ABSTRACT: Among the wearable sensor family, the triboelectric nanogenerator has excellent potential in human healthcare systems due to its small size, self-powered, and low cost. Here is the design and simulation of the triboelectric nanogenerator using the 3D model in COMSOL Multiphysics software for blood pressure measurement. As a reliable indicator of human physiological health, blood pressure (BP) has been utilized in more and more cases to predict and diagnose potential diseases and the dysfunction caused by hypertension. The main focus of this study is to prognosis and preserve human health against BP. It is one of the significant challenges in predicting and diagnosing BP in the human lifestyle. The self-powered triboelectric nanogenerator can diagnose BP using the wrist pulse pressure. To optimize the performance of the modeled triboelectric nanogenerator, the known wrist pulse pressure is applied explicitly, which converts the applied pressure into an equivalent electrical signal across the output terminals. An output open circuit voltage for the applied pulse pressure is 26 V. The generated output electrical signal is proportional to the applied pulse pressure, which is used to know the BP range. It ensures that the triboelectric nanogenerator is an opted sensor to sense the minute nadi pressure signal. This work validates that the simulated model has the potential to act as several health care monitors such as respiratory rate, heart rate, glucose range, joint motion sensing, gait, and CO₂ detectors.

1. INTRODUCTION

In the modern lifestyle, wearable sensors in biomedical monitoring systems provide tremendous health information on an individual’s physiological parameters such as blood pressure, heart rate, pulse rate, respiration rate, lactate concentration, and temperature.1−4 Wearable sensors are low cost, flexible, light in weight, easy to design, highly comfortable to wear and have self-powered capability. Several wearable biosensors are available to harvest the subtle biological signals, such as strain gauge, piezoelectric, piezoresistive, capacitive, and triboelectric nanogenerators (TENGs).3,4 Among the listed wearable sensors, the TENG has recently gained considerable attention due to its high conversion efficiency at low-frequency mechanical loads, compactness, and ease to manufacture.5 TENG is an elongated application of Maxwell’s equation; it was first demonstrated by Prof. Zhong Lin Wang’s at the Georgia Institute of Technology. The TENG carries a pair of opposite triboelectric characteristic polymer materials. One will gain the electrons from that pair, and another will lose the electrons.

Both materials are placed on one another. When the pair of triboelectric materials are rubbed or touched, the charge transaction takes place between the paired material in a combination of triboelectrification and electrostatic induction.6

In this research, the TENG is modeled to harvest the wrist pulse pressure for diagnosing hypertension. Since hypertension is not maintained within the specified limit, it is the major impetus to cause diseases in the heart, peripheral arteries, brain, kidney, and premature death.7 The World Health Organization reported that worldwide about 1.28 billion people aged more than 30 years had hypertension in 2021. Estimation states that 46% of adults and 42% of less than half of the adults with hypertension are diagnosed and treated.8

The Nadi signal is used to detect blood pressure in the ancient method and it is named as Nadi Pariksha. Among the vata, pitta, and kapha nadi, the abnormality in vata nadi is the main symptom of blood pressure. Hence, it is used to detect blood pressure.9 The vata nadi has high pressure compared to pitta and kapha nadi, as shown in Figure 1.10 Therefore the modeled TENG is also suitable for harvesting the vata nadi to measure
blood pressure. For simulating the modeled TENG, the wrist pulse pressure is less than 3 kPa, which is applied externally to the modeled TENG, which converts the given pulse pressure into an electrical signal. The generated electrical signal is used to know the range of hypertension. The TENG converts an externally given wrist pulse pressure into an electric signal. Hence, it ensures that the TENG is a self-powered wearable sensor.

Based on the structural arrangement and working principle, the operating modes are classified into four methods, they are vertical contact-separation mode, lateral sliding mode, single electrode mode, and freestanding triboelectric-layer mode. Among the four modes, the vertical contact-separation way produces high output. Hence, this model is preferred in this research. In addition, triboelectric production also depends on the surface roughness to increase the surface roughness. Some structures are introduced on the tribomaterials, which increases the friction effect between tribomaterials due to these induced potential differences also increases. Several TENGs are modeled and simulated in COMSOL multiphysics software as follows: Mainra et al. in 2022 modeled and simulated the three different TENGs with different triboelectric materials, and their output voltages were distinguished. Then, the variations on output voltage concerning change thickness of the triboelectric material are also done. Mathew and Vivekanandan in 2022 designed a 2D model of single electrode mode TENG (SE-TENG) to harvest the wrist pulse single and optimize the suitable thickness and area of the SE-TENG. Also concluded was the surface morphology to obtain the maximum output voltage of the designed SE-TENG. Through the simulation can find the optimized materials, shape, and surface morphology for improving the output voltage of the modeled TENGs. The various healthcare devices worked based on the TENG principle are listed below.

Zhang et al. in 2019 introduced a wearable wireless respiration sensor to monitor respiratory rates. The modeled TENG is placed on the wearable bilayer belt. The materials used in the modeled TENG are polytetrafluoroethylene (PTFE) and copper. Here, the PTFE acts as a negative layer thickness of 100 μm, and the nylon acts as a positive layer whose thickness is 30 μm, respectively, and then the two copper foils each with a thickness of 50 μm, are fixed on the outer surface of the tribolayers. Two acrylic sheets are used to maintain the two dielectric layers in a flat shape. The overall size of modeled TENG is 5 × 5 cm² which is covered by the plastic sleeve to ensure the contact between the tribolayers while monitoring the respiratory rate. The designed belt is fixed on the circumference of the abdomen. The variation in the abdominal pressure makes the TENG operate on lateral sliding mode with the amplitude of traction force of 3.09 N and sliding displacement of 2.5 mm, which produces the electrical signal between the electrodes of modeled TENG. Thus, the generated electrical signal is used to know the respirator rate.

Lin et al. in 2017 presented a wireless self-powered body sensor network (BSN) for real-time non-invasive heart rate monitoring. This monitoring system carries a downy structured TENG (D-TENG), heart rate sensor, power management circuit, signal processing unit, and Bluetooth module. The downy structured TENG (D-TENG) consists of two multi-layered structural units, the first unit is composed of copper back-coated PTFE. The second unit is composed of copper thin films, and both teams have acrylic back support. In each unit, the thin films are fixed with an acrylic frame on one end, and the other ends are left free. These two unit films are arranged alternatively to form a downy-like structure. Finally, the entire system is covered by stretchable rubber. The modeled BSN harvests the human walking inertia energy into an electrical signal with the conversion efficiency of 57.9% and the maximum generated electrical power as 2.28 mW at a low frequency. The BSN system uses this generated power to acquire the heart rate signal.

In 2019, Lin et al. demonstrated an intelligent insole for real-time gait monitoring based on a TENG. On the front and rear of the insole, two TENG-based sensors are placed. To design the top layer of the TENG, a convex cambered rubber film with a 20 mm diameter is used, over the rubber film, a copper film is attached, which acts as a shielding layer, and for the bottom layer, a copper film supported by an acrylic layer is used. An elastic air chamber is placed between the TENG and the insole to hold the air temporarily from the TENG. An applied external pressure makes contact between the tribolayers resulting the contact electrification with a low response time. The proposed TENG distinguishes the different gait patterns such as jump, step, run, and walk. The patients’ data collected from the smart sensors are analyzed for rehabilitation assessment. This sensor also acts as an alert system for aged people and patients to detect their fall down events.

Wang et al. in 2017 developed a portable amenity sensor based on a water–air TENG (WATENG) to detect CO₂ concentration. The WATENG top layer is air with ITO electrode and wetted sponge with PET electrode is the bottom layer, between the two layers PDMS is suspended which separate both layers. The structural arrangement of WATENG can eliminate the two significant interference on the self-powered sensor. The two independent transferred charges are used to characterize the effect of force and humidity. The WATENG with polyethyleneimine (PEI) coating can sense the CO₂ in static and dynamic conditions. The modeled WATENG sensing range can be up to 6000 and 30,000 ppm in static and dynamic conditions. During the CO₂ concentration measurement, the coated PEI on the top electrode can absorb the CO₂ and then change the electronegativity on its surface. Thus, the change electronegative is used to measure the CO₂ concentration.

Pu et al. in 2018 developed a wearable joint motion triboelectric quantization sensor (jmTQS) for robot joint gesture control and rotation sensing via human gestures. The modeled TENG has two parts one is the electrode part, and another one is the slider part. To design the set electrode part, an acrylic sheet with 1 mm thickness is used, which acts as a substrate over that copper is coated with the consistency of 200 nm by vacuum magnetron sputtering. Later, the surface-modified FEP film with a thickness of 25 μm is placed over

**Figure 1.** Illustration of vata, pitta, and kapha nadi position.
one electrode, which acts as a sliding way. To design the slider part, 1 mm thickness sponge foam is used, placed on another with the minute gap, and electrodes are arranged on the back of the two layers. When the discrete type of physical interaction acts on the paired triboelectric layers, which creates a press and release, the charge transaction exists between the triboelectric layers as per the triboelectric effect and electrostatic induction. When the applied physical interaction is over, the paired dielectric layers are separated, and then, the induced opposite charge on the dielectric layer creates a potential difference between the electrodes, as shown in Figure 2. The induced potential difference is directly proportional to the given physical interaction on the dielectric layers.

The contact-separation mode is subdivided into two models based on the material used in the dielectric pair; they are dielectric-to-dielectric and conductor-to-dielectric model. The modeled contact-separation mode resembles the conductor-to-dielectric model; here, the positive dielectric acts as a layer and a terminal, but for the negative dielectric layer, the terminal is used separately from the negative dielectric. The theoretical model and equivalent circuit of the conductor-to-dielectric model are shown in Figure 3A,B.

To evaluate the $V=Q−x$ relationship of the designed conductor-to-dielectric model of contact-separation mode, assume the two dielectric layers’ thickness as $t_1$ and $t_2$ and their relative dielectric constant are $\varepsilon_{r1}$ and $\varepsilon_{r2}$ respectively. The distance between the two dielectric layers is represented as $x$, which varies based on the applied pulse pressure. When the pulse pressure acts on the two dielectric layers, the layers come into contact; due to the contact electrification on the two dielectric inner surfaces, the opposite tribo-charges exist with an equal density of $\sigma$. If the pulse pressure is absent, the separation operation takes place, and it increases the distance $x$ between the two layers, which induces the potential difference $(V)$ between the two dielectric layers. The total charge in metal 1 is based on the triboelectric charge $(S\sigma)$ and transferred charge between the two electrodes $−Q$. Thus, the total charges in metal 1 are $(S\sigma−Q)$, where $S$ is the area of the metal. In the experimental case, the area of the metal is larger than the separation distance $(d_1 + d_2 + x)$. Based on the electrodynamics, the output characteristics $(V_{OC}, Q_{SC}$, and $C)$ of the contact-separation mode are derived as follows.

$$V = \frac{Q}{S\varepsilon_0(t_0 + x(t))} + \frac{\alpha x(t)}{\varepsilon_0}$$  \hspace{1cm} (1)

The output open-circuit voltage $V_{OC}$ of the conductor-to-dielectric model of contact-separation mode is given by

$$V_{OC} = \frac{\alpha x(t)}{\varepsilon_0}$$ \hspace{1cm} (2)

The amount of charge transfer between the dielectric layers is obtained by

$$Q_{SC} = \frac{S\alpha x(t)}{t_0 + x(t)}$$ \hspace{1cm} (3)

The capacitance of the two separated dielectric layers are

$$C = \frac{\varepsilon_0S}{t_0 + x(t)}$$ \hspace{1cm} (4)

In the above equation, the effective dielectric thickness $t_0$ is the summation of the entire dielectric thickness $t_i$ between the two metal electrodes divided by its relative effective thickness $\varepsilon_{r_i}$ as shown below

$$t_0 = \sum_{i=1}^{n} \frac{t_i}{\varepsilon_{r_i}}$$ \hspace{1cm} (5)

When the $x$ is adequately large, the charge transfer efficiency $\eta_{CT}$ is defined as the ratio between the final transferred charges to the total triboelectric charges. The $\eta_{CT}$ is given as

$$\eta_{CT} = \frac{Q_{SC,final}}{Q_S} = \frac{1}{1 + \frac{C_1(x=x_{final})}{C_2(x=x_{final})}} - \frac{1}{1 + \frac{C_1(x=0)}{C_2(x=0)}}$$ \hspace{1cm} (6)

3. METHODOLOGY

3.1. Model Development. Here, the comsol multiphysics 5.2 is used to develop the computation model. In this module, structural mechanics and electrostatic are combined. A 3D
model is used in this study; the normal meshing and stationary study simulate the modeled system.

3.2. Geometry. The designed TENG model is shown in Figure 4A. It has two opposite polarity dielectric layers designed in a circular form to get uniform deformation among the entire layers. Here, the bottom layer is the negative polarity layer, and the top is the positive polarity layer. The bottom negative layer is designed with the dimension of 1 μm diameter and 0.18 μm thickness. Instead of a flat surface on the negative layer, the entire layer is structured with a square shape morphology with the dimension of 0.08 μm × 0.08 μm × 0.08 μm to enhance the output performance of the designed TENG. Compared to the other surface morphology, the rectangular-shaped surface TENG produced an improved output voltage, as shown in Figure 4B. The terminal of the negative layer is placed on the back with the dimension of 1 μm diameter and 0.2 μm thickness. The top positive layer is designed with the dimension of 1 μm diameter and 0.2 μm thickness, the same act as the terminal also. The two opposite dielectric polarity layers are separated with a 0.915 mm interval.

3.3. Material. The following materials are given to the modeled TENG. For the negative layer, the material PTFE is used. PTFE has a more negative charge compared to other negative charge materials in the triboelectric material series. To design the terminal of the negative layer, aluminum is used. Copper is used for the positive layer, and the same copper acts as a positive terminal. Therefore, it does not require any additional material for the positive terminal. Table 1 shows the parametric value for positive, negative, and terminal material.

3.4. Multiphysics. The solid mechanics interface is deliberated for structural analysis, which performs the analysis and produces the result based on the solution of Navier’s equation. In this system, solid mechanics convert the pulse pressure into a discrete form of displacement. The negative dielectric layer of the designed TENG is placed over the wrist position of the human, whereas the positive layer is placed over the negative layer with a small interval. The wrist pulse has slight pressure, which acts on one side of the negative layer; on the other side, the layer gets deformation. This deformation is used to harvest the biosignal into electrical energy. In addition to solid mechanics, electrostatics physics is also used in this model. Electrostatics physics solves Gauss’ law for computing the electric fields of the designed TENG. The solid mechanics interface discrete form displacement output makes contact and separation operation between dielectric layers. During the contact operation, the charge gets transaction between the dielectric layers, whereas during separation, the transferred charge creates a potential difference across the output terminals of the TENG, as mentioned in the mechanism of the TENG. The output potential difference is based on transferred charge density across the two dielectric layers, and the charge transaction depends upon the distance between the two dielectric layers.

3.5. Meshing and Study. Meshing splits the entire modeled structure into a small block before computing, making a fast computation response. In this system, normal and coarse meshing is used for simulating the model in solid mechanics and electrostatics interfaces. To study the simulated output response of the modeled system, the stationary study is used. The load is variable on both interfaces but does not depend upon the time, so the stationary study is enough for simulating the proposed system in solid mechanics and the electrostatic interface.
4. RESULTS AND DISCUSSION

A combination of solid mechanics and electrostatic physics is used to simulate the modeled TENG.

4.1. Solid Mechanics. Solid mechanics interface is used to convert wrist pulse pressure into a discrete form of displacement. Here, the boundary load and fixed constraint in the solid mechanics interface are used for simulating the designed TENG. The wrist pulse pressure is applied explicitly on the bottom surface of the negative layer by using the boundary load. The wrist pulse has a pressure in the range of 3 kPa; the vata nadi pulse pressure lies within this range, so this value is taken as a reference for simulating the modeled TENG. While applying the pulse pressure on the bottom of the modeled TENG negative surface, the circumference of the surface may expand or compress to avoid this situation whose circumference is fixed by using the fixed constraint option in solid mechanics. The

Figure 5. (A) Deformation of modeled TENG. (B) Total displacement of modeled TENG.

Figure 6. (A) Circular shape modeled TENG. (B) Square shape modeled TENG. (C) Circular and rectangular shape modeled TENG output characteristics between the applied pulse pressures vs displacement.
applied pressure creates a deformation on the negative layer, as shown in Figure 5A. This deformation creates a displacement on the TENG negative layer, whose maximum and minimum values are shown in Figure 5B. The deformed negative layer makes contact with the positive layer, so the negative charges in the negative layer will move toward the positive layer and the positive charges in the positive layer will move toward the negative layer until the contact operation completes. During the absence of pulse pressure, the separation operation exists now that the tribolayers are separated. Hence, the transferred charge between the two layers creates a potential difference across the output terminals. An induced potential difference across TENG output terminals is the proposition of the amount of charge transferred between the tribolayers. The transferred charge between the tribolayers depends upon the range of the negative layer that makes contact with the positive layer. Finally, the negative layer contact range is based on the applied pressure.

4.1.2. Benefits of Circular Geometry. The layers of TENG are designed in circular and square shape geometry, as shown in Figure 6A,B with the same dimension. In the circular shape geometry, the applied pulse pressure is distributed uniformly on the entire surface of the negative layer due to this having a maximum displacement on the negative layer as a result; it produces a maximum charge transaction between the two tribolayers, hence having an improved output voltage in the circular geometry. Whereas in square shape geometry, the applied pulse pressure is distributed unevenly on the entire surface of the negative layer, which makes less displacement on the negative layer. Due to this, the transferred charge between the tribolayers is low. Hence, the induced output voltage is also very low here. It is evident that the circular geometry handles the applied pulse pressure in a helpful form and converts it into an equivalent displacement. It ensures that the circular geometry is an optimum shape for designing the TENG for harvesting the wrist pulse pressure. Moreover the graph distinguishes the applied pulse pressure versus displacement of circular and rectangular shape sensors as shown in Figure 6C. It is clear that the circular-shaped sensor produces more displacement for the applied 500−3000 Pa of pulse pressure instead of the rectangular-shaped sensor.

4.1.3. Point Diagram. Selecting the point graph option in the result of the solid mechanics interface can get the linear characteristics between the applied pulse pressures and displacement that occurred on the negative layer. Select some points on the designed TENG negative layer to obtain these characteristics. For example, Figure 7A depicts that six points have been chosen on the entire surface of the negative layer of the modeled TENG to view those particular points’ applied pulse pressure versus displacement characteristics. Figure 7B shows the linear characteristics between the applied pulse pressure and displacement for the selected single point at the center of the modeled TENG negative layer. Hence, it has a maximum displacement because the applied pulse pressure penetrates more toward the center of the negative layer in a circular geometry. Similarly, Figure 7C shows the three-point characteristics; here, three different points have been selected on the negative layer, which is at the center and apart from the center, whose magnitudes of displacement are varied based on the

Figure 7. (A) Point selection on the designed TENG, (B) one-point straight-line characteristics, (C) three-point straight-line characteristics, and (D) six-point straight-line characteristics.
selected points. For the six-point characteristics, six different points have been chosen on the entire negative surface of the model whose outputs are in different magnitudes, based on the selected points as shown in Figure 7D. It describes that all together are in straight-line characteristics.

### 4.2. Electrostatics

Finally, an electrostatics interface is used to convert the displacement into voltage. The surface charge density and other parametric values for the positive and negative layers of the modeled TENG are given as per the value mentioned in Table 2. The floating potential is used to obtain the open-circuit voltage across the positive layer and ground; the ground is made on the bottom of the negative layer. The maximum displacement on the negative layer of the modeled TENG for the applied 3 kPa of pulse pressure in the solid mechanics interface is 0.915 mm, which is the input to this electrostatics interface. This value is used to maintain the distance between the two triboelectric layers of the modeled TENG. After computing the simulation, the modeled TENG converts the given displacement into an electric potential of 26 V, as shown in Figure 8A. The line graph option in the electrostatics interface is used to view the generated output voltage. The parabolic and straight-line characteristics in the line graph are used to obtain the generated output voltage in a different form. To get the parabolic characteristics, an arc length has to be selected on the top surface of the positive layer. After selecting arc length using the plot, the option can get a parabolic curve between the arc length is chosen and electric potential, as shown in Figure 8B. Then, to get the straight-line characteristics, the entire circumference of the positive layer has to select. Here, the whole rim is split into four sectors equally; each sector has a start and endpoint, so the four sectors have eight points, 0–7. Figure 8C shows the straight-line characteristics between the 0 and 7 points of four sectors in electric potential.

### 5. CONCLUSIONS

In summary, a detailed simulation of a 3-D-based TENG is investigated. The novelty of this paper is the incorporation of a TENG for blood measurement based on the nadi signal. To optimize the proposed TENG, the known 3 kPa pulse pressure is given; the vata nadi is the leading cause of blood pressure whose pressure lies within the pulse pressure range. Therefore, the pulse pressure is taken as a reference to simulate the designed TENG. The solid mechanics converts the applied pulse pressure into 0.915 mm of displacement, and the electrostatics interface converts the given 0.915 mm of displacement into an open-circuit voltage as 26 V. Thus, the TENG can harvest several human biological signals, mechanical vibrations and more, act as a self-powered system in IoT applications, and be a household health guard.

### Table 2. Surface Charge Density Values for the Positive and Negative Layer

| s. no | material | parametric value |
|-------|----------|------------------|
| 1     | PTFE     | surface charge density = $5 \times 10^{-4}$ |
| 2     | copper   | surface charge density = $8 \times 10^{-6}$ |
| 3     | distance between the two layers | 0.915 mm |
| 4     | arc length for line graph | 0.08 μm |

Figure 8. (A) Modeled TENG electric potential outputs. (B) Parabolic characteristics of output voltage and (C) straight-line characteristics of output voltage.
AUTHOR INFORMATION

Corresponding Author
Vivekanandan Shanmugasundaram — Associate Professor, School of Electrical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu 632 014, India;

orcid.org/0000-0003-1932-6177;
Email: svivekanandan@vit.ac.in

Author
Karthikeyan Venugopal — Research Scholar, School of Electrical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu 632 014, India

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c03281

Notes
The authors declare no competing financial interest.

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