INTRODUCTION

Triboelectric nanogenerators (TENGs) are clean self-powering devices that efficiently convert mechanical energy to electrical energy (Wang, Yang, & Wang, 2017). Since mechanical energy is already present in human activity, these nanogenerators bioharvest such a ‘wasted’ energy and convert it into useful energy. In this way, TENGs become self-powering motion sensors (Abdullah, Chowdhury, et al., 2020; Yang et al., 2018; Zhang et al., 2019). TENGs are cost-effective, flexible, lightweight, highly sensitive to motion and non-toxic (Wang et al., 2017). These features have attracted the attention of the research development industry, and of professionals interested in collecting real-time body movement. Moreover, the compact size of the TENG permits it to be integrated into assorted wearable items.
The emerging notion of the Internet of things (IoT) has now made it possible to embed technology into wearable devices that allow continuous measurement of physiological data (Kang, Park, Cho, & Lee, 2018). It is predicted that by 2020, the IoT market will reach $3.04 trillion in wearable devices (Haghi, Thurow, & Stoll, 2017). Hence, IoT-enabled devices have attracted the attention of healthcare professionals who seek to continuously track body movement (Traverse, Pandey, Barr, & Lunt, 2017). Coupled with this fact are the rapid population increase and the expanding cost of health care (Cuckler et al., 2018). This has led to a global need for the healthcare industry to adopt a better strategy towards patient health monitoring at a reduced cost (Chowdhury et al., 2018). Commercially available health devices have an interrupted flow of incoming data, most are expensive, and require some type of manual data input. Additionally, these same sensors lack a source of renewable energy.

The pioneering of TENG by Wang led to a novel generation of power supply (Wang et al., 2017). Since its invention at 2012, TENG has gone through numerous stages of development which focused mostly on their structures, applications, output and material selection (Ahmed et al., 2019). In 2013, Han et al. hybridized piezoelectricity and triboelectricity to develop a hybrid nanogenerator with polyvinylidene fluoride (PVDF) and polymethylsiloxane (PDMS) to harvest mechanical energy (Han et al., 2013). In another notable work, Bai et al. fabricated an integrated multilayered TENG to harvest biomechanical energy from human motions (Bai et al., 2013). The role of TENG as a body motion sensor was further developed by Yi et al. (2015) through aluminium and elastic rubber to detect diaphragm breathing and joint motion. TENG devices use the coupling of triboelectric effect and electrostatic induction to harvest the multifarious forms of mechanical energy to convert them into electricity (Wang et al., 2017; Reilly & Kwon, 2020; Liao et al., 2016). Depending on material selection in the triboelectric series, TENGs create static polarized charges to various degrees upon an external force applied onto the layers (Kaur & Pal, 2018). When the two triboelectric materials get into contact, induced charges flow between the two conductive electrodes, leading to opposite static charge acquisition on the surface (Kaur & Pal, 2018). As the two layers then separate, the layer with larger electronegativity partakes charge, while the less electronegative layer becomes charge depleted. This charge transformation between the two electrodes offsets potential difference to create an output of electrical signals (Rathore, Sharma, Swain, & Kr, 2018; Wu, Huang, Xu, Duan, & Yin, 2016). In application, the relative motion causes this induction of charges. Mechanical energy is already present in human activity due to spontaneous and voluntary muscle contraction. So, these nanogenerators simply take advantage of the employable kinetics to transform it into useful energy. In this way, TENG can bioharvest mechanical energy to perform self-powered motion sensor (Yang et al., 2027; Zhang et al., 2019).

In this work, we present a paper-based TENG with polydimethylsiloxane (PDMS)/polytetrafluoroethylene (PTFE) on copper film as versatile biocompatible and self-powered health monitoring and energy device. This TENG possess novelty of simplicity with wide range of versatility. This system adapts the vertical contact-separation mode, which generates power based on recurrent conversion between contact and separation. As it is mechanically triggered, an electric output signal is generated. This working mode makes it a commendable system for harvesting periodic motion and vibration, that is everyday real movement. Though there have been several studies about PTFE/PDMS (Chowdhury, Abdullah, et al., 2019) copolymer as triboelectric materials, there have almost no studies utilizing PTFE/PDMS with paper. Also there are very few studies about utilizing triboelectricity for body motion sensory application (Wu et al., 2018). This work emphasizes on the performance of a polymer-based TENG as a biomedical sensor for monitoring human movement, body motion, blood pressure fluctuation, muscle contraction, respiration and vocal cord disorders as well as harvesting biomechanical energy through body motion.

The composite was evaluated on three different parameters: respiration, motion, vocal cord and vibratory energy levels. For respiration, fast and normal breathings were tested. The second parameter consisted of 30, 60 and 90 beats per minute frequencies for applied stresses. Wrist opening and closing, signalling of finger opening and closing as well as more casual body motions such as handshake and high-five have been tested with the device. The output signals from these motions have been thoroughly analysed. Lastly, spoken letters ‘A,B,C,U,T,R,G,V,P,E,R,L’ for vibration recognition of vocal cords were assessed. The device was also tested at variable air gap between the triboelectric layers for effective optimization. Thorough characterization of the composite was attained by Fourier-transformed infrared spectroscopy (FTIR) and Scanning Electron Microscopy (SEM).

2 | MATERIALS AND CHARACTERIZATION

The TUHMD was fabricated with paper and PTFE/PDMS copolymer composites due to their positions in the triboelectric series, relative availability and cost efficiency (Figure 1a). The difference in the triboelectric series of paper and PTFE denotes good triboelectric effect between the materials. (Lee & Orr, AlphaLab Inc; Pan & Zhang, 2019) Application of PDMS with PTFE for synthesizing PTFE/PDMS composite provides higher mechanical strength, better electrical conductivity (due to thin layer of triboelectric materials on electrode) and durability. (Ruan et al., 2017; Sun, Li, & Xu, 2013) Both of these triboelectric layers are attached with copper films which operate as electrodes. Copper was chosen to be the electrodes because of its higher resistance to corrosion by human sweat from the skin (Porcayo-Calderon, Rodriguez-Diaz, Porcayo-Palafox, & Martinez-Gomez, 2016; Sykes & Bond, 2013). Besides Cu is very suitable for electrode application due to its high conductivity (Abdullah, Flores, et al., 2020). Fabrication of a single TUHMD device costed about 5 US dollars (USD) which is more cost effective compared to the magnetic motion sensor by Samsung (24.99 USD) and passive infrared ray (PIR) adjustable motion sensor by Coolwest (13.99 USD). Large-scale production can reduce the cost below 3 USD for each device.
Figure 1b represents the FTIR spectrum of paper and PTFE/PDMS sample. The FTIR data were also taken from pure PTFE and PDMS for comparison purposes. Figure 1d shows the enlarged view of the FTIR spectrum in 600–1500 cm$^{-1}$. Two sharp peaks can be observed at 790 and 1,255 cm$^{-1}$ which points the presence of Si-CH$_3$ from the PDMS of PDMS/PTFE composites. Besides, the peaks at 690 and 1,015 cm$^{-1}$ mark the stretching of the Si-O-Si bond of PDMS of PDMS/PTFE composites. The FTIR spectrum from pure PDMS exhibited similar peaks like the PDMS of the composite. Furthermore, the two strong symmetric peaks at 1,155 and 1,213 cm$^{-1}$ correspond to the C-F stretching of PTFE. These peaks are quite similar like the symmetric peaks of pure PTFE. C-H stretches from PDMS are responsible for the sharp peak at 1,411 and 2,958 cm$^{-1}$. The spectra are clear evidence of the presence of PTFE and PDMS in the composite. These FTIR graphs demonstrate the coexistence of PTFE and PDMS on copolymer state. Both PTFE and PDMS retain their chemical characteristics while being on the same composite surface. On the other hand, the FTIR spectrum from the paper shows a wide peak at 1,022 cm$^{-1}$ which is due to the vibration of C-O-C bond in the cellulose structure (Costa et al., 2014; Weng, Xu, Alcoutlabi, Mao, & Lozano, 2015). Also, the peaks at 1,425 and 3,313 cm$^{-1}$ are representing the presence of C-H bending and O-H stretching, respectively, in the cellulose. As paper is produced from cellulose fibres, it is expected that the FTIR spectrum of paper will show the characteristics of cellulose. (Sahin & Arslan, 2008) These peaks clarify the presence of cellulose from the paper.

SEM was used to observe the surface morphology of paper and PTFE/PDMS (Figure 1c). Paper was gold-sputtered coated before imaging at SEM. The sample was observed at 1,000 and 1,500 V of electron high tension (EHT) voltage. The fibre structure of the cellulose fibre from the paper, imaged via SEM image, results in higher roughness and higher area of the surface.

On the other hand, Figure 1ciii. and Figure 1civ. reflect the image taken by SEM at 1,300 V EHT to observe the surface morphology of PTFE/PDMS composite. Generally, pure PDMS shows smooth surface under SEM (Fischer et al., 2016; Majeed et al., 2012). But as PTFE is used for the formation copolymer composite the roughness of the surface rises. These grain-type structures in the surface clearly point out the roughness of PTFE/PDMS copolymer surface. The higher the amount of PTFE, the higher the amount of roughness (Ruan et al., 2017).

3 | WORKING MECHANISM

The TUHMD operates due to the contact triboelectrification and electrostatic induction between paper and PTFE/PDMS.
certainly works as a vertical mode triboelectric nanogenerator. Whenever an external load is applied on the device, the paper and PTFE/PDMS layer initiate coming to close at each other. Eventually, both layers get fully contacted with each other (Figure 2a). When they are in full contact, transient surface polarization is generated and triboelectrification occurs (Yoon, Ryu, & Kim, 2018). According to the triboelectric series, paper holds a higher position than PTFE as electropositive materials (Kim et al., 2017). As a result, paper will supply electron while PTFE/PDMS will receive electron at the surface. When external pressure is released from the device, the layers start moving far from each other and the transient surface polarization is broken (Figure 2b). This separation results in the higher output voltage at the paper connected Cu electrode. The electrons start flowing along the circuit to recompense the triboelectric charges and maintain electrical equilibrium in the device. An output voltage and current signal can be clearly detected due to this electrostatic induction. Once the external load is fully released, there will be no electron flow within the circuit (Figure 2c). Due to the electron flow from PTFE/PDMS-connected electrode to paper-connected electrode at the previous step, the electrodes at this stage reach a situation where they have the same electric voltage. When external pressure is applied on the device again, the triboelectric layers start moving close to each other (Figure 2d). The voltage of the electrode of paper becomes lower than the other electrode. So, electron starts to move in the opposite direction of the releasing stage and induce the positive charges of the electrode of PTFE/PDMS because of getting closer to each other. This initiates triboelectric action as opposite charges accumulate to the inward layers of triboelectric materials of paper and PTFE/PDMS because of expansion and contraction of the rib cage. Enlarged view on athletic breathing on Figure 3d demonstrates very harmonized responses. However, the ups and downs in Figure 3d is due to real-life body motion vibrations and spring actions, as well as cantilever movement of the nanogenerator. The polarity of the response depends on the electrode connection. Inhalation and exhalation follow the working mechanism that described in Figure 2a–d. Inhalation brings two opposite triboelectric materials closer to each other as nanogenerator is pushed outward, while the holding tape holds the device back. This initiates triboelectric action as opposite charges accumulate to the inward layers of triboelectric materials of paper and PTFE/PDMS because of getting closer to each other. This followed by the flow of electron from one electrode to another electrode through a connected circuit. Exhalation and inward movement of the rib cage trigger similar but opposite action. As the triboelectric layers get far away from each other through relaxation of the human body parts as well as relaxation of the device, the triboelectric materials start acting in the opposite way by charge transfer to compensate the relaxation. This reverse action generates exactly the opposite voltage compared to the inhalation and outward movement of the
FIGURE 3  Electrical output signal of TUHMD on different body motions on different body locations. The electrical signal of (a) fast breathing and (b) regular breathing from TUHMD in the chest (position-1). c, Signal of finger opening and closing from TUHMD in the wrist (position-2). d, Enlarged view of fast breathing (inhale and exhale). e, Enlarged and demonstrated view of the electrical signal of finger opening and closing from Figure 3c. f Electrical signal of wrist opening and closing from TUHMD in the wrist (position-1). g, Electrical signal of high-five from TUHMD in the wrist (position-2). h, Enlarged view on the electrical signal of Figure 3h. i, Enlarged view of the electrical signal of Figure 3g. j, Positions on the human body under test.
rib cage. From Figure 3b, d, it is easily inferred that fast breathing generates small vibratory response compared to slow breathing, which makes the device better suited for understanding athletic or regular motion as well as inhalation or exhalation. Also, fast breathing (Video V2) generates electricity with nearly 0.4 V (~0.2 to + 0.2 V) of range. But this range goes 10 times larger during regular breathing (~2 to + 2 V). Throughout slow/regular breathing (Video V1), the device got enough time to get back to original position after every stretching. Hence, the response is smoother and the voltage is larger due to the ability to retain full capacity during the whole working cycle. During fast rib cage movement, two triboelectric layers had lesser time to release the charge and get back to the original state. As a result, it did not generate higher voltage comparable to the slow breathing. Fabricated device was also tested with side-by-side movement (Figure S1; Video V3) and jogging movement (Figure S2; Video V4) while being attached to the chest (position 1). These both movements show symmetrical response though jogging response is more abrupt looking due to dynamic movement. However, this response is largely symmetrical in shape rather than peak value as body movement is dependent on the number of variables and humans are unable to replicate exact same body movement repeatedly.

After thorough testing of the device in position 1 (chest), the device was tested with different body motions in position 2 (wrist, as shown in Figure 3). The response of the device due to body movement in the wrist is depended on two-axis movement of different muscles. Not only flexor retinaculum and flexor digitorum profund but also flexor carpi radialis, flexor carpi ulnaris and flexor digitorum superficialis are related to the movement. All these flexor and extensor components are the reason behind controlling the finger movements. Finger opening and closing response (Main Video) at Figure 3c, e of the nanogenerator device are a result of voluntary and involuntary action of the human body tissues mentioned in the last sentence. Contraction of thumb makes flexor digitorum superficial tissue contracted as it pushes flexor retinaculum upwards; hence, it pushes the nanogenerator device outwards. But the inability to compensate the outward push of the device by moving away from its original position, the device begins contraction which makes the triboelectric layers to approach each other and initiates triboelectric voltage generation (~0.3 V). Contraction of thumb followed by the contraction of the index finger is triggered by contraction and expansion of index tendon of extensor digitorum. This contraction and expansion push flexor retinaculum, which already have been pushed outward due to the contraction of thumb. Movement of flexor retinaculum does a similar action that has been described in Figure 2c,d. The generated voltage due to the action of contraction of index finger reaches up to 0.5 V. Contraction of index finger action is followed by contraction of middle, ring and pinky finger which causes contraction of palmaris longus, flexor carpi radials and flexor carpi ulnaris, subsequently. These contractions generate voltages of 0.5, 0.1 and 0.7 V, sequentially. Also noticeable is the movement of ring finger decreasing the voltage and then increasing again because of cortical neurons that move the ring finger coupled to the pinky finger. Hence, the central nervous system is unable to distinguish between ring and pinky finger movement. The extension of the ring finger’s ulnar nerve and contraction of radial nerve requires relaxation following by tension. This condition makes the reduction in voltage following by increase during the ring finger movement. The opposite movement initiates a decrease in voltage as extensor retinaculum and flexor retinaculum imitate relaxation following by the relaxation of ulnar nerves and contraction of radial nerves, which relaxes the nanogenerator from a previously stressed condition. However, it can be easily inferred from the relaxation cycle from Figure 3c,e that relaxation of the ring finger and pinky finger greatly differs from any other movement due to cortical neurons control from the central nervous system. Figure 3c,e shows a symmetrical response to every single finger movement. These reproducible data demonstrate the nanogenerator as a very sensitive body motion sensor. The nervous contraction and relaxation of all fingers are repeated in simultaneous motion through wrist opening and closing. The electrical response of wrist opening (simultaneous five ulnaris relaxation, Figure 3f,h; Video V5) reached equivalent voltage (~3 to +5 V) of accumulated response of finger closing or opening (Figure 3c,e) one after another. Response in Figure 3f, h shows small deflection from ideal smooth response due to cortical neurons and accumulated response of 18 different muscles including flexor pollicis longus, flexor digitorum profundus and flexor digitorum superficialis. The response for wrist opening and closing was found to show a sinusoidal shape, which resembles continuous motion-generated response.

The response of the sensor in position 2 (wrist) was further tested by casual body movements, such as high-five (Video V6) and handshake (Video V7) of the subject. Response of high-five is demonstrated in Figure 3h, i (enlarged response) and Video V6. The response is owing to not limited to the contraction and relaxation of triceps brachii, brachioradialis, brachioradialis with radialis muscle’s contraction on flexor retinaculum which partially transfer the contraction stresses to the nanogenerator device. This stress moves triboelectric layers towards and away from each other which results in the identical response on each high-five. This response reached from ~3 to +5 V. Subject was also tested with sudden shock with startling by external sound and body posture (Figure S3) while keeping the device attached to position 2. The subject showed tremendous blood pressure through his arteries in the wrist which exemplified the triboelectric response. These responses are the peaks that are shown in Figure S3. After a few different methods of startling the subject, as the brain started to get accustomed to the startling, the blood pressure was not fluctuating. This ensured no peaks after 33 s.

By following these studies, it can be easily inferred that the fabricated nanogenerator shows a high degree of sensitivity and easily can be used in everyday life for body movement sensory application. Any response created by the device can be analysed by comparing with previously recorded identical responses and generate data of human body motion; henceforward, burnt calories or any similar value can be achieved with logged user’s body mass index (BMI). This
sensor also has the potential to be used as a sleep monitoring system as it can analyse blood pressure fluctuation and any sudden movement. Both of these data can be recorded and analysed by computer-aided system to generate sleep data (e.g. sleep hour, dreaming). Prolonged data can generate how blood pressure is changing in a longer period of time. This change can give a brief idea about stroke and coronary heart diseases (MacMahon et al., 1990). By utilizing this method, millions of lives could be saved. Indeed, monitoring and analysis of physiological variables via biomedical sensors will allow for the diagnosis and monitoring of users and patients, and could be exploited in the context of eHealth.

5 | VOCAL SENSOR

The ability of the device to work as a vocal sensor has been tested with the device while sticking on the epidermis (skin) next to the throat. As voiceless or voice sounds are affected by the vibrations of the larynx, the device was placed next to the vocal cord to absorb most of the vibrational energy. Just the copper electrode and epidermis were in between the vibration of the larynx and the triboelectric layers to reach the energy from the source to the sensor. The subject made four attempts of making the sound of the letters ‘A,B,C,U,T,R,G,V,P,E,R,L’ (Video V8). The response of the sound is represented in Figure 4a–e. First two responses (Attempts 1 and 2) in Figure 4b,c and last two responses (Attempt 2 and 3) in Figure 4d,e are recorded with completely opposite electrical polarity connection, as shown in Figure 4g, h. Human voice vibratory energy level cannot be controlled very precisely; hence, the shape of the response will be considered as the primary matter of study in this part. Because of the high level of sensitivity of the device, it showed a very good symmetrical shaped response during the identical polarized response in paired attempts (Attempts 1 and 2; Attempts 3 and 4). In these responses, the sound sensor has been tested in pairs to demonstrate reproducibility of the data. The vibration caused by the human subject’s vocal system transferred from the vocal cord to thyroid cartilage to epidermis to the device. As voice sound is dependent on larynx, tongue, lingual tonsil and the oesophagus (human sound generating body parts), the device exhibited an excellent combined response from the larynx vibration. This splendid response continued during the response of voiceless sounds. The larynx covered by thyroid cartilage (with higher plasticity) acted as a barrier between the vibration from the larynx to the sensor. However, the rings of thyroid cartilage also behaved as a symmetrical sound amplifier (Lehrer, 2018; US9728176B2, 20152015). These rings nullified the effect of loss of vibrating energy which absorbed by the body filters, like epidermis and junction between the electrode and the triboelectric layer. In this experiment, nanogenerator with paper next to throat showed higher peaks in voiceless sounds when placed next to vocal cords. In voiceless sounds (A,E,U), PDMS/PTFE next to larynx showed the higher responses compared to paper next to the larynx because the vibration carried out from vowel quadrangle is transmitted through the larynx and shifted towards the device with much broader frequency compared to other sounds. However, voice sounds (B,C,T,R,G,V) made a very identical response on both polarized conditions due to higher amounts of larynx vibration. Response of the voiceless sound of A is identical on both paired responses. This similarity is carried away for almost all the responses. However, the response largely depended on the previous voices as the vibration energy from the last sound is carried away for a few seconds. This happened due to the residual stress in previously stressed vocal parts. This created small fluctuation in the response of R. This response is also due to the part of the vibration absorbed by inferior turbinate as the vibration is generated by tongue and inferior turbinate. Response during pronunciation of G, V and P showed a higher level of symmetry due to the more energy frequent vibration. Sound E showed flatter because the creation of the sound generates far away from the larynx between soft palate and tongue. Because of the higher amount of mechanical flexibility in the polymer, polymer closer to vocal cord (larynx) is well responded through higher peaks during voice sounds. This also produced a higher voltage compared to the lesser mechanically flexible paper next to the larynx. The response from both polarizations showed an excellent representation of sound response. This phenomenon continued until further experiments. However, this represented that the sound response is largely dependent on how triboelectric layers are placed next to sound source. These pair of materials in the device showed an extraordinary answer to the current generation of costly sound sensor, which could potentially be used in phoniatrics, for patients who have vocal cord damage (e.g. traumas, cancer surgery, radiotherapy), birth defects and degenerative conditions, or may need voice rehabilitation. The response from the subject can be compared to the previously recorded responses from the system and can be detected as perfect vocal sound.

By comparing both vocal and body motion responses, it can be inferred that each body parts has been demonstrating different responses. These different responses can be understood by thorough investigation of different body parts which has been discussed thoroughly in this study. The output signal of TUHMD is directly related to the force of impact which controls the amplitude and signal pattern (Abdullah, Flores, et al., 2020; Aminullah, Kasi, Kasi, & Uddin, 2020). Highly sensitive TUHMD has demonstrated different responses due to numerous tiny actions by vocal cord and body muscles which resulted in larger responses. These responses led towards different forces of impact on the TUHMD. Thus, the signal pattern and amplitude from different body parts are different from each other.

There have been several studies which utilized triboelectricity as motion sensors before (Chowdhury, Lopez, Abdullah, & Uddin, 2019; Huang, Li & Sun, 2016; Abdullah, Chowdhury, et al., 2020; Liang et al., 2019; Yi et al., 2015; Zhang et al., 2018). However, there has not been any dedicated triboelectric motion sensor as well as vocal sensor. Also, other reported studies have not demonstrated detailed body motion detection by the sensors. In this study, we have demonstrated detailed body motion studies and made detailed discussion for the understanding of the mechanism behind the triboelectric
A particular study by Jin et al. have demonstrated the utilization of triboelectric nanogenerator as finger motion sensor (Jin, Tao, Bao, Sun, & Pan, 2017). In our study, we have demonstrated the motion sensors can be used for large as well as small body motions. We have integrated the triboelectric sensors for vocal sensors as well. These integrations are first ever in scientific worlds.

6 | PERFORMANCE OF TUHMD AT VARIABLE LOAD FREQUENCY

Proficiency of TUHMD as a probable power source has been tested with applied minimal stress as different beats per minute (BPM). Figure 5a demonstrates the comparative voltage production of the
device with different load frequencies (30 BPM, 60 BPM, 90 BPM). It can be easily inferred from the data that the amount of voltage production can be increased with the amount of applied stresses. From Figure 5d–f, it is easily deductible that the value of voltage produced during different frequencies shows different characteristics. Figure S4a–c reveals the highest voltage has been reached for 30, 60 and 90 BPM as 4.5, 5 and 6 V, respectively, after 100s of operation. Lower stress frequency contributes smoother voltage production as the PDMS/PTFE and paper are having more time to get closer and return to their original positions hence. This leads towards more possibilities for smoother charge transfer from one surface to another and one electrode to another electrode through the circuit. Higher frequency makes the device more susceptible to charge transfer that has been accumulated in the last cycle of induced stress. As stress frequency intensifies, voltage gets more improbable. This similar pattern is visible in Figure 5b, where energy is represented with respect to the time. More frequent induced stress brings triboelectric layers closer and away from each other more frequently. Therefore, charge transfer and energy production become more frequent. This reciprocation actions generated the highest 15.5, 15 and 13 nWh for 30, 60 and 90 BPM, respectively, which is demonstrated in Figure S4d–f. The increase in voltage with time with applied stress in Figure 5d–f verifies the characteristics of the TUHMD as the capacitor. As triboelectric layers have stayed as close to each other with a small gap between them, this commended acting as a capacitor. Accumulated charge from the previous cycle continues to the next cycle; hereafter, the device shows higher charge on every single cycle compared to the previous cycle. However, this deflects from original characteristics in 90 BPM (Figure 5f,i) stress frequency as
8 | EXPERIMENTAL METHODS

Preparation of Paper Triboelectric Positive Layer on Copper Sheet: The cellulose paper was collected from PaperOne (70 gm) is attached to the copper sheet (thickness 0.1 mm, dimension 5 × 4 cm) through applying PDMS (Sylgard 184 Silicone Elastomer Base with 10 wt% silicone elastomer) as sticking element between paper and copper sheet following by drying at room temperature for 72 hr.

Preparation of PDMS/PTFE Copolymer Triboelectric Negative Layer on Copper Sheet: 2 g polydimethylsiloxane (PDMS) (Sylgard 184, Silicone Elastomer base) and 0.2 g curing agent (Sylgard 184, Silicone Elastomer Curing Agent) with 2 g PTFE (Aldrich, 2 µm particle size) particles were added in a 20-ml disposable scintillation vials. The mixture was well mixed in a vortex mixer. The solution was placed and spread by doctor blade technique using a smooth surface cylindrical glass test tube on the clean surface of the copper sheet (thickness 0.1 mm, dimension 5 × 4 cm) following by drying in room temperature for 72 hr.

Preparation of Nanogenerator: The nanogenerator was prepared by placing two PU spacers (1mm thickness) between two triboelectric layers (facing inwards) between two triboelectric layers.

8.1 | Measuring of output

Electrical contacts were made by attaching wires to the two copper sheets connected to two electrodes of VersaSTAT3 machine through intermediate connector wires to measure the sensory open-circuit voltage as well as nanogenerator’s electrical output.

8.2 | Morphological characterization

SEM characterization of the samples was performed using a JEOL 7,800 F Field Emission Scanning Electron Microscope, equipped with an Electron Dispersive X-ray Spectroscopy system (EX-37270VUP).

8.3 | FTIR characterization

Fourier-transform infrared spectroscopic analysis was performed using a VERTEX 70 v FTIR Spectrometer. Relative transmittance was collected in transmittance mode over a full range of 4000–450 cm⁻¹ wavenumber.

ACKNOWLEDGEMENTS

A. R. Chowdhury gratefully acknowledges the Deans’ Graduate Research Scholarship. This work was partially supported by the Welch Research Foundation through grant BX0048. A. M. Abdullah acknowledges support from Graduate College for his President’s Graduate Research Assistantship. The authors also express their gratitude to Dr. Karen Lozano and Raul Barbosa from

triboelectric layers move faster and produced charge has lesser time to get accumulated and released. Because of higher conductivity, the release becomes higher compared to charge accumulation. This characteristic also effects on charge accumulation as higher stress frequency shows smoother charge versus resistance than lower frequency. Because of higher number of short circuits in higher frequency, the device starts getting more opportunity to release charge and it reflects a lesser accumulated charge. Due to the same reason, the lower frequency demonstrates more charge versus resistance and steeper results. Though accumulate charge and voltage differ from stress frequencies, it is evident that the ability of device as nanogenerator in terms of energy generation is not very much affected by how frequent the device is stressed. Therefore, it can be boldly said that fabricated TUHMD can be used as a power source in any load conditions.

For further optimization of the device, the device was tested between variable air gap between the triboelectric layers. Four TUHMDs were used for this test varying the air gap from 1mm to 2.5mm keeping the load frequency at 60 BPM. The result (Figure 5S) clearly shows that the output peak-to-peak voltage increases with increasing air gap. The maximum peak-to-peak voltage was observed to be 7.4 V for 2.5mm air gap, while the minimum was 2.5 V for 1mm air gap. As the air gap increases, the velocity of impact also increases with constant load frequency which results in contact between the triboelectric layers at higher kinetic energy (Aminullah et al., 2020). Larger amount of electron transfers from paper layer to the PTFE/PDMS layer due to this higher kinetic energy (Abdullah, Flores, et al., 2020). Thus, higher voltage can be observed in the output. Though output voltage increases with increased air gap, it requires higher volumetric space which can be disadvantageous for its integral application.

7 | CONCLUSION

In summary, we have demonstrated a universal cost-effective, self-powered highly sensitive health monitoring device with the capability of detecting the human body motion and sound signal quantification. Because of cost-effective materials and simple structure, the device showed a potential of mass production for consumer-oriented electronic market, such as eHealth and IoT. Identical signals on different body motions make the device competitive to any current body motion sensor while diminishing the necessities for charging the wearable electronics. Under applied stresses on any axis, the device has the ability to operate smoothly as a biomedical sensor to monitor body movement and vocal cord vibrations. Also, the maximum output voltage of the device was observed to be 12 V which makes it a latent medium to harvest biomechanical energy. This device can reduce the cost of health monitoring systems and increase consumer satisfaction. The potential to save human lives that require uninterrupted monitoring of the human body causes this device to have a significant impact on the healthcare sector. This incorporation will result remarkable impact on the health, environment and economy.
the Department of Mechanical Engineering, The University of Texas Rio Grande Valley for their help with the Scanning Electron Microscopy.

CONFLICT OF INTEREST
The authors declare that they have no competing financial or non-financial interest.

AUTHOR CONTRIBUTION
M.J.U. conceived the project and supervised the research. A.R.C., I.H. and U.V.R synthesized and fabricated the TUHMD. Also, A.R.C., U.V.R., A.M.A. and C.O. performed and analysed the experiment. A.M.A. performed and analysed the FTIR spectroscopy of the materials and the Scanning Electron Microscopy of the surfaces. Besides, the manuscript and sketches were prepared and organized by A.R.C., A.M.A., C.R. and U.V.R. S.D. and J.L. helped with the manuscript review and explanation.

DATA AVAILABILITY STATEMENT
The data set generated while performing or analysing the experiment are available from the corresponding author on a reasonable request.

REFERENCES
Abdullah, A. M., Chowdhury, A. R., Yang, Y., Vasquez, H., Moore, H. J., Parsons, J. G., ... Uddin, M. J. (2020). Tailoring the viscosity of water and ethylene glycol based TIO2 nanofluids. *Journal of Molecular Liquids*, 297, 111982. http://doi.org/10.1016/j.molliq.2019.111982
Abdullah, A. M., Flores, A., Chowdhury, A. R., Li, J., Mao, Y., & Uddin, M. J. (2020). Synthesis and fabrication of self-sustainable triboelectric energy case for powering smart electronic devices. *Nano Energy*, 73, 104774. https://doi.org/10.1016/j.nanoen.2020.104774
Ahmed, A., Hassan, I., El-Kady, M. F., Radhi, A., Jeong, C. K., Selvaganapathy, P. R., ... Kaner, R. B. (2019). Integrated Triboelectric Nanogenerators in the Era of the Internet of Things. *Advanced Science*, 6(24), 1802230. http://doi.org/10.1002/advs.201802230
Aminullah, I., Kasi, A. K., Kasi, J. K., Uddin, M., & Bokhari, M. (2020). Triboelectric nanogenerator as self-powered impact force sensor for falling object. *Current Applied Physics*, 20(1), 137-144. http://doi.org/10.1016/j.cap.2019.10.016
Bai, P., Zhu, G., Lin, Z., Jing, Q., Chen, J., Zhan, G., ... Wang, Z. L. (2013). Integrated Multilayered Triboelectric Nanogenerator for Harvesting Biomechanical Energy from Human Motions. *ACS Nano*, 7(4), 3713-3719. http://doi.org/10.1021/nn4007708
Lee, B. W., & Orr, D. E. The Triboelectric series from AlphaLab Inc. AlphaLab Inc. Utah 84115 USA © 2018 AlphaLab, Inc. https://www.alphalabinc.com/triobelectric-series/
Chowdhury, A. R., Abdullah, A. M., Hussain, I., Lopez, J., Cantu, D., Gupta, S. K., ... Uddin, M. J. (2019). Lithium doped zinc oxide based flexible piezoelectric-triobolectric hybrid nanogenerator. *Nano Energy*, 61, 327–336. http://doi.org/10.1016/j.nanoen.2019.04.085
Chowdhury, A. R., Jaksik, J., Hussain, I., Longoria, R., Faruque, O., Cesano, F., ... Uddin, M. J. (2019). Multicomponent nanostructured materials and interfaces for efficient piezoelectricity. *Nano-Structures & Nano-Objects*, 17, 148–184. http://doi.org/10.1016/j.nanoen.2018.12.002
Chowdhury, A. R., Jaksik, J., Hussain, I., Tran, P., Danti, S., Uddin, M. J. (2019). Surface-Modified Nanostructured Piezoelectric Device as a Cost-Effective Transducer for Energy and Biomedicine. *Energy Technology*, 7(5), 1800767. http://doi.org/10.1002/ente.201800767
Chowdhury, A. R., Lopez, D., Abdullah, A. M., & Uddin, M. J. (2019). Polymer Based Cost-Effective Triboelectric Nanogenerator. AICHe Annual Meeting. https://aiche.confex.com/aiche/2019/meetingapp.cgi/Paper/578431
Costa, M. N., Veigas, B., Jacob, J. M., Santos, D. S., Gomes, J., Baptista, P. V., ... Fortunato, E. (2014). A low cost, safe, disposable, rapid and self-sustainable paper-based platform for diagnostic testing: lab-on-paper. *Nanotechnology*, 25(9), 094006 http://doi.org/10.1088/0957-4484/25/9/094006
Cuckler, G. A., Sisko, A. M., Poisel, J. A., Khehan, S. P., Smith, S. D., Madison, A. J., ... Hardesty, J. C. (2018). National Health Expenditure Projections, 2017–26: Despite Uncertainty, Fundamentals Primarily Drive Spending Growth. *Health Affairs*, 37(3), 482–492. http://doi.org/10.1377/hlthaff.2017.1655
Fischer, S. C. L., Levy, O., Kroner, E., Hensel, R., Karp, J. M., & Arzt, E. (2016). Bioinspired polydimethylsiloxane-based composites with high shear resistance against wet tissue. *Journal of the Mechanical Behavior of Biomedical Materials*, 61, 87–95. http://doi.org/10.1016/j.jmbbm.2016.01.014
Haghi, M., Thourow, K., Stoll, R. (2017). Wearable Devices in Medical Internet of Things: Scientific Research and Commercially Available Devices. *Healthcare Informatics Research*, 23(1), 4. http://doi.org/10.4258/hir.2017.23.1.4
Han, M., Zhang, X., Meng, B., Liu, W., Tang, W., Sun, X., ... Zhang, H. (2013). r-Shaped Hybrid Nanogenerator with Enhanced Piezoelectricity. *ACS Nano*, 7(10), 8554–8560. http://doi.org/10.1021/nn401023v
Huang, H., Li, X., & Sun, Y. (2016). A triboelectric motion sensor in wearable body sensor network for human activity recognition. 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) (pp. 4889–4892). Orlando, FL. https://doi.org/10.1109/EMBC.2016.7591823
Jin, L., Tao, J., Bao, R., Sun, L., & Pan, C. (2017). Self-powered Real-time Movement Monitoring Sensor Using Triboelectric Nanogenerator Technology. *Scientific Reports*, 7(1). http://doi.org/10.1038/s41598-017-10990-y
Kang, M., Park, E., Cho, B. H., & Lee, K. S. (2018). Recent Patient Health Monitoring Platforms Incorporating Internet of Things-Enabled Smart Devices. *International Neuroeurology Journal*, 22(Suppl 2), S76–82. http://doi.org/10.5213/inj.1836114.072
Kaur, N., & Pal, K. (2018). Triboelectric Nanogenerators for Mechanical Energy Harvesting. *Energy Technology*, 6(6), 958–997. http://doi.org/10.1002/ente.201700639
Kim, Y. J., Lee, J., Park, S., Park, C., Park, C., & Choi, H. J. (2017). Effect of the relative permittivity of oxides on the performance of triboelectric nanogenerators. *RSC Adv.*, 7(78), 49368–49373. http://doi.org/10.1039/c7ra07274k
Lehrer, S. (2018). *Understanding Lung Sounds* (3: rd ed.). New York, NY: Steven Lehrer.
LiangX., Zhao, T., Jiang, W., Yu, X., Hu, Y., Zhu, P., ... Wong, C. P. (2019). Highly transparent triboelectric nanogenerator utilizing in-situ chemically welded silver nanowire network as electrode for mechanical energy harvesting and body motion monitoring. *Nano Energy*, 59, 508–516. http://doi.org/10.1016/j.nanoen.2019.02.071
Liao, X., Liao, Q., Zhang, Z., Yan, X., Liang, Q., Wang, Q., ... Zhang, Y. (2016). A Highly Stretchable ZnO@Fiber-Based Multifunctional Nanosensor for Strain/Temperature/UV Detection. *Advanced Functional Materials*, 26(18), 3074–3081. http://doi.org/10.1002/adfm.201505223
Macmohan, S., Peto, R., Cutler, J., Collins, R., Sorlie, P., Neaton, J., ... Stamler, J. (1990). Blood pressure, stroke, and coronary heart disease: Part 1. prolonged differences in blood pressure: prospective observational studies corrected for the regression dilution bias. *The Lancet*, 335(8692), 765–774. http://doi.org/10.1016/0140-6736(90)90878-9
Majeed, S., Filiz, V., Shishatsky, S., Wind, J., Abetz, C., & Abetz, V. (2012). Pyrene-POSS nanohybrid as a dispersant for carbon nanotubes in
solvents of various polarities: its synthesis and application in the preparation of a composite membrane. Nanoscale Research Letters, 7(1), 296. http://doi.org/10.1186/1556-276x-7-296

Pan, S., & Zhang, Z. (2019). Fundamental theories and basic principles of triboelectric effect: A review. Friction, 7(1), 2–17. http://doi.org/10.1007/s40544-018-0217-7

Porcayo-Calderon, J., Rodriguez-Díaz, R. A., Porcayo-Palafox, E., & Martínez-Gómez, L. (2016). Corrosion Performance of Cu-Based Coins in Artificial Sweat. Journal of Chemistry, 2016, 1–11. https://doi.org/10.1155/2016/9542942

Rathore, S., Sharma, S., Swain, B. P., & Ghadai, R. K. (2018). A Critical Review on Triboelectric Nanogenerator. IOP Conference Series: Materials Science and Engineering, 377, 012186. http://doi.org/10.1088/1757-899x/377/1/012186

Reilly, S., & Kwon, Y. W. (2020). Oscillating column and triboelectric nanogenerator for ocean wave energy. Multiscale and Multidisciplinary Modeling, Experiments and Design, 3(1), 23–32. https://doi.org/10.1007/s41939-019-00057-y

Ruan, M., Zhan, Y., Wu, Y., Wang, X., Li, W., Chen, Y., ... Deng, X. (2017). Preparation of PTFE/PDMS superhydrophobic coating and its anti-icing performance. RSC Advances, 7(66), 41339–41344. http://doi.org/10.1039/c7ra05264b

Sahin, H., & Arslan, M. (2008). A Study on Physical and Chemical Properties of Cellulose Paper Immersed in Various Solvent Mixtures. International Journal of Molecular Sciences, 9(1), 78–88. http://doi.org/10.3390/ijms9010078

Sun, D., Li, B. B., & Xu, Z. L. (2013). Preparation and characterization of poly(dimethylsiloxane)-polytetrafluoroethylene (PDMS-PTFE) composite membrane for pervaporation of chloroform from aqueous solution. Korean Journal of Chemical Engineering, 30(11), 2059–2067. http://doi.org/10.1007/s11814-013-0147-z

Sykes, S., & Bond, J. W. (2013). A Comparison of Fingerprint Sweat Corrosion of Different Alloys of Brass. Journal of Forensic Sciences, 58(1), 138–141. http://doi.org/10.1111/j.1556-4029.2012.02300.x

Traverse, C. J., Pandey, R., Barr, M. C., & Lunt, R. R. (2018). Publisher Correction: Emergence of highly transparent photovoltaics for wearable/portable electronics. Nano Energy, 55, 151–163. http://doi.org/10.1016/j.nanoen.2018.10.078

Yoon, H. J., Ryu, H., & Kim, S. W. (2018). Sustainable powering triboelectric nanogenerators: Approaches and the path towards efficient use. Nano Energy, 51, 270–285. http://doi.org/10.1016/j.nanoen.2018.06.075

Zhang, Q., Zhang, Z., Liang, Q., Gao, F., Yi, F., Ma, M., ... Zhang, Y. (2019). Green hybrid power system based on triboelectric nanogenerator for wearable/electronic devices. Nano Energy, 55, 151–163. http://doi.org/10.1016/j.nanoen.2018.10.078

Zhang, R., Hummelgård, M., Örtegren, J., Olsen, M., Andersson, H., Yang, Y., & Olin H. (2018). Human Body Constituted Triboelectric Nanogenerators as Energy Harvesters, Code Transmitters, and Motion Sensors. ACS Applied Energy Materials, 1(6), 2955–2960. http://doi.org/10.1021/acsae.8b00667

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Chowdhury AR, Abdullah AM, Romero UV, et al. Decentralized triboelectric electronic health monitoring flexible microdevice. Med Devices Sens. 2020;3:e10103. https://doi.org/10.1002/mds.3.10103