable insights into its properties and behaviour under different loading conditions.

### *2.1. Piezoelectric stress-strain adaptive bone remodelling*

The piezoelectric strain-adaptive bone remodelling theory suggests that bone tissue can adjust and remodel its structure in response to mechanical loading through the piezoelectric effect. According to this theory, when bone experiences mechanical loading, the deformed fibres generate an electric charge due to the piezoelectric effect (Fig. 2). This electric charge subsequently attracts osteoblasts and osteoclasts to the site of deformation, resulting in bone remodelling [28–30]. Experimental evidence supporting this theory demonstrates that bone tissue possesses piezoelectric properties, and mechanical loading can induce bone remodelling. Piezoelectric stress-strain adaptive bone remodelling is crucial in maintaining bone strength and preventing loss. Furthermore, this theory has contributed to developing innovative therapeutic approaches for bone disorders like osteoporosis. For instance, it has been proposed that controlled mechanical loading on bones can promote bone remodelling and prevent bone loss. Additionally, piezoelectric materials in bone implants and prostheses can aid bone growth and integration with surrounding bone tissue.

An assumption was made that the bone has a hexagonal crystal like shape, with the electric permittivity tensor represented as a diagonal matrix with two constants and the third-order piezoelectric stress tensor E defined by four values [5,31,32]. These tensors can be described using a matrix, where the third dimension corresponds to the femur's longitudinal axis. A displacement field is required for the bone to regenerate through piezoelectric strain adaptation. The formulation was confined to isothermal and quasi-static situations to simplify the work.

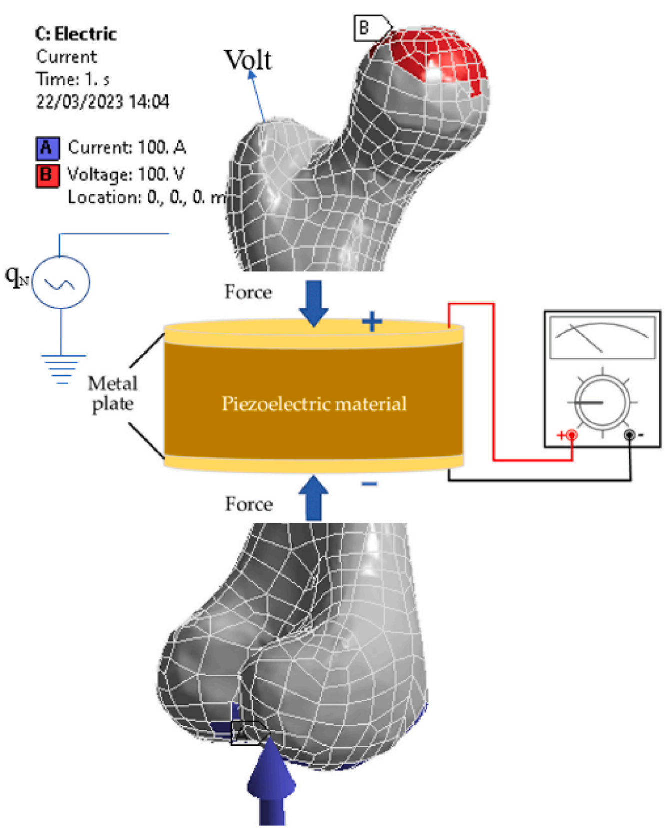


**Fig. 2.** Strain bone modelling with the direct energy harvesting/piezoelectric effect.

### *2.2. Finite element model*

This study simulated the piezoelectric effect in femur bone modelling using Ansys Workbench. A three-dimensional computer-aided design model of the femur bone was imported. The material properties were defined, including elastic modulus, Poisson's ratio, and piezoelectric coefficients. A new static structural analysis system and mesh geometry of the femur bone was created using appropriate element types, such as tetrahedral or hexahedral elements [33–35]. The analysis's boundary conditions were established, including fixed or prescribed displacements, forces, and electric potentials.

A load or electric potential was applied to the femur bone to simulate the piezoelectric effect. Ansys Workbench was then used to simulate and analyse the results, such as deformation, stress, and electric field distribution. The results were interpreted and validated, and the model or analysis setup was adjusted if necessary. A report or presentation was prepared to document the findings and conclusions of the analysis. The specifications of the piezoelectric effect in femur bone modelling may require additional steps or considerations depending on the research or engineering objectives.

### *2.3. Mechanical boundary conditions*

The human femur was used as a traditional benchmark to simulate strain bone modelling with and without the piezoelectric effect, . The proximal femur FEM was meshed using 10-node isoparametric tetrahedral elements. The side plate, consisting of 4209 elements and 1403 nodes, was assigned an elastic modulus of 3.5 GB and 17,000 MPa and a Poisson's ratio of 0.3 for polylactic acid and bone, providing mechanical properties comparable to cortical bone. The plate's potential for change was assumed to be limited, and its properties were considered stable over time and space, preventing rigid body movement during the analysis. For planar strain, the front and posterior faces of the femur and side plate were constrained in the z-direction, corresponding to the anterior-posterior direction (Table 1) (see Table 2).

When modelling the piezoelectric effect in femur bone, the mechanical boundary conditions played a crucial role in determining the deformation and stress distribution within the bone. Some common mechanical boundary conditions were applied in Ansys Workbench (Fig. 3). The fixed support condition was used to constrain certain regions of the bone from movement or rotation. For example, the femur was fixed at one end and subjected to a load at the other. In this case, the fixed support was applied to the fixed end to prevent displacement. Prescribed displacement was conditioned to simulate a certain deformation or motion of the femur bone. For example, the femur was subjected to a bending load. In case, a prescribed displacement was applied

**Table 1**
Analytical setup table for deformation after different modelling in piezo Electricity generating different frequency.

| Object Name | Maximum (mm) | Average (mm) | Frequency (Hz) |
|---|---|---|---|
| Total Deformation | 3.73 | 1.141 | 310.2 |
| Total Deformation 2 | 3.71 | 1.150 | 356.88 |
| Total Deformation 3 | 4.75 | 1.188 | 2213.1 |
| Total Deformation 4 | 3.86 | 1.199 | 2660.3 |
| Total Deformation 5 | 5.60 | 1.241 | 2999.1 |
| Total Deformation 6 | 4.057 | 1.332 | 6521 |
| Total Deformation 7 | 4.19 | 1.280 | 6944 |
| Total Deformation 8 | 2.93 | 1.378 | 10058 |
| Total Deformation 9 | 4.23 | 1.318 | 12957 |
| Total Deformation 10 | 3.99 | 1.322 | 13215 |
| Total Deformation11 | 5.40 | 1.326 | 19741 |

**Table 2**
Optimisation of bone modelling showing the deformation of the first four of strain and stress loading.

| Type | Total Deformation(mm) | | | | Elastic Strain | Von-Mises Stress (Pa) |
|---|---|---|---|---|---|---|
| Mode | 12. | 13. | 14. | 15. | 1. | |
| Minimum | 0. m | | | | $2.62 \times 10^{-5}$ | $7.51 \times 10^{5}$ |
| Maximum | 3.75 | 7.01 | 5.50 | 3.75 | 9.01 | $3.24 \times 10^{10}$ |
| Average | 1.36 | 1.25 | 1.42 | 1.42 | 1.31 | $4.61 \times 10^{9}$ |
| Frequency KHz | 20.31 | 22.33 | 27.12 | 27.81 | 0.31 | |

**Table 3**
Output result after loading of the stress-strain on the bone modelling optimisation.

| Type | Minimum | Maximum | Average |
|---|---|---|---|
| Electric Voltage (V) | 100. | 100.15 | 100.09 |
| Total Electric Field Intensity (μV/m) | 9.59 × 102 | 7.0152 | 2.4896 |
| Directional Electric Field Intensity (μV/m) | −4.3845 | 3.8554 | −8.53 × 103 |
| Total Current Density (μA/m$^2$) | 5.64 × 105 | 4.13 × 107 | 1.46 × 107 |
| Directional Current density (μA/m$^2$) | −2.58 × 107 | 2.27 × 107 | −50281 |
| Joule Heat (μW/m$^3$) | 93077 | 1.97 × 108 | 5.21 × 108 |

to the region of bone, where the load was applied to simulate bending. Symmetry constraint is a condition that was used to model a portion of the symmetric femur bone. For example, suppose only half of the femur bone was modelled. In this case, a symmetry constraint can be applied to the plane of symmetry to simulate the other half of the bone. Pressure load is a condition that can be used to simulate an external pressure applied to the surface of the femur bone. For example, the femur bone is subjected to a compressive load from the surrounding tissue. In this case, a pressure load can be applied to the bone's surface to simulate the pressure's effect. It is essential to carefully consider the choice of mechanical boundary conditions when modelling the piezoelectric effect in femur bone and to ensure loading conditions in real life.

### 2.4. Electrical boundary conditions

When modelling the piezoelectric effect in femur bone, the electrical boundary conditions are essential in determining the electric field distribution within the bone. Some common electrical boundary conditions that can be applied in Ansys Workbench of the electric potential condition can apply a fixed electric potential to some areas of the bone. For example, suppose a piezoelectric material is embedded within the femur bone. In this case, an electric potential can be applied to the material's surface to simulate the piezoelectric effect. Electric current is a condition that can be used to simulate the flow of electric current within the bone. For example, suppose the femur bone is subjected to an external electric field. In this case, an electric current can be applied to the bone to simulate the piezoelectric material's response. The insulating boundary can be used to model a region of the insulating femur bone, meaning no electric charge can flow through it. For example, suppose the femur bone is in contact with an insulating material; symmetry constraint can also be used to model a portion of the femur bone that is symmetric electrically. This was emulated by applying mechanical forces just once every day to reduce physical activity. When an electric current flowed through a piezoelectric material, it moved. This altered the density of the femur bone. The same results were obtained with elements and time steps of less than 1 mm and 0.1 time units.

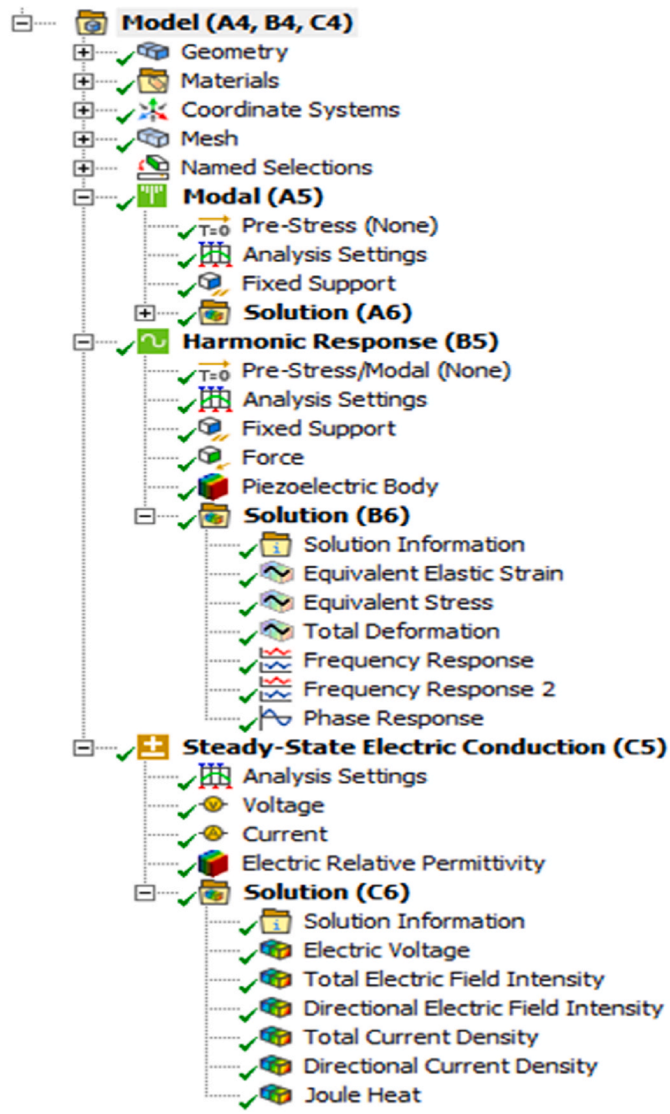


**Fig. 3.** Simulation flow diagram of mesh FEM of the femur and the piezo plate with mechanical boundary conditions applied.

## 3. Results and discussion

### 3.1. Stress-adaptive bone remodelling with the piezoelectric effect

Piezoelectric stress-adaptive bone remodelling is a model that considers mechanical and electrical signals during bone remodelling. This model suggests that bone cells react to the mechanical strain on the bone and the electrical charge generated by the piezoelectric effect, optimising the bone structure and function. Mechanical loading on the bone produces a piezoelectric charge, creating an electric field within the bone tissue. This electric field stimulates bone cells responsible for bone remodellings, such as osteoblasts and osteoclasts. Additionally, the electric field influences the orientation and alignment of mineralised collagen fibres in the bone matrix, resulting in a more organised and robust bone structure. The piezoelectric stress-adaptive bone remodelling model offers several advantages over the traditional strain-adaptive remodelling model. One advantage is its more accurate representation of the physiological process of bone remodelling, driven by both mechanical and electrical signals. This model also accounts for the unique properties of piezoelectric bone tissue, like its capacity to convert mechanical energy into electrical signals and vice versa. Furthermore, this model suggests developing new therapeutic approaches for osteoporosis-related bone disorders. Stimulating the piezoelectric effect could encourage the bone formation and prevent bone loss in individuals with osteoporosis or other bone-related conditions. Additionally, this model can help design new orthopaedic implants that mimic the natural piezoelectric properties of bone tissue, resulting in improved integration and long-term stability. In summary, the piezoelectric stress-adaptive bone remodelling model offers a more comprehensive understanding of the bone remodelling process and emphasises the importance of considering both mechanical and electrical signals in regulating bone health and disease (Fig. 4).

### 3.2. Strain-adaptive bone remodelling piezoelectric effect

Bone remodelling is a natural process occurring throughout an individual's lifetime in response to mechanical loading and other factors. This process involves osteoclasts removing old bone tissue and osteoblasts forming new bone tissue, resulting in changes to the bone's shape, density, and mechanical properties. Two proposed bone remodelling models are the strain-adaptive and the piezoelectric effect-assisted strain-adaptive remodelling models. The strain-adaptive remodelling model suggests that bone remodelling occurs in response to changes in mechanical strain on the bone. When mechanical loading increases, the bone tissue experiences higher strains, stimulating osteoblast activity to deposit new bone tissue in the loading direction. Conversely, when mechanical loading decreases, the bone tissue experiences lower strains, triggering osteoclast activity to remove old bone tissue, making the bone lighter. The piezoelectric effect-assisted strain-adaptive remodelling model considers the piezoelectric effect of bone tissue. The piezoelectric effect refers to the ability of certain materials, including bone, to generate an electric charge in response to mechanical loading (Fig. 5).

In this model, mechanical loading on the bone generates an electric charge capable of stimulating osteoblast and osteoclast activity, leading to more efficient bone remodelling. The study show that the energy harvesting/piezoelectric effect-assisted strain modelling model offers additional benefits compared to the strain-adaptive model alone. For example, the piezoelectric effect can enhance bone tissue's mechanical properties, such as stiffness and strength, by promoting the formation of a more organised bone matrix. Furthermore, the piezoelectric effect helps maintain bone health and prevent bone loss, which is particularly important in ageing populations and individuals with bone disorders. Overall, strain-adaptive and piezoelectric effect-assisted strain-adaptive remodelling models provide valuable insights into the complex bone remodelling process and have significant implications for preventing and treating bone disorders.

To investigate the impact of additional electrical stimulation on mechanically stressed femurs, the energy harvesting strain bone

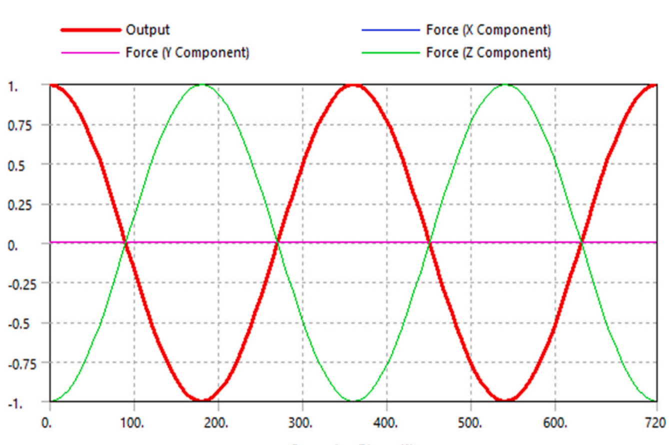


**Fig. 4.** Harmonic Response Model Solution: Phase response to sweeping phase measured in degrees.

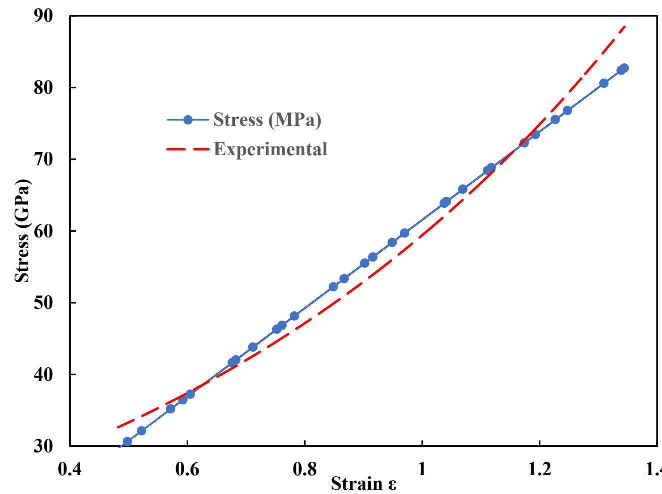


**Fig. 5.** The stress-strain curves after optimising different design points of the femur with mechanical simulating piezoelectric bone modelling.

modelling model displayed differences between the projected highest bone densities to quantitatively compare the strain-adaptive bone remodelling model with the piezoelectric strain-adaptive bone remodelling model (Fig. 4). Trabecular pathways were observed to vary slightly across simulated results. Consequently, the piezoelectric potential did not significantly influence bone density distribution. This can be attributed to the relatively low electrical potential induced by walking.

### 3.3. Effect of the initial bone density

Initial bone density can influence the piezoelectric effect of bone tissue (Fig. 6). The piezoelectric effect is the ability of certain materials, including bone, to generate an electrical charge in response to mechanical loading. This result depends on several factors: collagen fibre orientation, mineral content, and porosity of the bone matrix.

Studies have shown that the initial bone density can affect the piezoelectric effect of bone tissue. Specifically, bone tissue with a higher initial density tends to exhibit a more substantial piezoelectric effect than bone tissue with a lower initial density [36–38]. These factors contribute to a more substantial piezoelectric effect in bone tissue. The effect of bone density on the piezoelectric effect has significant implications for the study of bone tissue and the development of new therapies for bone-related conditions. Overall, the initial bone density is an essential factor to consider when studying the piezoelectric effect of bone tissue. It can affect the orientation of the fibres, mineral content and the porosity of the bone matrix, all of which contribute to the strength and efficiency of the piezoelectric effect, as shown in Fig. 7.

### 3.4. Piezoelectric analysis

Piezoelectricity is the ability of certain materials, including bone tissue, to generate an electrical charge in response to mechanical loading. The orientation and deformation of the structures under mechanical loading generate an electric potential difference, resulting in a piezoelectric effect. The piezoelectric effect of bone tissue has several implications for bone health and disease [39–41]. For example, the piezoelectric effect can play a role in bone remodelling: removing and replacing old bone tissue with new tissue. Mechanical loading on bone tissue can generate an electric charge, which stimulates bone-forming cells, called osteoblasts, to deposit new bone tissue in response to the stress. The piezoelectric effect of bone tissue also plays a role in bone healing and repair. In cases of bone fracture, for example, mechanical loading can stimulate the piezoelectric effect and promote the healing

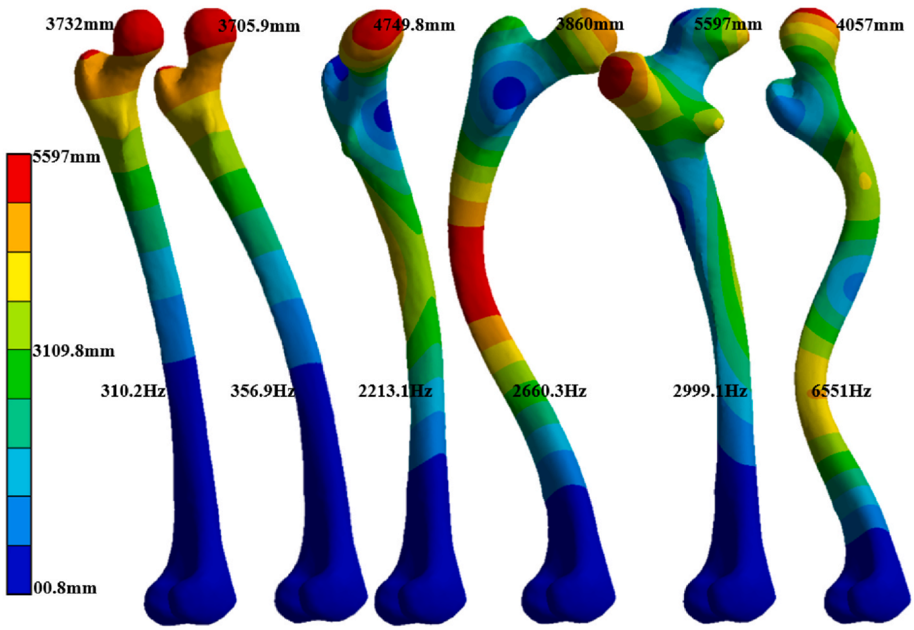


**Fig. 6.** Bone density modelling with different frequency generations on stress-strain adaptation loading, showing the displacements from six values.

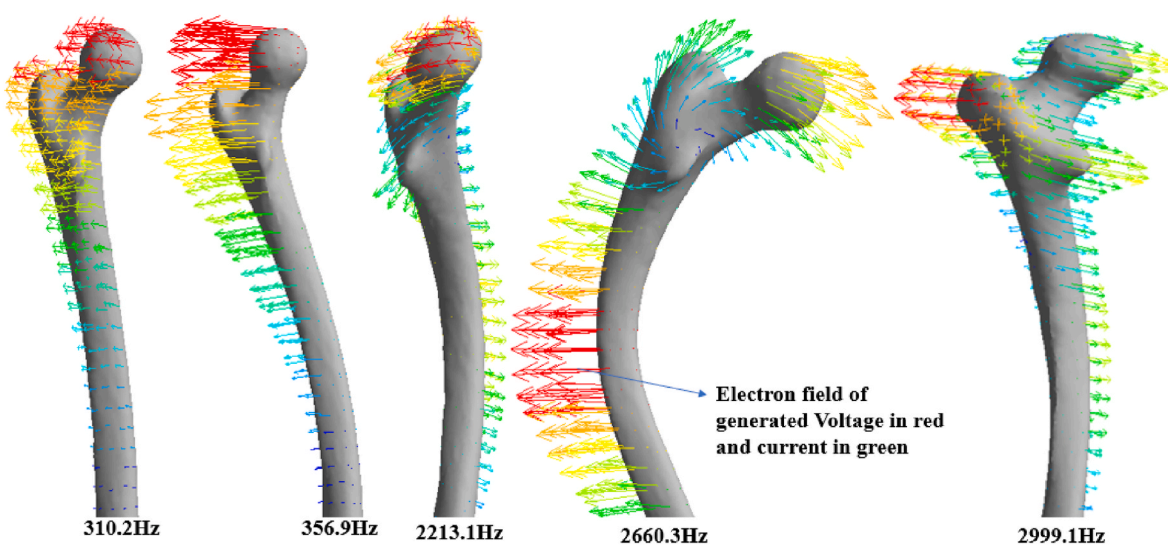


**Fig. 7.** Bone density distributions predicted at different uniform initial densities and frequency generated electron field of voltage (in red) and current (in green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

process by stimulating the activity of osteoblasts. Moreover, the piezoelectric effect implies developing new therapies for bone-related conditions, such as osteoporosis. By understanding the piezoelectric properties of bone tissue, researchers can develop new treatments that stimulate the piezoelectric effect and promote bone formation. Experiments show that applied strain affects the electric potential of bone; compressive pressures generate negative potentials, whereas tensile stresses yield positive potentials. Fig. 8 depicts changes in electric charges and amplitudes generated when walking due to mechanical loads at various times of day and the direct piezoelectric effect. Electric potentials were normalised by their mean amplitude.

Therapeutic electrical stimulation (TES) is a non-invasive technique that utilises electrical currents to promote bone healing and tissue repair. The technique is based on the principle of piezoelectricity, which is the ability of certain materials, including bone tissue, to generate an electrical charge in response to mechanical loading. TES can stimulate the piezoelectric effect in the femur bone to promote bone healing and tissue repair in fracture and other bone-related conditions [42–44]. Several studies have demonstrated the effectiveness of TES in promoting bone healing and tissue repair in the femur bone. For example, a study reported that TES accelerated the healing of femur fractures in rats by stimulating the activity of osteoblasts and promoting the formation of new bone tissue. Another study established that it improved the mechanical properties of femur bone tissue in rats with osteoporosis by enhancing the orientation of collagen fibres and increasing the mineral content of the bone matrix. TES is, therefore, a promising therapy for bone-related conditions that utilises the natural properties of bone tissue, including piezoelectricity, to promote healing and repair [45–48]. The technique is non-invasive and has minimal side effects, making it a safe and effective treatment option for various bone-related conditions. However, further study is needed to optimise the parameters of TES and develop standardised protocols for its use in femur bone therapy. For a fair comparison with other comparable research, the starting point for the simulation of decreased physical activity and electrical stimulation

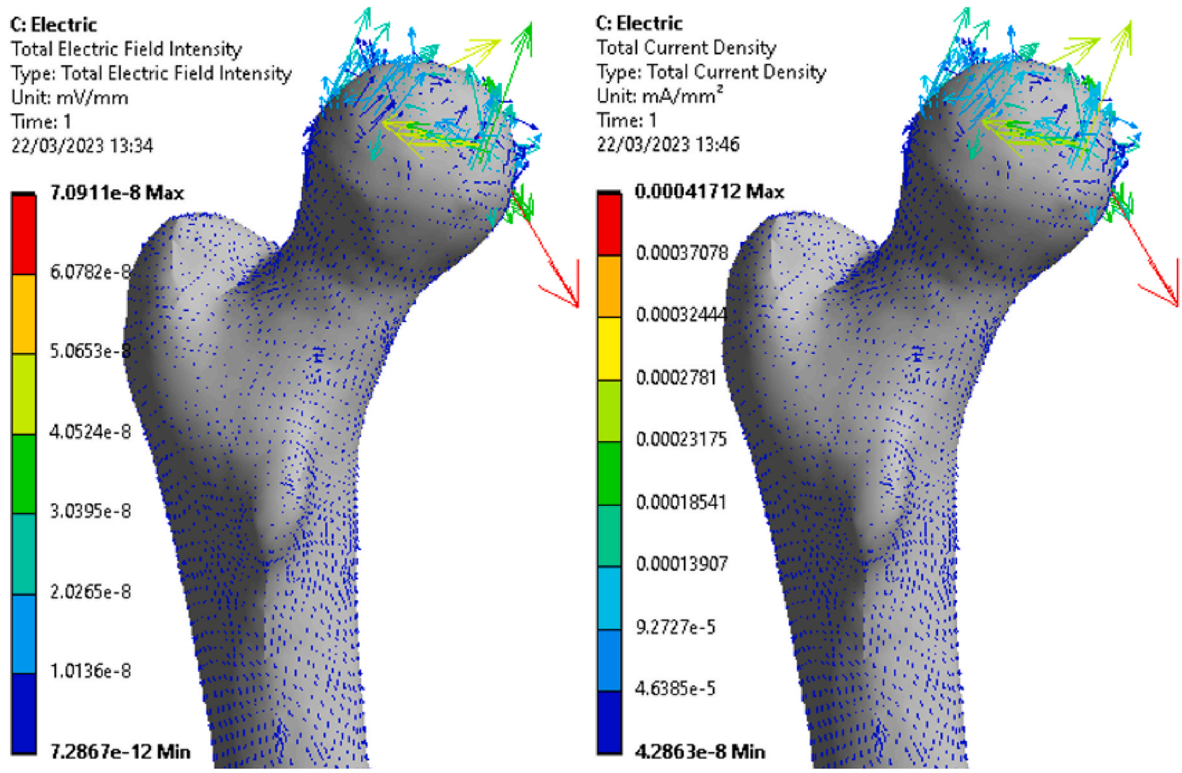


**Fig. 8.** Normalised electric potentials generated for total electric field intensity and current density.

was the density distribution following the remodelling phase. How strain-adaptive piezoelectric bone remodelling predicts bone density distribution after reduced physical activity has been demonstrated. The time of reduced physical activity illustrates how bone density varies in different regions due to decreased physical activity. In summary, the piezoelectric effect of bone tissue is an essential factor in bone health and disease. It plays a role in bone remodelling, healing and repair. It implies developing new therapies for bone-related conditions (Fig. 9).

This first innovative study created a framework based on Ansys to simulate strain bone modelling in the femur without and with the energy harvesting effect. Due to the difference in starting bone density values, the bone density distribution and average bone density were also different. Under normal circumstances, the piezoelectric effect makes bones less dense and makes people less active. The greater trochanter can be treated with therapeutic electrical stimulation during less physical activity. The results can be compared with mechanical stressors Fig. 10.

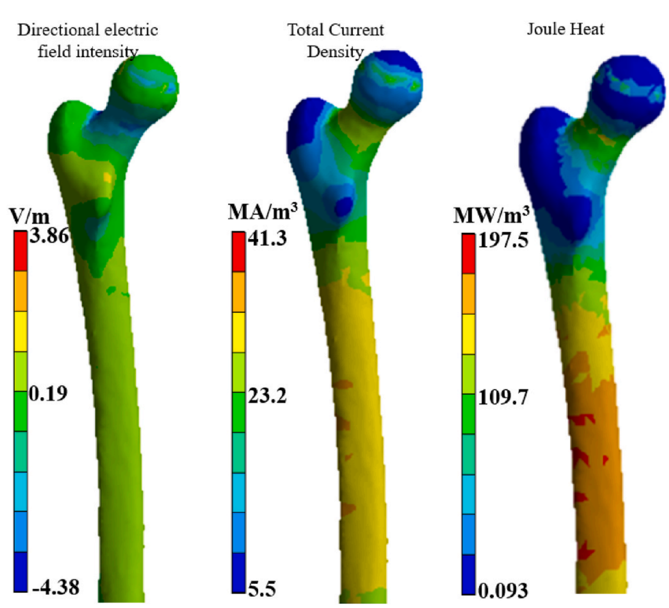


**Fig. 9.** Electric field generated of the directional and total current density of bone modelling showing a maximum Joule Heat after stress-strain loading.

## 4. Conclusions

In conclusion, this research provides valuable insights into the complex bone remodelling, healing, and repair process by investigating the piezoelectric effect-assisted strain-adaptive bone remodelling model. The study demonstrates that the piezoelectric effect plays a crucial role in bone health and disease, offering additional benefits compared to the strain-adaptive model alone. The piezoelectric effect is an essential factor in bone remodelling by enhancing the mechanical properties of bone tissue, promoting the formation of a more organised bone matrix, maintaining bone health, and preventing bone loss. The novelty of this research lies in its comprehensive exploration of the piezoelectric effect in bone tissue and its potential applications in therapeutic electrical stimulation (TES). TES is a promising, non-invasive therapy for bone-related conditions that utilise the natural properties of bone tissue, such as piezoelectricity, to promote healing and repair. This current research demonstrates that incorporating electrical stimulation on the surface of bones leads to increased bone formation. It further establishes that electrical charges can be utilised as an alternative to physical pressure for bone strengthening.

As a result, this innovative study presents a computational approach that combines the impacts of mechanical and electrical loads on bone response. This approach contributes to a deeper knowledge of bone energy harvesting/piezoelectricity in Ansys software. It holds the potential to aid future biological and numerical investigations necessary for advancing the fields of bone tissue and biomedical engineering. This research paves the way for further optimisation of TES parameters and

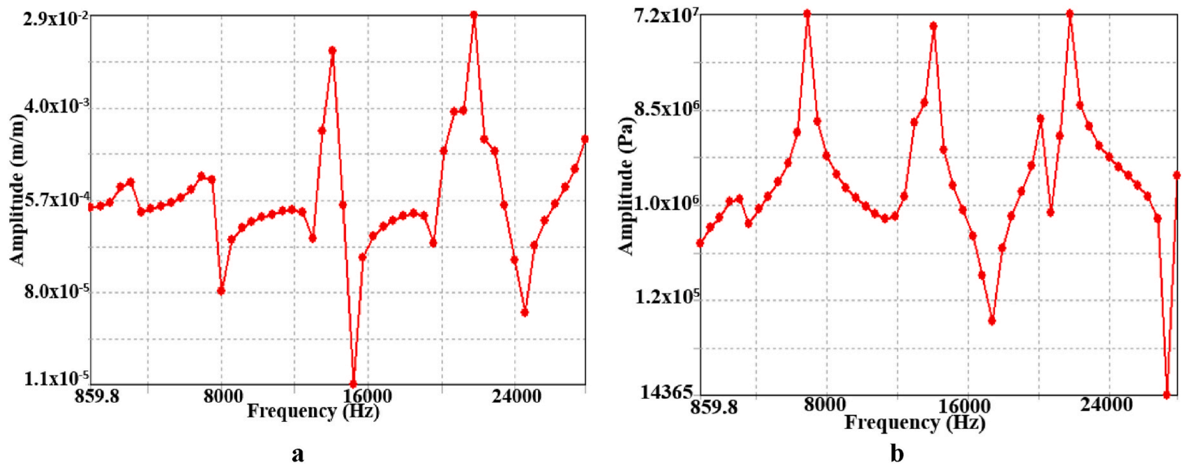


**Fig. 10.** A model of the solution modal of output result for the amplitude of (a) strain of loading (b) Stress of loading.

the development of standardised protocols for its use in femur bone therapy. Overall, this study shows a deeper knowledge of the piezoelectric effect in bone tissue and its implications for bone health and disease. By exploring the potential of piezoelectricity in developing new therapies for bone-related conditions, this research sets the stage for future advancements in bone remodelling and regeneration.

## Ethical approval

This study does not contain any studies with human or animal subjects performed by any of the authors.

## Compliance with ethics guidelines

None.

## Ethical statement

The authors declare no ethical issue; the study was conducted in complete agreement with ethical standards. Also, the manuscript is neither under review nor published elsewhere.

## CRediT authorship contribution statement

**Bankole I. Oladapo:** Data curation, Conceptualization, Formal analysis, Methodology, Investigation, Writing – original draft. **Sikiru O. Ismail:** Formal analysis, Methodology, Writing – review & editing. **Joseph F. Kayode:** Formal analysis, Software, Investigation. **Omolayo M. Ikumapayi:** Formal analysis, Software, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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