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Original Article

Modeling of Energy Generation Using Piezoelectric Material for Wearable Devices

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Abstract *- Piezoceramics hold the most significant market share among piezoelectric materials in the device sector. In addition to being employed for picture stabilization, they are also used in robotics, mechanics, and medicine. This substance is controlled and responds well to mechanical and electrical stimuli. Micro Electrical Mechanical Systems (MEMS), which have distinct qualities and a small size that enables them to be incorporated into nearly any product on the market, are currently being developed. Energy-collecting system research and development can benefit from simulation. In this study, a piezoelectric material is created and used to make shoes and other types of footwear. When put under pressure, the piezo material may become stressed, and the mechanical energy is transformed into electrical power. Using transducers, we can store energy that soldiers can use while conducting operations in the forest. An ideal geometry has been presented and studied using the analysis of a finite element geometry based on the electric response as a function of mechanical deformation. More technologies will have the possibility to profit from energy gathering as these devices' efficiency keeps increasing.*

Keywords *- Electric displacement, Electric potential, Finite Element Method, Lead zirconate titanate, Piezoelectric energy.*

1. Introduction

Piezoceramics are the piezoelectric materials with the highest market share in the device sector. They are utilized in image stabilization, robotics, and, last but not least, medicine. This material is manageable and has good mechanical and electrical response qualities. Simulation is a valuable tool for studying and improving energy harvesting systems.

A piezoelectric accelerometer is constructed and optimized in this work using simulation. An optimal shape has been proposed and investigated based on the electric response as a function of mechanical deformation and the finite element analysis approach using the Comsol Multiphysics software package.

Battery or power retention concerns pose the soldiers' most significant difficulties during jungle operations. This is one of the DRDO's (Defence Research and Development Organisation) most important research emphasis areas. Since conventional energy is insufficient to supply electrical needs in remote locations, particularly thick forests, a novel energy harvesting device must be invented to address the abovementioned issue. A low-cost wearable piezoelectric energy harvesting system that generates electric potential at the human foot by biological pressure is proposed in this work [1-6].

2. Literature Review

The rapid growth of wearable technology has fundamentally changed how we use and incorporate technology into our daily lives. Developing wearable technology while guaranteeing a sustainable and dependable power source that can fulfil the rising energy needs of these devices is one of the most significant difficulties. Piezoelectric materials have come to light as a viable response to this problem for energy production in wearable technology.

The capacity of piezoelectric materials to transform mechanical energy, such as vibrations and deformations, into electrical power is unmatched. Due to this characteristic, they are the best choices for capturing energy from bodily motions, environmental vibrations, and even physiological processes. Piezoelectric materials are used in wearable technology to increase energy efficiency while lowering reliance on traditional battery technologies, helping to create a more sustainable and environmentally friendly future [7-12].

A distinctive quality of piezoelectric materials is their ability to transform mechanical energy such as vibrations and deformations-into electrical power. Because of this feature, they are an appealing option for energy harvesting in wearable technology. The organic polymers Polyvinylidene Fluoride (PVDF), Lead Zirconate Titanate (PZT), and others are frequently used piezoelectric materials. Several modelling strategies have been implemented to comprehend and improve the energy generation process using piezoelectric materials in wearable devices. These strategies can be divided into experimental, numerical, and analytical approaches.

Mathematical equations often express the relationship between mechanical stress/strain and electrical output in analytical models. These models shed light on the fundamental ideas underlying piezoelectric energy conversion, but they could oversimplify the intricacies of the real world. On the other hand, numerical simulations use computer methods like Finite Element Analysis (FEA) to portray the energy generation process better. The optimization of device design is made possible by FEA, which enables researchers to consider complex geometries and material properties [13-18].

Numerous research studies have examined the connection between the energy generation efficiency of wearable devices based on piezoelectric technology and design factors like size, shape, and material choice. To maximize energy output, these parameters must be optimized.

Wearable technology can capture mechanical energy from various sources, such as breathing, background vibrations, and body motions [19]. To create effective energy harvesting devices, modelling efforts have been concentrated on characterizing multiple energy sources. Piezoelectric materials present hurdles in mechanical stability, longevity, and aesthetics when incorporated into flexible, comfortable wearable devices. Models aid in foreseeing and resolving these problems. To increase overall energy autonomy and reliability, some study examines integrating various energy harvesting techniques, including piezoelectric, solar, and thermoelectric [20-23].

While less piezoelectric and dielectric than ceramics, polymers are soft and flexible. PZT [24] stands for Lead Zirconate Titanate (Pb (ZrTi)). It is currently one of the most widely used piezoelectric ceramic materials. Also, it was shown that several piezoelectric nanoparticles (ZnO, MnO, and PZT) and graphene nanopowder could be dispersed in a silicone matrix to create flexible nanocomposite-based Piezoelectric Nanogenerators (PENGs). The next step in demonstrating the usefulness of PENGs was the development of a fully functional Shoe-Insole Nanogenerator (SING). The SING generated significant open-circuit voltage (27V), short-circuit current, and power density under real-time human walking [25]. The Triboelectric Nanogenerator is a revolutionary type of energy source (TENG).

TENGs transform mechanical energy captured from the environment into electricity for small devices like sensors or consumer electronics recharging [26, 27]. Also, a simple and affordable manufacturing technique for effective, skin-friendly, and highly stretchy biomechanical piezoelectric sensors is suggested. Stretchable electrodes made of multiwall carbon nanotubes and silicon were prepared in this regard to work with the sensors. The constructed sensors responded well to practically every joint movement, and the electrodes exhibited stability even under significant uniaxial elongation. This is entirely based on PZT Mechanical Energy Harvest (MEH).

Bioelectronic devices, including pacemakers, implanted cardioverter defibrillators, and heart rate monitors, will be continuously diagnosed with or without the battery aid mode. The human body’s chemical, mechanical, electrical, and thermal activities can generate electricity in various ways, including by swapping out batteries [28]. Determine the electric field and displacement in the PZT using constitutive modes of piezoelectric behaviour by capturing the type of deformations in distinct device layers. The potential for a wide range of devices in energy generation and harvesting, sensing, and biological applications has focused primary research on environmentally benign, adaptive, and durable sensors.

Utilizing a nanocomposite film composed of MgO nanoparticles with widths of around 50 nm embedded in PVDF [29]. According to measurements of the piezoelectric, ferroelectric, and leakage on current samples containing various concentrations of MgO nanoparticles, these properties drastically improved at two wt% MgO, with a roughly 50% increase in the piezoelectric coefficient compared to pure PVDF.

The outcomes indicated that the manufactured PENGs might be applied as self-powered biomechanical energy harvesters/sensors in wearable electronics, haptic sensing, or Internet of human applications. Piezoelectricity is based on the polarisation effect on the piezoelectric material; this polarization does not happen simultaneously. When the stress is applied, polarisation is generated in every unit cell of the piezoelectric material [30-32]. The primary objectives of piezoelectric material energy generation modelling for wearable technology are to increase wearable technology’s efficiency and sustainability. First and foremost, the aim is to create precise mathematical models that forecast energy output based on various variables, including material qualities, device design, and human motion.

The method of wearable technology is also being optimized to enhance energy harvesting, resulting in longer battery life and less negative environmental impact. It also intends to investigate creative applications of piezoelectric materials, such as their incorporation into apparel and accessories, to enable self-powered wearables. The ultimate objective of this research is to develop wearable technology by offering adequate and sustainable energy solutions. Figure 1 illustrates the overall mechanism of piezoelectricity.

3. Methodology

Piezoelectric materials can produce energy through various mechanical forces, including tensile, compressive, expansion, compression, and shear deformation. A thorough methodology combining materials science, physics, and engineering principles is required to model these mechanical forces. By utilizing piezoelectric materials' unique ability to transform mechanical stress into electrical energy, this method uses their value in various fields, including energy harvesting and sensor technologies. Conversely, compressive force entails exerting pressure on the piezoelectric substance to modify the crystal lattice structure. Electric charges are produced by this deformation, which can be harnessed to produce electrical energy.

The applied force distribution, the material's response to compression, and piezoelectric coefficients must be considered to describe this process effectively. Two opposing forces, contraction and expansion, combine to produce piezoelectric energy. While reduction entails compressing the material, development includes extending it. Both procedures cause the fabric to become strained, which results in the production of electrical charges.

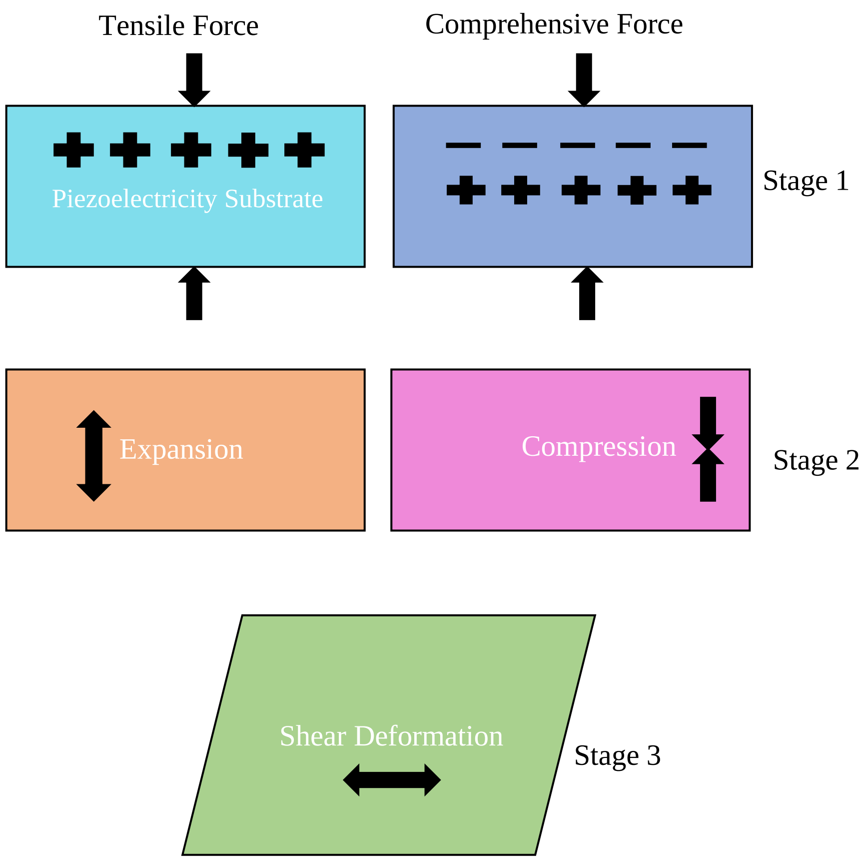

Fig. 1 Mechanism of piezoelectricity

The mechanical characteristics of the material, such as its elasticity and piezoelectric coefficients, as well as the magnitude and direction of applied forces, must be thoroughly investigated to model this phenomenon. When the material is subjected to stresses that are applied parallel to its surface, shear deformation, another crucial aspect of piezoelectric energy generation, occurs. This produces a shear stress, which can lead to charge separation inside the material and the creation of electrical energy. Understanding the material's anisotropic nature and how it reacts to shear pressures is necessary for modelling shear deformation. Finite element analysis, which aids in simulating the behaviour of piezoelectric materials under various mechanical loads, is a crucial component of a thorough methodology for modelling piezoelectric energy production. Using this method, professionals in the sciences can forecast the electrical output of a specific piezoelectric device under various circumstances. In COMSOL multi-physics, the stress and strain tensors are represented using the Voigt notation. Although stress and strain are tensors, they can also be written as vectors due to the symmetry of the tensor. The direct piezoelectric effect is given by in Equation (1),

$$\vec{P}_{piezo} = d\,\vec{T} \tag{1}$$

Where, The immediate piezoelectric effect is defined in the following equation (2),

$$\vec{D} = \in^{T} \vec{E} + d\,\vec{T} \tag{2}$$

Where,

$\in^{T}$: Applied electric field V/m

$\vec{E}$: Permittivity in F/m^2 under constant stress $\vec{T}$

For zero external mechanical stress, the inverse piezoelectric effect is described in equation (3),

$$\vec{S} = d^{T} \vec{E} \tag{3}$$

The total strain $\vec{S}$ with the piezoelectric effect is defined in Equation (4),

$$\vec{S} = S^{E} \vec{T} + d^{T} \vec{E} \tag{4}$$

Where, S^{E} is the compliance [m^2/N] for a constant electric field.

Combining Equations (2) and (4) leads to (5), which combines both direct and indirect piezoelectric effects in the strain-charge form.

d : Piezoelectric charge constants in C/N

$\vec{T}$: Applied stress in N/m^2

$\vec{P}_{piezo}$: Mechanical induced polarization in C/m^2

$\vec{D}$: Total electric displacement in C/m^2

$$\begin{bmatrix} \vec{S} \\ \vec{D} \end{bmatrix} = \begin{bmatrix} S^{E} & d^{T} \\ d & \in^{T} \end{bmatrix} \begin{bmatrix} \vec{T} \\ \vec{E} \end{bmatrix} \tag{5}$$

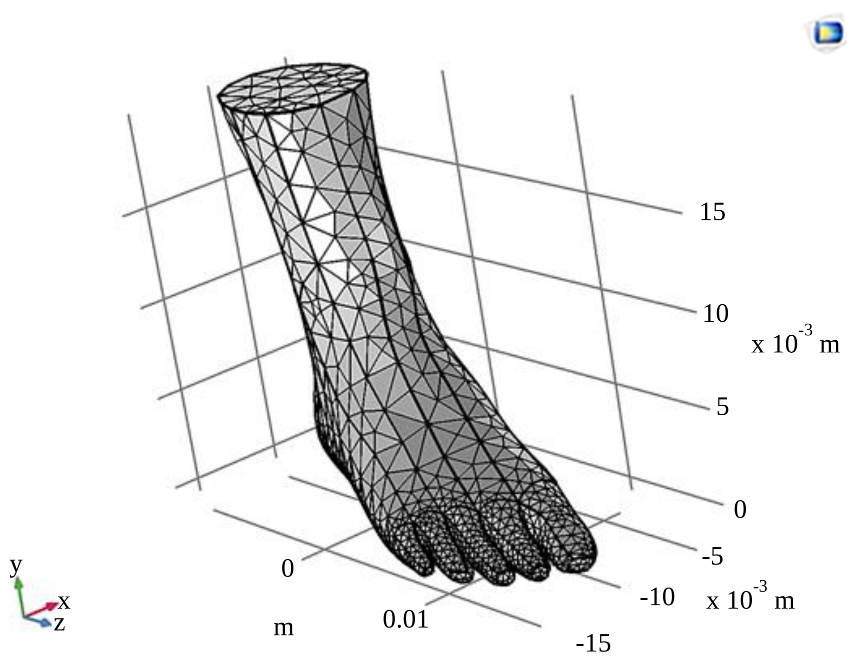

Fig. 2 Mesh of the foot sample

4. Results and Discussion

Mesh analysis yielded a 3D representation of Von Mises stress in a piezoelectric foot sample that sheds light on the material's mechanical properties. Due to their ability to change mechanical stress into electrical voltage and vice versa, piezoelectric materials have unique characteristics. Understanding Von Mises stress is essential for evaluating the structural integrity of a foot sample and its potential to produce electrical signals during weight-bearing activities.

Figure 2 illustrates the mesh of the foot sample of the executed system. The colour or height of the surface in the figure denotes the Von Mises stress distribution, while the x, y, and z axes represent the geographic coordinates inside the foot sample.With this knowledge, scientists and engineers may locate stress hotspots, probable failure places, and areas where piezoelectric effects might be most noticeable. Scientists may modify the design of the piezoelectric components in the foot sample, enhancing their performance and durability for various applications, such as energy harvesting or biomechanical sensing, by visualizing this data in three dimensions. Such research is essential for developing piezoelectric materials for innovative medical and energy-harvesting applications.

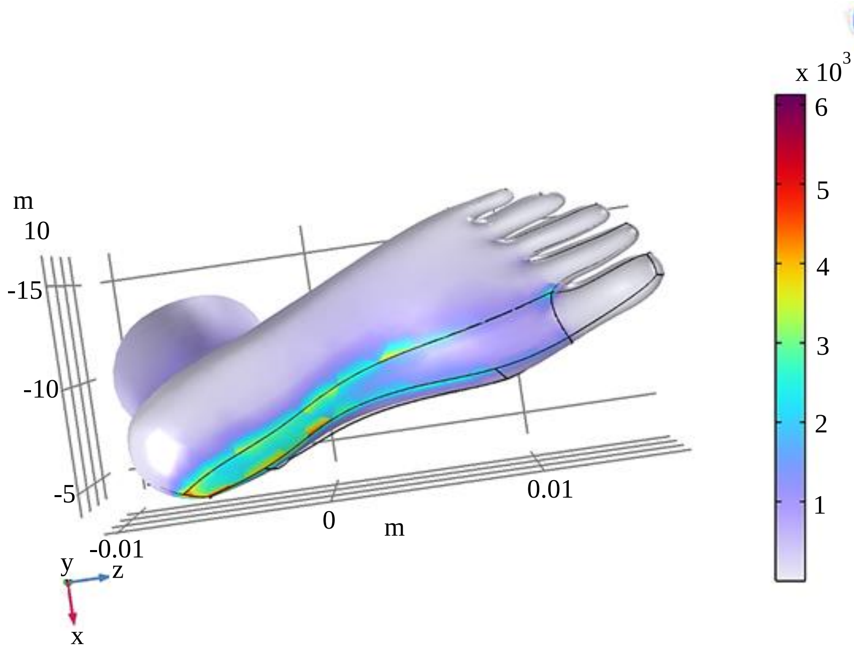

Fig. 3 3D plot for Von Mises stress of foot sample

Stress analysis can be used to assess the integrity of a vessel, machine, or component. This fundamental stress analysis calculates the weight a structure can support per square inch. A thorough stress analysis can assist you in avoiding physical and monetary damages. The study of strains and stresses happens when structures and materials are subjected to forces. Stress can cause materials to crack or deform. Stress analysis determines the amount of stress that causes deformation in a particular material. When the basis of other stress tensors is zero, the components of priorities are known as maximum core stresses, which describe the tension concentrated in a specific place.

The Von Mises stress, on the other hand, is a scalar quantity that is derived from the pressures applied to any structure. Von Mises Stress is viewed as a haven by design engineers. Using this knowledge, an engineer can state that his design will fail if the greatest Von Mises stress that the material can withstand exceeds the material's strength.

The Von Mises failure theory states that a material will fail if its Von Mises stress, or effective stress, under a load, is equal to or higher than its yield limit on a simple uniaxial tension test. Von Mises stress (N/m^2) units are used to measure it, and the maximum values for women are 7x105 N/m2 and 1x105 N/m2, respectively. The ankle and heel held the most tension, and the shin points had minor pressure. The most stress is represented by red, while the blue represents the least stress. The boundary load, the terminal selected topics, the boundary load in Pascal, and the boundary load in the geometry's -Y direction all contribute to the stress. According to the materials, the foot pressure is delivered at roughly 60000 for men and 40000 for women. Figure 3 illustrates how less tension is created due to less force applied to the foot.

The maximum voltage shown is 130 mV, and the lowest value is -20 mV. The ankle had the highest electric potential, with the shin, heel, and above-the-heel areas having average and low electric potentials. As the colour gradually fades, blue represents maroon red, which denotes more electric potential, while yellow symbolizes low average electric potential. The electric potential in this model is lower even though it can be maintained as power and is based on the pressure applied to the foot, as shown in Figure 4.

The estimated and observed findings of the piezoelectric material system are shown in Table 1. When something is referred to as 3D, it always refers to having three dimensions, much like a genuine object would. In 2D animations, characters and objects are only perceptible regarding their X- and Y-axis height and width. Depth is the third dimension in

3D animation. As a result, characters look much more realistic than they would in 2D. Figure 5 depicts the field behaviour of an applied stress and a typical electric displacement. The variance is discovered to be between 0 and 45 C/m^2. The most vital electric fields have been at the calcaneus and heel of the hind foot. The boundary load impacts the lateral cuneiform, intermediate, navicular, and talus. 17.23 MPa is the applied boundary load.

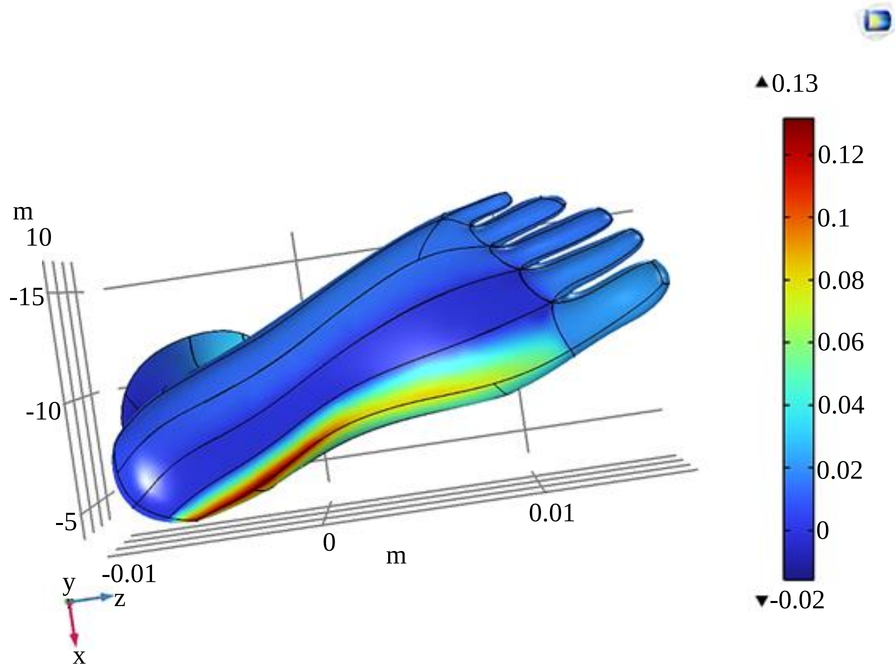

Fig. 4 Foot sample showing electric potential

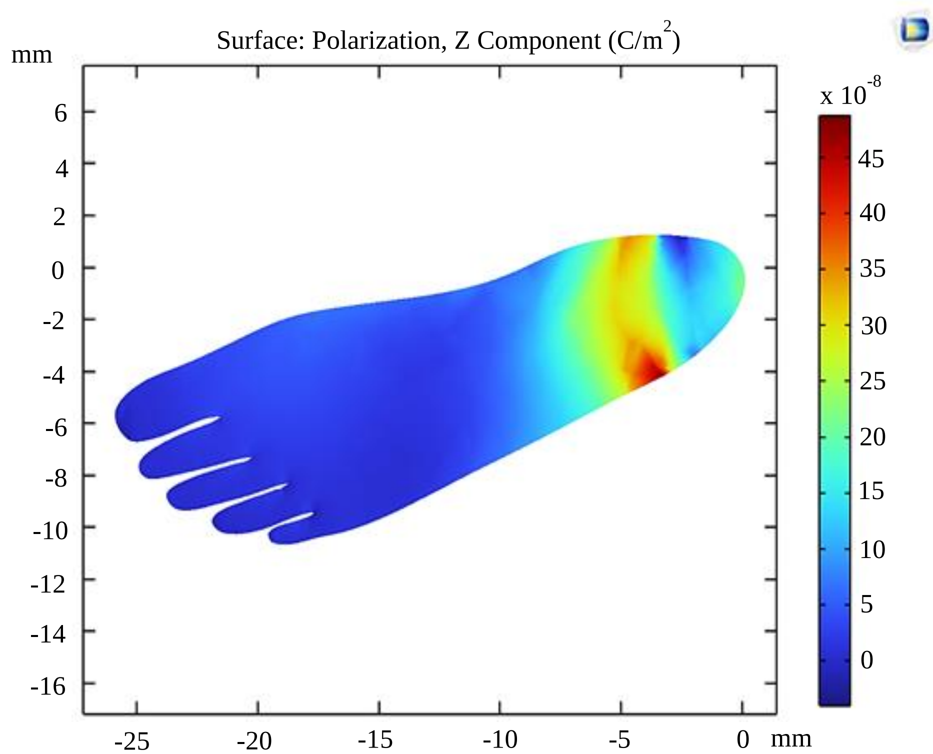

Fig. 5 Foot sample showing the displacement in 2D

According to animators, the fundamental difference between 2D and 3D animation is that the former is more artistic while the latter is more mechanical or technical.

Each 2D frame has to be drawn extensively, either by hand or with a computer tablet. Creating two-dimensional plans, designs, and drawings is known as two-dimensional modelling. These articles can explain a place's broad structure and locations, but the depth dimension is absent. Figure 5 displays the foot's displacement graph in two sizes at a force of 24.13 MPa. Any value between 0 and 2 nm can be the displacement. Between 1.6 and 4.5 nm is the range of the highest removal at the heel. No displacement exists at the toe. As it approaches the heel, it linearly grows over time.

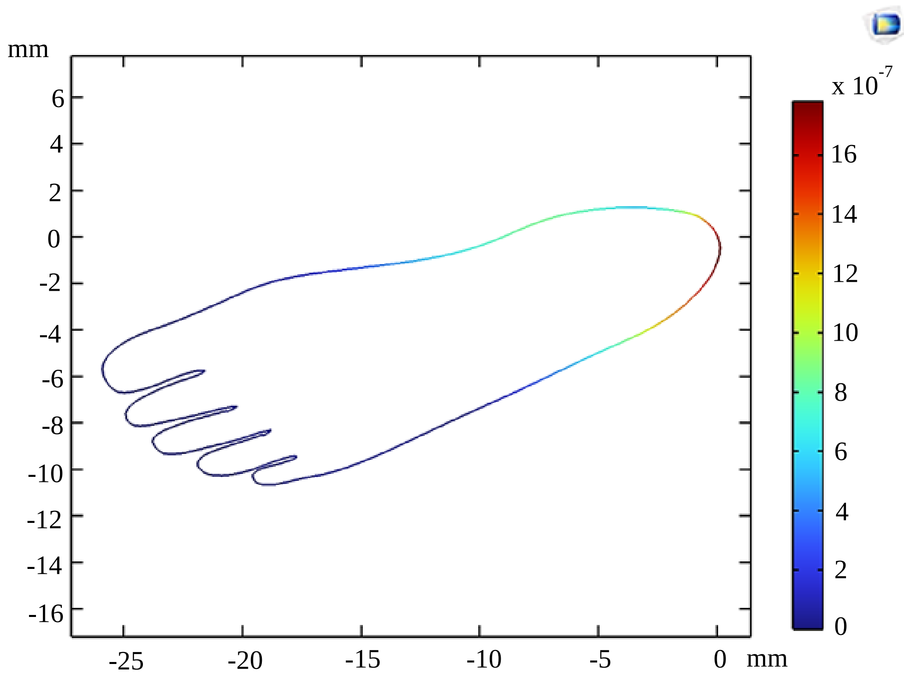

Fig. 6 Foot sample showing the displacement in 1D

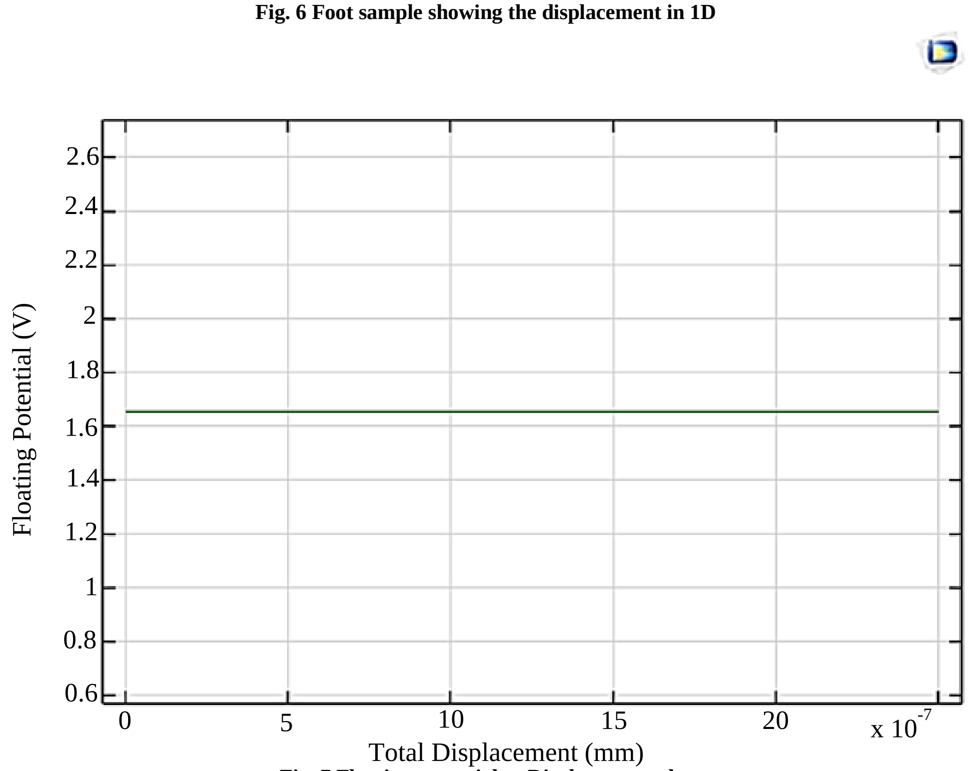

Fig. 7 Floating potential vs Displacement plot

A complex system's dynamics and interactions can be mathematically represented using a 1D system model. Using a library of modules and the object-oriented paradigm makes it possible to reuse model components. Geophysical observations can be performed in 1D, 2D, or 3D, depending on how the data is collected and processed. 1D measurements only collect data below a single point at the surface, while 2D measurements provide a profile, and 3D measurements cover a ground volume. A 3D simulation shows how individual components interact with this more extensive system instead of a 1D simulation, which offers a system's complete design and interactions between its many features. Figure 6 displays the foot sample's 1D graph along with its displacement. The heel has a maximum of 1.6 nm.

A floating potential, as depicted in Figure 7, is stated to exist in an isolated ideal electric conductor where there is no flux through the surface. The floating possibilities can be directly incorporated into the calculations, or a dielectric medium with a high permittivity can imitate them.

The global parameters of the node, such as the voltage, are identified using it. The Floating potential group check box on the settings window for floating potential regulates how potentials are assigned to boundary segments in the boundary selection of the feature. 1.64 V is displayed in the figure's floating potential. Figure 8 compares the various parameter values used to compute and simulate the piezoelectric effect.

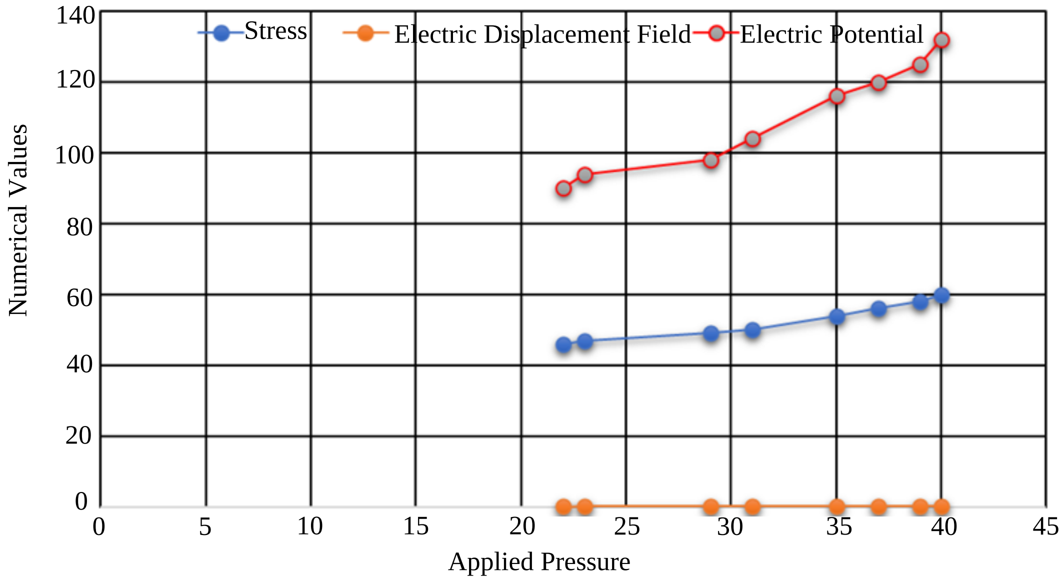

Fig. 8 Comparison graph of simulated and calculated values of various parameters involved in the piezoelectric effect

Table 1. Calculated and observed results

Applied Pressure (MPa)		Stress (MN/m^2)		Electric Displacement Field (µC/m^2)		Electric Potential (mV)	
Simulated Values	Numerically Calculated Values	Simulated Values	Numerically Calculated Values	Simulated Values	Numerically Calculated Values	Simulated Values	Numerically Calculated Values
20	22	44	46	0.05	0.07	88	90
24	23	48	47	0.06	0.08	95	94
28	29	50	49	0.08	0.09	101	98
32	31	52	50	0.09	0.11	108	104
34	35	55	54	0.10	0.13	115	116
36	37	58	56	0.15	0.17	121	120
38	39	60	58	0.19	0.18	126	125
40	40	65	60	0.22	0.2	130	132

5. Conclusion

The energy produced by this effort can be saved and used for private purposes, such as a torchlight or mobile charger. This concept benefits rural areas and indigenous groups that inhabit forested areas. The only dimensions of a two-dimensional form are length and height. 2D shapes include things like a square, triangle, or circle. On the other hand, a three-dimensional shape has three dimensions: length, breadth, and height. Length and height measurements are displayed in two dimensions on a flat, depthless surface. Even though 3D drawings or models are mentioned, they describe an object's height, width, and depth. The whole displacement of the leg is shown in the illustration at the ankle. The ankle's maximal electric potential is 130 mV. The research's future potential can be realized by making piezo materials that can be applied to garments. We can produce the 130mV required to activate diode base applications while travelling.

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