A Natural Gradient Biological-Enabled Multimodal Triboelectric Nanogenerator for Driving Safety Monitoring

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ABSTRACT: A key element to ensuring driving safety is to provide a sufficient braking distance. Inspired by the nature triply periodic minimal surface (TPMS), a gradient and multimodal triboelectric nanogenerator (GM-TENG) is proposed with high sensitivity and excellent multimodal monitoring. The gradient TPMS structure exhibits the multi-stage stress-strain properties of typical porous metamaterials. Significantly, the multimodal monitoring capability depends on the implicit function of the defined level constant $c$, which directly contributes to the multimodal driving safety monitoring. The mechanical and electrical responsive behavior of the GM-TENG is analyzed to identify the applied speed, load, and working mode. In addition, optimized peak open-circuit voltage ($V_{oc}$) is demonstrated for self-awareness of the braking condition. The braking distance factor ($L$) is conceived to construct the self-aware equation of the friction coefficient based on the integration of $V_{oc}$ with respect to time. Importantly, $R^2$ up to 94.29% can be obtained, which improves self-aware accuracy and real-time capabilities. This natural structure and self-aware device provide an effective strategy to improve driving safety, which contributes to the improvement of road safety and presents self-powered sensing with potential applications in an intelligent transportation system.

KEYWORDS: Triply periodic minimal surface, Gradient, Multimodal, Triboelectric nanogenerator, Driving safety

INTRODUCTION

Nature serves as a constant source of inspiration for mankind, offering a multitude of optimized forms and performances. A minimal surface with zero average curvature is a remarkable type of structure widely existing in nature. Among these, triply periodic minimal surfaces (TPMSs) are composed of infinite, non-self-intersecting, periodic surface structures in three main directions, including Schwarz Primitive (P), Schwarz Diamond (D), Schwarz Hexagonal (H), Schwarz cross layers of parallels, and Neovius (N). Remarkably, similar TPMSs also exist widely in biological structures such as butterfly wing scales, crustacean shells, sea urchin bone plates, shells, and weevil exoskeletons. Different from other artificially designed porous structures, TPMS is an excellent model for the gradient design, functional gradient, and free energy of natural structures. Recently, there has been increasing attention toward biomimetic inhalation sensors based on the TPMS biological mechanism. Three-dimensional (3D) printing in the production of multi-scale, multi-material, and multi-functional 3D biomimetic materials and structures exhibits remarkable advantages and plays an irreplaceable role in the manufacturing of multifunctional, complicated, and biomimetic flexible electronic devices, such as multi-axis pressure sensor, versatile porous flexible sensor, and deformable sensors.

Currently, a series of 3D printing-based or porous triboelectric nanogenerators (TENGs) have been developed to improve sensing efficiency. The first ultra-flexible and porous three-dimensional TENG (3D-TENG) was reported in 2018, which can reach an instantaneous peak power density of 10.98 W/m$^3$ and a transferred charge density of 0.65 mC/m$^3$ under a low frequency of about 1.3 Hz. But it cannot be ignored that the printing accuracy of printed composite resin parts is 1 mm. Common printing equipment on the market has

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difficulty meeting this requirement. In addition, the flexible and porous structure will move synchronously under external forces, which limits the TENG’s multifunctional application. Moreover, a printed elastic TENG (PE-TENG) was designed to self-power the electro-Fenton (EF) degradation of pollutants. The results showed that the self-powered EF system is capable of cleaning up to 97.0% of the methylene blue (MB) in 140 minutes. Similarly, an innovative self-powered EF degradation system was obtained by 3D-printed flexible multilayer TENG (PFM-TENG) as EF cathode catalysts with degradation rate exceeding 90% in 60 min and printed flexible wave-like TENG (PFW-TENG) with the decolorization efficiency up to 98.1% in 58 mins. In addition, a honeycomb-inspired TENG (h-TENG) was reported with multilayered thin-film surface structure for biomechanical and unmanned aerial vehicle (UAV) morphing wing energy harvesting. Compressible hexagonal-structured TENGs (CH-TENGs) were arranged on tire beads to harvest the mechanical energy of rotating tires. In addition, the liquid-metal embedded sponge-type TENG (LMST) was designed with randomly distributed pores, which can return to its original state even after being bent, twisted, or stretched due to the porous and flexible structure. Note that these TENGs all have overall synchronous motion characteristics due to the uniform or random porous structure. It means that they do not have gradient capabilities, and the array installation is the only strategy to meet multimodal perception in practical situations. Thus, the combination of 3D printing, biomimetic structure, and TENG has ample scope for designing flexible and individualized TENGs.

The rapid development of intelligent transportation and self-driving technology has attracted increasing attention to driving safety issues. Although the anti-lock braking system (ABS) can improve braking ability and vehicle stability, it cannot completely eliminate the braking distance or replace the driver’s reaction, especially on low-speed or wet pavements.
Therefore, the self-powered sensing devices that contribute to braking performance monitoring still play an important role in improving driving safety. Since TENG was reported in 2012,\textsuperscript{24,25} TENG has been seen as a milestone discovery in the field of self-powered sensing.\textsuperscript{26−30} Certainly, TENGs also have great advantages in an intelligent transportation system, including driving behavior and vehicle operation monitoring.\textsuperscript{31−33} More and more TENGs were integrated into facilities such as steering wheels, tires, wind barrier, and speed bump to harvest the wasted mechanical energy.\textsuperscript{34−39} On the one hand, they can harvest the mechanical energy of vehicle vibration, and on the other hand, they serve as self-powered sensors to monitor real-time traffic information. Nevertheless, almost no TENG-enabled vehicle braking performance monitoring was identified, but numerous traffic accidents are directly related to braking and hydroplaning during emergency braking. The vehicle braking performance is affected by pavement dynamic peak friction coefficient.\textsuperscript{40−43} Numerous detecting devices for braking performance only use manual detection under specific conditions, and real-time monitoring is not possible. Therefore, it is a critical safety requirement to monitor vehicle

Figure 2. Multimodal aware characterization of GM-TENG. (a) GM-TENG multimodal aware diagram. (b) The open-circuit voltage of multimodal aware. (c) The short-circuit current of multimodal aware. (d) Output signals with different load resistance. (e) Durability test over time.
braking performance for improving driving safety of autonomous vehicles.

To address the above-mentioned challenges in driving safety, a natural TPMS-enabled gradient and multimodal TENG (GM-TENG) is developed to alert the risk of driving safety in the braking process as shown in Figure 1. Inspired by butterfly wings, Schwarz primitive-TPMS (P-TPMS) is optimized to detect multi-modal vehicle braking conditions, including long-distance braking, medium braking, and emergency braking.24,45,46

To achieve the above objectives, the GM-TENG is developed from forward engineering (theory) and reverse engineering (application). In forward engineering, the constant c in the implicit function of the P-TPMS is adjusted to be a linear function of the variable $z$, so that the gradient TPMS mechanical structure along the $z$ direction was obtained (See Figure 1b). In reverse engineering, in order to meet the application requirements of traffic safety mode assessment, the brake pedal force borne by different safety modes can be used as the intermediate bridge to further back-calculate the required implicit functions, material stiffness, and other relevant parameters of TPMS structure. Based on this, GM-TENG with contact-separation mode is designed, which not only has multi-level porosity similar to the animal’s natural skeleton but also can monitor pedal force with high accuracy and excellent multi-modal recognition capability (See Figure 1c). Compared to nature-inspired TENGs such as a honeycomb-inspired TENG device, the designed GM-TENG has variable displacement along the $z$-axis direction under external loads, and the movement of GM-TENG is not synchronous but is layered motion. Therefore, GM-TENG has the ability to sense multiple modes, while most porous structures, such as honeycomb structures, are only single mode. In general, the gradient TPMS is the fundamental mechanical structure that ensures multimodal perception of GM-TENG, which is an electronic device supported by gradient TPMS mechanical structure. It means that the proposed GM-TENG has the ability to perfectly characterize gradient TPMS by electrical signals. This work provides the possibility to solve the problem of real-time sensing of driving safety during braking, which promotes the safety margin of autonomous vehicles.

RESULTS AND DISCUSSION

Design and Characterization of GM-TENG. Firstly, the gradient TPMS is designed based on $c = 0.0125z + 0.875$ with $60 \times 60 \times 60 \text{ mm}^3$ to achieve multimodal awareness. The thickness of the three layers of the gradient TPMS is about 1, 1.25, and 1.5 mm, respectively. A three-dimensional structural scheme of the proposed GM-TENG is shown in Figure 1c, which couples contact electrification and electrostatic induction with contact separation mode.46

The continuous alternating current waveform can be obtained by contacting and separating between thermoplastic polyurethanes (TPUs) and polytetrafluoroethylene (PTFE, 0.1mm). Whereas selective laser sintering technology (SLS) and 3D printing technology adopt a discrete stacking forming principle, solid powder materials are directly formed into a three-dimensional solid structure (Figure S1). In order to quickly manufacture the gradient TPMS structure, SLS laser 3D printing technology is adopted, and TPUs with 90A powder is used as the raw material. Relevant research shows that TPU material has strong positive electricity in the triboelectric series. This means that TPU material easily loses electrons after contact electrification with other materials. The 3D printed TPMS structure plays a dual role including positive tribo-layer and support structure. Specifically, the inner surface of the gradient TPMS is the tribo-layer, and conductive strips are applied to its outer surface to form the GM-TENG electrode layer. In addition, a rubber tube is selected as the bearer of positive tribo-layer material, because of its flexibility, toughness, and high resilience. About 60 mm long aluminum foil acted as the electrode on the rubber tube at 30 mm intervals. Then the PTFE film is covered on the outer surface of the aluminum foil as the negative tribo-layer. Finally, the processed rubber tube is integrated into the gradient TPMS structure. The manufactured GM-TENG can be installed on the brake pedal to monitor the pedal force and braking distance, which contributes to achieve early warning of driving safety and accurate self-awareness of pavement skid resistance.

As illustrated in Figure 2a, the multimodal operation of GM-TENG can be divided into four stages, including initial mode, Mode 1, Mode 2, and Mode 3. In the initial mode, GM-TENG almost keeps its initial state due to little external excitation; thus, the compression of the porous and gradient TPMS mechanical structure is very small. This means that the initial mode can be applied to very little or even zero external excitation. Then, with an increasing external load, the thinnest layer of the gradient TPMS mechanical structure is gradually compressed. Furthermore, if the load continues to increase, then the middle layer adjacent to the thinnest layer will also be gradually compressed. At that time, the GM-TENG’s self-aware mode switches from Mode 1 to Mode 2. When the load is increased enough to easily crush the middle layer, the thickest layer starts to be compressed. It is evident that the reported TPMS results are functional gradients. Specifically, the wall thickness, aperture, and applied force of GM-TENG can be controlled by the implicit function of the defined level constant $c$. This means that TPMS structures with different mechanical and electrical features will be developed by different implicit function equations.

The electrical signals generated in Mode 1, Mode 2, and Mode 3 are shown in Figure 2b,c. Both the open-circuit voltage ($V_{oc}$) and the short-circuit current ($I_{sc}$) gradually increase with regular compression of the three layers. When the thinnest layer of wall thickness is compressed, the $V_{oc}$ and $I_{sc}$ are very small due to the small applied force and contact area, which are $\sim$3 V and $\sim$45 nA, respectively. Then, $V_{oc}$ and $I_{sc}$ increase to $\sim$10 V and $\sim$80 nA, respectively, mainly due to the dual effects of contact area and external excitation. Furthermore, if the GM-TENG is fully compressed, $V_{oc}$ and $I_{sc}$ reach $\sim$20 V and 120 nA, respectively. The gradual increase in electrical signals further proves the electrical multimodal perception of the GM-TENG. Moreover, resistors were used as external loads to further investigate the electrical outputs of the GM-TENG. The current amplitude drops with increasing load resistance from 10,000 $\Omega$ to 10 G$\Omega$, while the voltage follows an opposite trend (Figure 2d). Peak current decreases from $\sim$160 to $\sim$0.08 nA with increasing load resistance, while peak voltage increases from $\sim$0.36 to 13.35 V. Peak current and voltage tend to saturate at both high and low ends of the load resistance.

Great long-term stability is the basis for further application of GM-TENG. Figure 2e shows the mechanical stability of the GM-TENG. In the initial state, the GM-TENG can produce continuous compression and rebound motion for two hours (14,400 cycles) due to dynamic load excitation with 2 Hz and

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180 N, and the electrical signals of the last 18 cycles are shown in Figure 2e. The same experiment is repeated one week, two weeks, and one month later. As the testing time increases, the electrical signal output by the GM-TENG has hardly decreased. In fact, 14,400 cycle tests were conducted every week, and after one month, 72,000 cycle loads were already conducted. This demonstrates its superior mechanical and electrical stability after long-term operation of 72,000 cycles.

Multimodal Sensing Mechanism and Simulation.

Driving safety is a complex and integrative issue facing all of humanity. In terms of vehicles, it is difficult to control the driving state during the braking process. Here, the GM-TENG, packaged with a flexible telescopic and spiral tube (poly-ethylene terephthalate, PET) is installed under the brake pedal of the driving simulator to monitor the pavement skid resistance information (Figure 3a), recalling that the distance of the braking process is controlled by sensing distance and the braking distance. In the sensing distance stage, the vehicle speed and the electrical signals perceived by the GM-TENG basically maintain a constant value. The vehicle starts to decelerate until the driver sends the brake command to the pedal, and the electrical signal perceived by the GM-TENG will instantly increase. As shown in Figure 3b, the braking distance depends on the road friction coefficient $\mu$ and the
initial velocity \( v \) of the vehicle. Moreover, related studies have shown that \( \mu \) of tire-road surface is directly related to the acceleration (a, acceleration with positive, deceleration with negative) and roadway grade (G) expressed as a positive decimal value for upslope and negative for downslope and the vehicle deceleration rate.\(^{40,41}\) Since the fact that the pedal force remains almost constant during the braking process, the peak electrical signal of GM-TENG remains practically constant from the start of braking until the vehicle stops (Figure 3b). Braking start time \( t_0 \) and vehicle stop time \( t_1 \) can be fully monitored using GM-TENG. Therefore, it can be assumed that it is feasible to use the electrical signals from \( t_0 \) to \( t_1 \) to evaluate the braking performance. Moreover, mechanical structure design theory and related mechanical-electrical simulations were conducted to verify the multimodal sensing capability of the proposed GM-TENG.

The Schwarz-Primitive belongs to a type of TPMS, which is defined by the implicit function of \( \phi(x, y, z) \) consisting of a combination of satisfactions and trigonometric functions, according to the formula

\[
\phi(x, y, z) \equiv \cos(k_x x) + \cos(k_y y) + \cos(k_z z) = c
\]

where the defined level constant \( c \) represents the horizontal plane of the P-TPMS surface. The TPMS has periodic changes in three directions, which means that after moving a period of distance in a certain direction the shape of the surface returns to the same state. Specifically, \( k_x, k_y \), and \( k_z \) are the frequency parameters of the TPMS structure; increasing these parameters will cause the surface to change faster in the corresponding direction, forming denser corrugations. If the defined level constant \( c \) is zero (i.e., \( \phi = 0 \)), then the space will be divided into subdomains of equal volume by this minimum surface. When the level-set constant \( c \) increases or decreases, it will cause offsetting of the level-set surface from the zero value in the normal direction or in the opposite direction. Moreover, if the level constant \( c \) is modified from a constant to a function that varies with \( x, y, \) or \( z \), the TPMS structure will undergo a gradient along the corresponding direction.

To achieve monotonic functional graded performance, the level-set constant \( c \) is a function of \( z \) (i.e., \( c = 0.0125z + 0.875 \)). In this \( 60 \times 60 \times 60 \) mm\(^3\) three-dimensional space, the P-TPMS structure is distributed in three layers along the \( z \)-axis, and each layer is arranged along the \( x \) and \( y \) direction as \( 3 \times 3 \) units. As shown in Figure 3c, the wall thickness of each layer center is 1, 1.25, and 1.5 mm, respectively. Considering the superiority of Ls-dyna finite element simulation software in the analysis of the static and dynamic response of highly strained structures, this paper combines Hypermesh and Ls-dyna software to simulate the deformation stage of the proposed graded P-TPMS under different applied load speeds. Specifically, the P-TPMS structure designed by Matlab software is imported into Hypermesh to create the graded structure mesh. Meanwhile, the Mooney-Rivlin model is adopted, whose values of the relevant parameters can be found in Supporting Information Note 4. The P-TPMS failure modes are significantly different with different applied loading speeds (i.e., Figure 3d,e). In this model, the compression amount is 50 mm, and the applied loading speed is determined by changing the time required for compression of this structure. As shown in Figure 3d, the P-TPMS structure indicates that the thickest layer is destroyed until flattened, then the middle layer is destroyed, and finally the thinnest layer is destroyed. On the contrary, the thinnest layer is destroyed first, and then the delamination is gradually compressed, regardless of stress or strain deformation (Figure 3e). It is evident that the difference between Figure 3d,e is mainly caused by the applied loading speed. Therefore, the strain deformation and stress distribution of the P-TPMS under compression time of 0.0005 s, 0.01, 0.012, 0.015, 0.02, and 0.1 s are further analyzed. Corresponding results are shown in Figures S4 and S5, indicating that the failure modes of the P-TPMS structure can be divided into five types, including (i) when the compression time is less than 0.012 s, the thickest layer is destroyed first, mainly because the compression speed in this time is completely greater than the speed of stress propagation; (ii) when the compression time is in the range of 0.012 to 0.0135 s, the thickest layer is destroyed first, but when the strain deformation is greater than 35%, it gradually shows that three layers are destroyed at the same time. This is mainly because there is a balance point between the stress propagation speed and compression speed after the thickest layer produces a certain amount of damage. Once the balance point is reached, the three layers will be destroyed at the same time; (iii) when the compression time is 0.014 s, the compression speed and the stress propagation speed are completely balanced, and the P-TPMS structure is characterized by the simultaneous destruction of three layers; (iv) when the compression time is between 0.014 and 0.015 s, three layers are destroyed at the same time in the initial stage, and the thinnest layer is destroyed first when the strain deformation is about 46.7%. This shows that the compression velocity is gradually lower than the stress propagation velocity with decreasing loading speed; (v) when the compression time is greater than 0.2 s, because the compression velocity is completely less than the stress propagation velocity, the P-TPMS shows that the thinnest layer is destroyed until it is compressed, and then the middle layer is destroyed. The transformation of failure modes for varying applied loads also demonstrates the gradient of the P-TPMS.

To better investigate the influence of different modes on GM-TENG, the simulation of potential distribution by Comsol Multiphysics is performed (Figure 3g). The structure and dimension of this simulation model built in this paper are the same as the actual devices. A surface charge density of 80 \( \mu \)C/
m<sup>2</sup> and a floating potential of 3.7 μV are assigned to two tribocharged surfaces to maintain charge conservation. As the GM-TENG is in an open-circuit condition, no electron transfer takes place between the two electrodes. The potential distribution has a maximum when the GM-TENG is compressed layer by layer. When the GM-TENG is in the fully released state, the potential distribution increases with the increasing TPMS hole diameter, mainly because the larger the diameter, the greater the distance between the two tribo-electrodes. Thus, the potential naturally increases under the same electric field intensity. The maximum potential is about ∼57.1 V. Moreover, when the thinnest TPMS structure at the bottom is compressed, the potential of the entire device is mainly distributed between the middle layer and the bottom layer (light blue area in Figure 3g ii)), which is caused by the contact and separation of the GM-TENG structure at the bottom layer. As the area of the tribo-pairs increases, the maximum potential also increases to ∼98.2 V. When the middle layer of the GM-TENG continues to be compressed, although the potential distribution is still consistent with the fully released state, the distribution range is not limited to the surroundings of the TPMS thin-walled hole but to the entire structure. This demonstrates that the unbalanced potential distribution is gradually broken, and the potential distribution area is larger. At the same time, the peak value is reduced to ∼66.2 V. Finally, when the three layers of the TPMS structure are compressed, the distance between the two tribo-pairs is greatly reduced, and the potential is further reduced based on the previous stage. Because the TPMS hole diameter is very small when it is compressed, it almost completely contacts the opposite electrode layer, resulting in no potential distribution on that layer. Meanwhile, the peak potential is reduced to ∼59.9 V. To further determine the actual potential distribution law, a single load discharge experiment can be used to analyze the motion law of the P-TPMS structure and the output electrical signal.

**Characterization of The Mechanical and Electrical Responsive Behavior of GM-TENG.** The above simulation results demonstrate the correspondence between the applied loading speed and structural deformation performance. Here, quasi-static compression testing is conducted on P-TPMS structures in accordance with relevant mechanical testing standards of metal ductility testing-compression testing for porous and cellular metals (ISO13314:2011).

Firstly, the multifrequency excitation and multiload excitation tests of Mode 1, Mode 2, and Mode 3 were carried out...
to calibrate the response law of GM-TENG to speed and load in different modes. Figure 4a–c shows the electrical signals of GM-TENG under excitation loads of 5, 80, and 160 N, respectively. It can be found that the amplitude of $I_{sc}$ can be utilized as the index of frequency perception in the three modes since the current amplitude increases with the increase of frequency. However, $V_{oc}$ hardly changes with the excitation frequency. Besides, both the $I_{sc}$ and $V_{oc}$ increase with the increase of the number of modes, mainly because the larger the mode is, the larger the contact area of GM-TENG, and more induced charges are generated. Specifically, the amplitude of $I_{sc}$ in Mode 1 is about 45–128 nA, and the amplitude of $V_{oc}$ is about 6.5 V. The amplitude of the short-circuit current in Mode 2 is about 74–201 nA, and the amplitude of $V_{oc}$ is 12.1 V. Mode 3 has an $I_{sc}$ magnitude of about 145–532 nA and a voltage magnitude of about 29 V.

Moreover, an external load of 5–260 N was applied to the GM-TENG with an excitation frequency of 8 Hz. The peak voltages under different loads and modes are extracted and shown in Figure 4d–f. It can be found that the maximum loads...
that Mode 1, Mode 2, and Mode 3 can withstand are 80, 160, and 260 N, respectively. When the applied external load is greater than 80 N, the GM-TENG transforms from Mode 1 to Mode 2. If the applied external load continues to increase to 160 N, then GM-TENG transforms from Mode 2 to Mode 3. Each mode transition causes a change in the load sensing sensitivity. Specifically, the load sensing sensitivities in Mode 1, Mode 2, and Mode 3 are 0.14, 0.04, and 0.11 N/V, respectively. It can be found that the load sensing sensitivity of Mode 2 is smaller than that of Mode 1 and Mode 3. It is mainly because of Mode 2 that the contact-separation movement of the middle layer of the TPMS structure is not as sufficient as the movement of the thinnest and thickest layers. The top and bottom of the middle layer structures are constrained by the thinnest layer and the thickest layer, respectively. Thus, the movement of any layer will have an adverse effect on the middle layer.

Besides, the quasi-static testing in different working modes was performed to explore the potential application of GM-TENG as a self-aware device (Figure 5a). In mode 1, only the thinnest layer is compressed, and the loading ends when the thin walls are fully in contact, which means that the unloading process starts. Likewise, mode 2 ends the loading process when the thinnest and middle layers are flattened. Corresponding mode 3 is to end the loading process until all layers are flattened, causing GM-TENG to rebound. Typical force and time response (displacement) with different applied load speed are shown in Figure Sb,c. Three peaks can be observed in each force-time curve. Besides, the force peak value appears earlier than the maximum voltage value in the three modes. That is to say, the force peak generates halfway through each compressed layer, but the voltage maximum occurs only when each layer is completely flattened. This result can be explained by the fact that the proposed P-TPMS structure has three layers and each layer needs to overcome a greater force at the beginning of compression, called critical stress. However, once the P-TPMS is damaged, only a force less than the critical stress is required to further damage the structure. Therefore, the proposed P-TPMS exhibits three critical stresses, which are the basic guarantee for its multimodally aware application.

To illustrate the mechanical-electrical coupling performance of P-TPMS as a GM-TENG with typical metamaterial mechanical properties, \( V_{oc} \) in different modes is further observed. The peak value of \( V_{oc} \) gradually increases with the transition of the work mode. However, contrary to the results of the mechanical characterization, wave valleys are not observed at the instant of the mode transition, and the voltage-time curve just becomes flat. This is mainly due to the constant charge transfer during the loading process.

Figure 5b shows a typical time-history response of the proposed GM-TENG for cyclic loading at 25 mm/min. The loading process can be monitored based on \( V_{oc} \). In Mode 1, only the thinnest layer was compressed; the \( V_{oc} \) peak is about \( \sim 8.26 \) V. If GM-TENG is in Mode 2, two layers were compressed; \( V_{oc} \) increases to \( \sim 14.7 \) V. In approximately 25 s, a plateau reaches a voltage of \( \sim 7.64 \) V. This indicates that the gradient capability of the GM-TENG can be displayed through peak voltage amplitudes. The additional test of three compressed layers also proves the above assumption. Further, the \( V_{oc} \) reaches \( \sim 23.3 \) V after the entire P-TPMS structure has been compressed. Corresponding plateaus were observed at \( \sim 8.25 \) and \( \sim 15.9 \) V. Therefore, the voltage amplitude can be considered as the self-powered sensing index in the real application. To visually identify the different modes, the corresponding numbers 1, 2, and 3 have been marked on the voltage-time curve and the force-time curve to represent Mode 1, Mode 2, and Mode 3, respectively. In addition, histograms have been plotted to display peak voltage and peak force. The findings demonstrate that it is possible to identify the working modes of the P-TPMS metamaterial by monitoring the generated voltage.

There are the same rules between Figure 5c,b. In addition, the slope of the voltage-time rise section under different modes is calculated further. The average value of the slope in the voltage-time curve is 0.67. The maximum value is 0.83, and the minimum value is 0.58, as shown in Figure 5c. Moreover, when the applied force velocity is 25 mm/min, the average, maximum, and minimum values are 0.35, 0.31, and 0.39, respectively. In Figure 5c, \( k_1 \), \( k_2 \), and \( k_3 \) represent the voltage increase rates during the compression of the thinnest layer, the compression of the middle layer, and the compression of the thickest layer, respectively. It is worth noting that the same trend of \( k_1 \), \( k_2 \), and \( k_3 \) can be found with decreasing first and then increasing at 25 and 50 mm/min. This is mainly due to the characteristics of the TPMS structure. Being different from the thinnest and thickest layers, the middle layer is constrained in both directions, including the thinnest layer above and the thickest layer below. That is to say, the load borne by the actual middle layer is far less than the set applied load after being buffered by the thinnest layer and the thickest layer. In addition, the contact between the positive and negative friction layers of the middle layer is not sufficient due to the constraints and pinning effects of the upper and lower layers. The combined effect of the above reasons has caused \( k_2 \) to be the smallest result. Considering the relatively small change in slope, \( s = (k_1 + k_2 + k_3)/3 \) was adopted to uniformly predict the applied speed, thereby eliminating the influence of different layers. Moreover, the slopes of the loading speed of 25 mm/min have nearly half the slopes of 50 mm/min. This result implies that the loading speed \( v \) can be interpreted as

\[
v = 75.76 \text{ s}
\]

where \( v \) is the applied force velocity of the GM-TENG, and \( s \) represents the velocity perception index based on the voltage-time slope.

Furthermore, Figure 5d summarizes the GM-TENG's sensing capabilities during the quasi-static load test. On the one hand, the device's working mode can be identified based on the peak value of the voltage signal; on the other hand, the loading speed to which the device is submitted can be evaluated based on the voltage time slope. In short, this device can be used as a self-powered speed, force, and mode identification sensor.

It is well-known that the normal work of the GM-TENG requires the TPMS structure to be able to produce continuous compression and resilience motions. It means that it is very important to investigate the mechanical resilience performance and durability performance of GM-TENG after cyclic loading. Therefore, the MultiTest2.5-i tensile and compression test system was used for continuous fatigue testing. Specifically, the loading parameters at a speed of 800 mm/min and a load of 200 N were adopted to trigger structural movement. The compression rate and resilience rate of GM-TENG were calculated on the initial loading, one week after repeated loading, and one month later, to prove its normal working ability for long-term continuous loading. As shown in Figure 5d.
6a, the height of the initial GM-TENG was 56 mm. Although the height designed in Solid Works 2019 was 60 mm, the structure shrank by 4 mm after curing due to the immersion strengthening treatment after 3D printing. Further, from the resilience results of GM-TENG in Figure 6a, it can be found that the compression of the overall structure of GM-TENG increases with the increase of cyclic loading time in the fatigue test. The reason for this phenomenon is that the fatigue test causes irreversible damage to the structure. As the number of fatigue loading increases, the Young’s modulus of the structure decreases, and the external load which GM-TENG can withstand decreases. Therefore, the GM-TENG will produce greater compression under the same external load. But it is worth noting that the compression value increased from 64% of the initial state to 66% after one month, an increase of only 3.1% of the initial compression. Correspondingly, the resilience rate of GM-TENG was reduced from 100% in the initial state to 96%, and the reduction was only 4% of the initial resilience. Therefore, the above analysis proves the reliable rebound performance of GM-TENG.

Moreover, Figure 6b—d shows examples of the compression and resilience of the specimen after cyclic loading for one month. It can be found that even after one month of continuous loading, the resilience of Mode 1 still reaches 100%. The resilience decreases to 96% as the middle layer of the structure compresses. Fortunately, the resilience in Figure 6d still reaches 96%. From Mode 2 to Mode 3, the reason that the resilience does not decrease is mainly because the middle layer of the structure is the weak part of the whole. After passing through the middle layer, although the loading continues, the damage to the thickest layer by cyclic loading is limited due to the larger Young’s modulus. Therefore, it is believed that the designed GM-TENG is capable of withstanding multiple driver’s pedaling actions.

**Theoretical Background and Driving Safety Monitoring Application.** Great skid resistance is the key to achieving a vehicle’s safe braking distance, and the tire-road skid resistance is different under different driving conditions. When the vehicle is braked on a dry pavement, the frictional torque generated by the brake disc is due to the compression of the wheel brake friction plate. Meanwhile, the pavement surface produces a reaction force to the tire’s driving direction. The vehicle gradually decelerates under the two forces until it stops. To better understand the relationship between the braking distance and tire-pavement skid resistance, it is critical to analyze its theoretical basis. In Figure 7a, assuming that air resistance and inertial force are ignored, the dynamic equation of the tire is

$$
\begin{align*}
J \dot{\omega} &= r F_x - T_b \\
nv &= -F_x
\end{align*}
$$

where $J$ is the rotational inertia of the tire, $m$ is the mass of a tire, and $v$ and $\omega$ are the velocity and angular velocity of the tire, respectively. $r$ is the tire radius. $F_x$ is the pavement braking force. $T_b$ is the brake torque, which depends on the pedal force ($F_b$).

Moreover, the braking force of the brake ($F_b$) is

$$
F_b = T_b/r = \psi F_N r_b/r
$$

where $\psi$ is friction coefficient of the brake friction pair, and $r_b$ is the radius of the brake.

In fact, the pavement friction force ($F_p$) is limited by the pavement adhesion force ($F_N$). When the pedal force ($F_N$) is small, $F_p$ is proportional to $F_b$. When the pedal force increases...
to $F_b = F_{\mu}$, the pavement friction force ($F_z$) is equal to the pavement adhesion force and will not increase with increasing pedal force ($F_N$),\textsuperscript{30,51} as shown by equation

\begin{equation}
F_z = \begin{cases} 
F_b \\
F_{\mu} = \mu mg
\end{cases}
\end{equation}

where $\mu$ is the pavement friction coefficient, which depends on the pavement surface toughness, vehicle speed, and tire tread.

Therefore, when the GM-TENG is installed on the brake pedal, the electrical signal of GM-TENG will increase with the increase of pedal braking force, thereby judging the driver’s operation (long-distance braking, middle braking, and emergency braking) based on the multimodal perception capability of GM-TENG. When the driver is in an emergency braking state, it is necessary to remind them to drive carefully. Specifically, the micro-controller unit (MCU, Arduino Mega 2560) processed by the signal amplification circuit collected electrical signals in real time and connected a buzzer in the circuit. When the peak voltage exceeds the threshold voltage and the product of the peak value of the voltage signal and time exceeds the threshold braking distance factor, it means that it is in an emergency braking state. The buzzer will alarm. The related circuit connections can be found in Supporting Information.

Figure 7. Application of GM-TENG device for tire-pavement skid resistance sensing. (a) The force distribution of the GM-TENG during the vehicle braking process. (b) Electrical signals under different braking conditions. (c) Pavement environment scene in the driving simulator and the packaged GM-TENG installation details. (d) The multimodal design and application of GM-TENG. (e) The open-circuit voltage-time curve during the braking process with different speeds. (f) The value of the braking distance factor ($L$) under different friction coefficients. (g) The value of the braking distance factor ($L$) at different speeds. (h) The friction coefficient calculation function depending on the braking distance factor and speed.
Furthermore, emergency braking under wet conditions on rainy days is more likely to cause side slip, rear-end collision, and other traffic accidents due to insufficient braking distance. Therefore, the braking distance factor can be calculated by extracting the time when the driver starts and ends operating the pedal and the peak electrical signal to act as the perception index of the road surface skid resistance and driving safety. The smaller the braking distance factor, the greater the frictional resistance, indicating good antislip performance. Therefore, the GM-TENG plays a crucial role in driving safety monitoring.

Given the above force analysis during the vehicle braking process, further combination with the application prospects of GM-TENG in driving safety monitoring is possible. Driving simulation tests under different braking conditions were conducted, including long-distance braking (Mode 1), medium braking (Mode 2), and emergency braking (Mode 3). Fortunately, three types of compression can be achieved due to different braking conditions, which include thinnest layer compression, two consecutive layers compression, and full compression. The corresponding electrical signal is shown in Figure 7b. The peak voltage $V_{\text{oc}}$ gradually increases with changing braking conditions, while the duration of the peak voltage gradually decreases. This is mainly caused by the gradual increase in the pedal force ($F_p$) from long-distance braking to emergency braking. Specifically, the peak voltages of the three braking conditions are $\sim 7.524$–$8.732$ V, $\sim 18.864$–$20.74$ V, and $\sim 30.724$–$32.448$ V, respectively. This result shows that the peak voltage can be used to preliminarily assess the safety of the vehicle’s braking process. When the peak voltage is less than $\sim 18.864$ V, the driver can be encouraged to maintain the condition and continue braking. If the voltage spike continues to increase to $\sim 20.74$ V, a reminder is given to the driver to pay attention to safety and drive carefully. When the peak voltage reaches $\sim 30.724$ V, it means the vehicle is in an emergency braking condition and the vehicle’s ABS system can be activated to avoid a hazard. Therefore, the above results demonstrate that GM-TENG has a wide-ranging sensing ability to monitor multiple braking states due to its gradient structural design. Compared with the uniform flexible 3D-TENG with 0.5–3 Hz sensing range, the GM-TENG widens the perception range from human motion to the monitor of driving safety condition.

The relevant test and driving simulation scenarios are shown in Figure 7c. At present, the GM-TENG can be packaged using a telescopic and spiral tube with an upper top plate and a lower bottom plate, with one end fixed to the lower surface of the brake pedal and the other end indirectly fixed to the vehicle’s internal bottom plate through a steel reinforcement support structure. This implantable method is easy to install, has high perception accuracy, and can achieve multimodal sensing applications with a single sensor (long-distance braking, medium braking, and emergency braking). However, frequent operation of the brake pedal will affect the braking performance of the vehicle itself. In the future, an integrated and multifunctional TENG-based brake pedal will be designed as a sensing device to provide brake control and evaluate driving safety. In addition, friction coefficients of 0.3, 0.4, 0.5, 0.6, and 0.7 are defined for the asphalt pavement with a length of 1000 m. Obstacles on the pavement are represented by a cow, and traffic signs are placed 100, 200, and 500 m away from the obstacles.

The above results and other TENG sensor dynamics studies show that the relationship between electrical output performance and external load can be expressed as

$$F_N = k \cdot V_{\text{oc}} \quad (k > 0)$$

where $k$ is constant, which depends on the electrical performance of the TENG sensor.

According to Equation 3, only in the emergency braking state, the pavement braking force ($F_p$) is affected by the pavement adhesion force ($F_a$). This also means that the braking distance at this point is related to the pavement friction coefficient ($\mu$). The braking distance ($d$) under other conditions shall not be used to assess the pavement skid resistance. Based on the results shown in Figure 7b and the theoretical analysis above, the gradient design and multimodal sensing application of the GM-TENG are summarized in Figure 7d. The design principle of GM-TENG includes forward engineering from control equation $c$ to driving safety mode prediction and reverse engineering to design the materials and structures of TPMS for traffic safety mode prediction. On the one hand, appropriate application scenarios are conceived based on the theoretical basis of forward engineering; on the other hand, the required materials and TPMS structures are programmatically designed through reverse engineering’s traffic safety mode assessment objectives. In this paper, the function of multimodal perception is mainly applied to the evaluation of driving safety modes based on braking parameters. Specifically, the GM-TENG working mode can be determined based on the peak voltage, including Mode 1, Mode 2, and Mode 3. When in Mode 1, it indicates that the pedal force emitted by the driver is relatively small, which is a safety stage. When working in Mode 2, driving safety is on the edge between safety and potential hazard, and the driver should be extra careful. When working in Mode 3, it means that an emergency braking situation has occurred and it will be necessary to calculate the road friction coefficient in detail to provide the driver with appropriate reminders.

Moreover, emergency braking tests were further carried out at different speeds, including 40, 60, 80, and 100 km/h. For example, the open-circuit voltage-time curve during the braking process with different speeds is shown in Figure 7e. Its peak voltage is almost constant, but it is apparent that the duration of the peak voltage increases with an increasing velocity. This implies that if the integral value of $V_{\text{oc}}$ is extracted in relation to the time in the periods of beginning and end of braking, denominated as the braking distance factor ($L$), it can be used to calculate the pavement friction coefficient, by equation

$$L = \int_{T_1}^{T_2} V_{\text{oc}} \, dt$$

where $T_1$ and $T_2$ are the start and end times of the braking process, respectively.

As shown in Figure 7f, the braking distance factor is related to the friction coefficient and speed. The braking distance factor decreases with an increasing friction coefficient and increases with an increasing vehicle speed. This tendency is consistent with the trend of braking distance with the friction coefficient and vehicle speed.

Furthermore, according to the energy conservation law, the kinetic energy ($E_k$) of the vehicles can be converted into
frictional energy ($E_k$) between the road and the vehicle within the braking distance:

$$E_k = \frac{1}{2}mv^2 = E_l = F_xd = \mu mgd$$

Thus, the braking distance ($d$) can be expressed as follows.

$$d = 0.039\frac{v^2}{\mu g}$$

Therefore, learning from experience is needed to calculate the friction coefficient per braking distance. The multiple power functions were attempted to adjust the friction coefficient determined by the braking distance factor ($L$) and speed, as shown below.

$$\mu = a\frac{v^b}{L}$$

Within the 95% confidence limits, the adjusted result is $a = 0.2311$, $b = 1$. At this time, the Coefficient of Determination ($R^2$) is up to 0.9429, while the sum of squares due to error (SSE) is only 0.0228. As shown in Figure 7h, this result indicates that the adjusted equation can be used to characterize the friction coefficient. The friction coefficient is a key index to characterize the tire-pavement skid resistance. This means that the proposed GM-TENG can evaluate pavement skid resistance.

$$\mu = 0.2311\frac{v}{L}$$

In addition, the application of GM-TENG is not limited to the evaluation of the pavement skid-resistance performance. It will be further applied to the structural health monitoring of road infrastructure and traffic information monitoring in the future (Supporting Information Note 7). For example, it can be installed in (1) road structures to monitor pedestrian crossing behavior, (2) the speed bump to harvest the mechanical energy of vehicles passing by, (3) the traffic markings for illegal behavior monitoring, such as vehicle pressure lines, (4) the electronic toll collection (ETC) expressway for weigh-in-motion of vehicles, including driving speed and load, (5) the joints of the bridge to monitor vehicle jumping at the bridge head, (6) the entrance of the tunnel for monitoring driving speed, etc. Of course, this future application includes, but is not limited to, health monitoring, medical applications, intelligent wearable devices, automatic driving, intelligent transportation systems, structural health monitoring, intelligent materials, robotics, and other fields. The three-channel array sensor with three different modes of GM-TENG can provide more channel information on motion status, improve perception accuracy, and expand perception applications.

CONCLUSION

The triply periodic minimal surface (TPMS) inspired gradient biological triboelectric nanogenerator (GM-TENG) was designed and developed for real-time awareness of driving safety in the braking process. The multimodal aware mechanism and mechanical properties of P-TPMS are described to prove its typical properties of a metamaterial. The difference in the layered destruction of the proposed TPMS structure implies the gradient ability to adapt to different application scenarios. Furthermore, the theoretical analysis of pavement skid resistance sensing in the braking process based on the mechanical-electrical coupling effect between pavement structure and TENG devices is investigated for the first time, which demonstrates TENG’s capability in estimating the pavement friction coefficient. In addition, the proposed GM-TENG was packaged into a dual telescopic and spiral tube to be installed on the automobile pedal. The braking distance factor ($L$) is obtained by integrating the $V_{oc}$ with time, which is used together with the vehicle speed to calculate the tire-road friction coefficient. Fortunately, the corresponding R-square value is up to 94.29%. In the future, real vehicle testing at the testing site will be carried out to further improve practicality and perception accuracy. Therefore, this work aids the future application expansion of GM-TENGs in the field of autonomous driving.

METHODS

Fabrication of GM-TENG. As shown in Supporting Information Figure S1, a gradient TPMS structure (60 mm × 60 mm × 60 mm) was made by means of SLS laser 3D printing technology. The surface treatment was conducted to ensure outstanding mechanical properties. The TPMS structure plays a dual role in the proposed GM-TENG sensor. On the one hand, the gradient TPMS can be considered as the carrier structure to control the contact and separation of tribo-pairs; on the other hand, it acts as a positive tribo-layer. As the carrier of the negative tribo-layer layer, the flexible rubber tube (inner diameter × outer diameter = 3 mm × 5 mm) is attached with conductive Cu-Ni tape and PTFE material with a thickness of 100 μm on its outer surface.

Electrical and Mechanical Properties Characterization of TPMS. The electrical measurement system is adopted to investigate the electrical performance of GM-TENG, including a function generator (YE1311E), power amplifier (YE5871A), electrodynamic shaker (JZK-5), electrometer (Keithley 6517), and data acquisition system. In this work, a series of parameters were analyzed, such as the frequency, load resistance, and layered compressed electrical performance. Besides, the Ls-dyna finite element simulation software was adopted to analyze the damage and strain deformation state of the gradient TPMS structure at different speeds. Moreover, the WDW-Y300D electronic universal testing machine was used to demonstrate the typical mechanical properties of metamaterials with a 300 kN sensor at displacement rates of 1.5, 24, 36, and 50 mm/min.

Experiment Measurement and Applications. Considering the hazard of real vehicle emergency braking, we used a driving simulator to perform the related measurement. Detailed parameters can be seen in Supporting Information Note 5. First, the GM-TENG is packaged by a flexible telescopic and spiral tube and installed in the brake pedal of the driving simulator. Then, linear asphalt pavement scenarios with friction coefficients of 0.3, 0.4, 0.5, 0.6, and 0.7 are obtained by the SCANERTM Studio software.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.3c08102.

SLS 3D printing principle and structure, fabrication of GM-TENG, measurement and performance of GM-TENG, finite element model and indoor test of TPMS.
structure, experimental equipment of driving simulation, driving safety warning demonstration, comparison of skid-resistance performance, application prospects, and drawbacks (PDF)

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Author Contributions

Y.F. Pang and X.Y. Zhu conceived the idea and designed the experiment. Y.F. Pang, X.Y. Zhu, and S.N. Liu designed and conducted the experiments. Y.F. Pang analyzed data and wrote the manuscript. C.K. Lee and X.Y. Zhu edited the manuscript.

Notes

The authors declare no competing financial interest.

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REFERENCES


(22) Park, J.; Kim, I.; Yun, J.; Kim, D. Liquid-Metal Embedded Sponge-Typed Triboelectric Nanogenerator for Omnidirectionally
2017, 32, 408–413.