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Research article

# A corn leaf based-strain sensor and triboelectric nanogenerator for running monitoring and energy harvesting

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ABSTRACT

Recently, advanced wearable devices with posture sensing and energy harvesting have received widespread attention. Thus, we proposed a dual-function device (energy harvesting and running posture sensing), including carbon attached corn leaf strain sensor (CC-strain sensor) and a corn leaf-based triboelectric nanogenerator (C-TENG).According to the results, the relative resistance rate ($\Delta R/R_0$) exhibits linear characteristics in the three strain regions, and its linear coefficients are all above 0.96. Besides, at low strain rates from 0.01% to 0.1%, the CC-strain sensor can reach high sensitivity for monitoring weak signals, such as expressions in dance performances. The C-TENG device can achieve mechanical energy harvesting, providing a way to power low-power portable devices. From the results, the maximum power of C-TENG can arrive at 222 μW (resistance: 100 MΩ). This research can provide a new path to integrate strain sensors and TENG devices in running monitoring.

## 1. Introduction

Recently, advanced wearable portable electronic products with lightweight, comfortable, and high response rates have attracted increasing attention in the industrial field due to their applications in human posture monitoring [1], sports training [2], medical diagnosis [3], and energy harvesting [4]. Especially for wearable electronic devices with skin or cloth compatibility, it can monitor the real-time human motion status through sensing signals [5]. The core component of flexible electronic products is flexible sensors. Also, the strain sensor based on the piezoresistive effect has potential application value in human posture sensing due to the advantages of low cost and high sensitivity [6,7]. Sensing subtle changes in human postures, such as facial changes of dancers, requires flexible sensors with high stability and sensitivity. However, complex deformation, such as stretching and squeezing, can cause fracture and damage for most strain sensors. The research and development of multifunctional flexible sensors is also an important field driving the development of wearable electronic products [8]. It is worthwhile to explore advanced materials for wearable products. By optimizing the resistance variation of the conductive layer, the sensing performance of strain sensors can be improved [9,10]. Additionally, the substrate can carry conductive materials through various methods such as infiltration, physical deposition, chemical deposition, and screen printing. Conductive materials like aluminum, copper, carbon, and conductive polymers can be used as the conductive layer on the substrate [11–14]. The carbon materials can serve as materials for the conductive layers due to green, environmental protection, and low cost. Due to the advantages of granular conductive materials that are prone to resistance changes, carbon-based materials can meet the needs of high-sensitivity strain sensors. In addition, conventional flexible substrates consist of polymer materials such as polyethylene terephthalate (PET) [15], Kapton [16], Polydimethylsiloxane (PDMS) [17], etc. However, elastic polymers typically have

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hydrophobicity and require special treatment to carry conductive materials. Etching various micro/nanostructures on the surface of flexible substrates is an effective way to improve the sensing sensitivity of sensors. Using 3D carbonized materials to manufacture flexible strain sensors is a feasible approach to enhance the sensing sensitivity of strain sensors, such as silk [18], cotton [19], and fruit peel [20]. Flexible sensors based on these materials have shown potential application value in human posture monitoring. However, 3D carbonized materials typically require tedious processes such as weaving, drying, and pre-treatment to achieve their preparation. Utilizing the micro-nano structure generated by the wrinkling of plant leaves to achieve strain sensing is a new strategy, which can reduce manufacturing costs.

Besides, portable power supplies are the energy source for wearable electronic devices, and thus the development of novel flexible power supplies is necessary. It is worth noting that triboelectric nanogenerators (TENGs) are an essential power generation technology proposed in recent years, which can convert mechanical energy generated by low-frequency human motion into electric power [21–25]. TENGs have the potential to be used in solving the power consumption problem for distributed, low-power electronic devices. Research has shown that TENG devices can effectively harvest energy from various sources in the environment, such as human movement [26], wind energy [27], wave power [28], and so on. Compared to traditional chemical batteries, flexible TENG devices possess several advantages such as portability, lightness, and wearability [29,30]. The extensive range of materials used for the TENGs provides an integration foundation for TENG devices and flexible strain sensors, achieving energy harvesting and posture sensing. Conventional structural integration of TENG energy harvesting devices and strain sensors can be challenging due to differences in the working mechanisms of the two devices, which leads to complex technical difficulties and high manufacturing costs. However, an integrated structure can help overcome these issues. Previous studies have shown that plant leaves possess good triboelectric properties and can serve as the material for preparing TENG devices, making energy harvesting possible [31–34]. Therefore, using plant leaves as manufacturing materials for TENG devices and strain sensors is a cost-effective way to meet functional requirements.

Here, we propose a dual-function device (energy harvesting and running posture sensing), including carbon attached corn leaf strain sensor (CC-strain sensor) and a corn leaf-based triboelectric nanogenerator (C-TENG). The corn leaf with natural surface wrinkles provides the foundation for the carbon oil loading and the high-sensitivity strain sensors. Meanwhile, the rough surface of corn leaf is also conducive to the generation/accumulation of triboelectric charges. The carbon-attached corn leaf can achieve the monitoring function of slight strain and improve stability and flexibility through PDMS packaging. And the C-TENG consists of a PDMS layer and corn leaf, which can harvest various mechanical energy. According to the results, the relative resistance rate ($\Delta R/R_0$) exhibits linear characteristics in the three strain regions, and its linear coefficients are all above 0.96. Besides, at low strain rates from 0.01% to 0.1%, the CC-strain sensor can reach high sensitivity for monitoring weak signals, such as expressions in dance performances. CC-strain sensors can sense the amplitude of body movements and the degree of facial expressions in dance performances. The C-TENG device

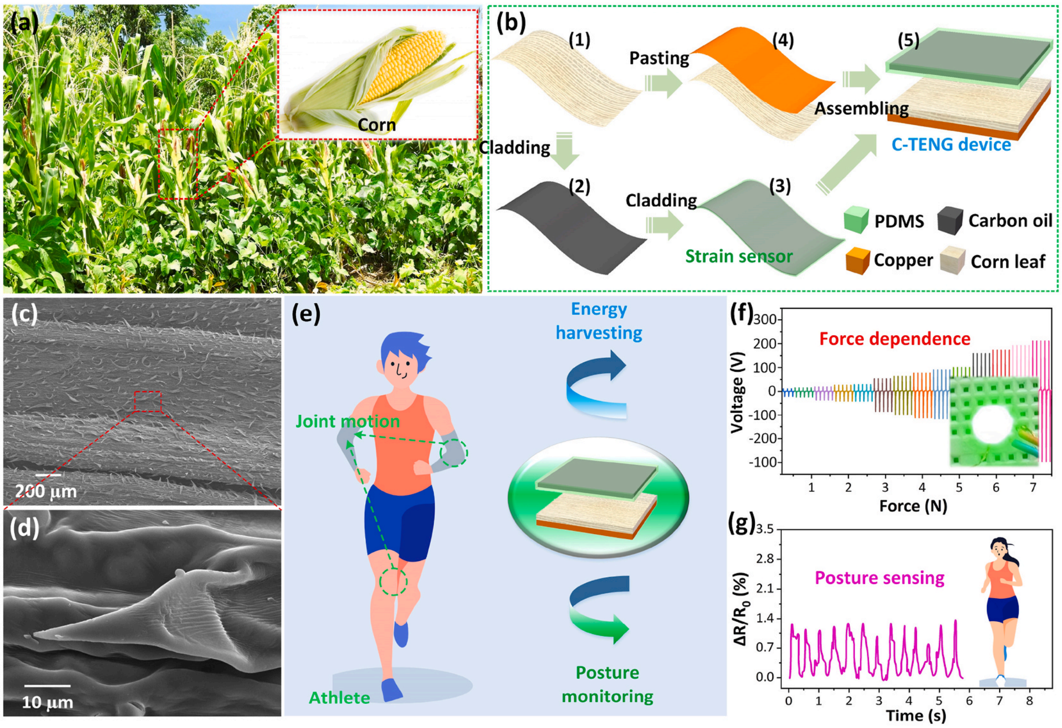


**Fig. 1.** (a) Photos of green corn field scenes (inset: photo of corn cob with corn leaves). (b1-b5) The manufacturing process of strain sensor and C-TENG device. (c, d) The SEM images of corn leaf surface. (e) The picture of athlete. (f, g) The energy harvesting and running posture monitoring application of C-TENG device and CC-strain sensor. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

can achieve mechanical energy harvesting, providing a way to power low-power portable devices. From the results, the maximum power of C-TENG can arrive at 222 μW (resistance: 100 MΩ).

## 2. Experiments

### 2.1. Materials

Corn leaves were obtained from Jingdong mall in China. PDMS preparation solution (A:B = 10:1) was bought from the Sigma Aldrich Trading Co., Ltd (Shanghai, China). Conductive copper foil and carbon oil (square resistance: 8 Ω/25 μm, viscosity: 250 ± 50 (dPa s)) were obtained from Qiandai Electronic Materials Co., Ltd (Shenzhen, China).

### 2.2. Preparation process of strain sensor and C-TENG device

As we all know, corn leaves can be obtained from the crop, which is agricultural waste, especially for dry corn leaves (Fig. 1(a)). Corn leaves are the leaves wrapped around the fruit of corn. And corn leaves are rich in starch, minerals, and other components, making them an environmentally friendly material. Significantly, the dried corn leaves have a rough surface texture, which provides a basis for the preparation of flexible strain sensors, and meanwhile, this also brings excellent triboelectric properties. Fig. 1(b) depicts the concrete preparation process of the C-TENG device and flexible strain sensor based on a corn leaf. In detail, the dried corn leaves were obtained by washing them with deionized water and drying them in the oven, then two pieces of corn leaf sheet (Size: 2 cm × 4 cm) were cut off from the dried corn leaf, as depicted in Fig. 1(b1). Next, soak one of two corn leaves in carbon oil and dry them for the fabrication of the strain sensor (Fig. 1(b2)). Immediately, immerse the corn leaf loaded with carbon oil in a PDMS mixed solution, and then dry the sample (Fig. 1(b3)). Packaging corn leaves loaded with carbon oil using PDMS (thickness: 2 mm) can achieve protection of the ink layer and avoid contamination by impurities in the environment. Also, paste conductive copper foil on the surface of another piece of corn leaf for triboelectric pair (Fig. 1(b4)). Finally, compose two components into a C-TENG device to achieve dual functions of energy harvesting and strain sensing, as depicted in Fig. 1(b5).

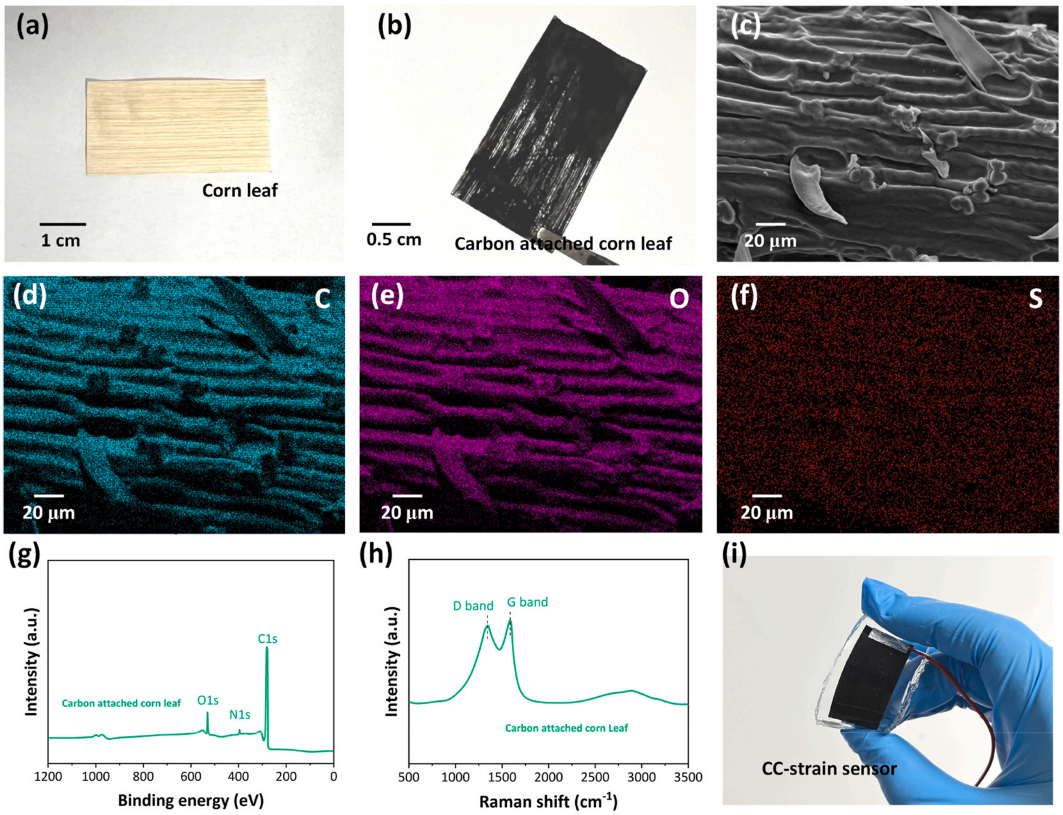


**Fig. 2.** The picture of (a) corn leaf and (b) carbon attached corn leaf. (c) The SEM image of corn leaf surface. (d–f) The element analysis of corn leaf. (g) XPS spectrum of carbon attached corn leaf. (h) Raman spectra of carbon attached corn leaf. (i) The picture of CC-strain sensor device.

### 2.3. Measurement and characterization

Fig. 1(c and d) presents the scanning electron microscope (SEM) image of the surface of a corn leaf. The image reveals that the surface is rough and wrinkled, which can enhance the sensing performance of the strain sensor and the electrical output of the C-TENG device. Additionally, the strain sensor and C-TENG device can be used to track the posture of a dancer and capture the mechanical energy generated by the dancer, as shown in Fig. 1(e). This unique structural design integrates dual functions of sensing and energy harvesting, and has important application prospects in human posture monitoring and energy capture, as illustrated in Fig. 1(f and g). Fig. S1 in Supplementary Materials shows the stress-strain curve of CC-strain sensor. The I/V curves of the CC-strain sensor were measured by using an electrochemical workstation CHI660E. The digital multimeter was used to measure the $\Delta R/R_0$ of the CC-strain sensor device. Moreover, the mechanical linear motor provides the external force to drive the C-TENG device. The oscilloscope was used to measure the output voltage of C-TENG. Additionally, Fig. S2 in Supplementary Materials illustrates the SEM image of carbon layer surface on the corn leaf.

## 3. Results and discussion

### 3.1. The characterization of fabricated materials

Fig. 2(a) illustrates the picture of the corn leaf sheet, which is used as both the triboelectric material and substrates of the carbon layer. There are many wrinkled textures on the surface of corn leaf, which are conducive to the generation of triboelectric charges and the adhesion of carbon oil. Fig. 2(b) shows a picture of a carbon-attached corn leaf, which is used as both the conductive electrode and the functional layer of the strain sensor. The resistance of corn leaf (size: 2 cm × 4 cm) with distributed conductive carbon oil can reach 2 KΩ. Fig. 2(c) shows the corn leaf surface scanning electron microscope (SEM) image, where the micro/nano stripe-like texture of the corn leaf will facilitate the accumulation of triboelectric charges. Furthermore, analysis of elements on the surface of corn leaf indicates the homogeneity of the material (Fig. 2(d–f)). According to the XPS spectrum in Fig. 2(g), corn leaf contains a significant amount of carbon, which is due to the effect of carbon oil. Fig. 2(h) shows the Raman spectra of carbon attached corn leaf. From the results, the characteristic peaks appear at 1602 $cm^{-1}$ (G-band) and 1412 $cm^{-1}$ (D-band), which are related to defects or heteroatom doping. Fig. 2

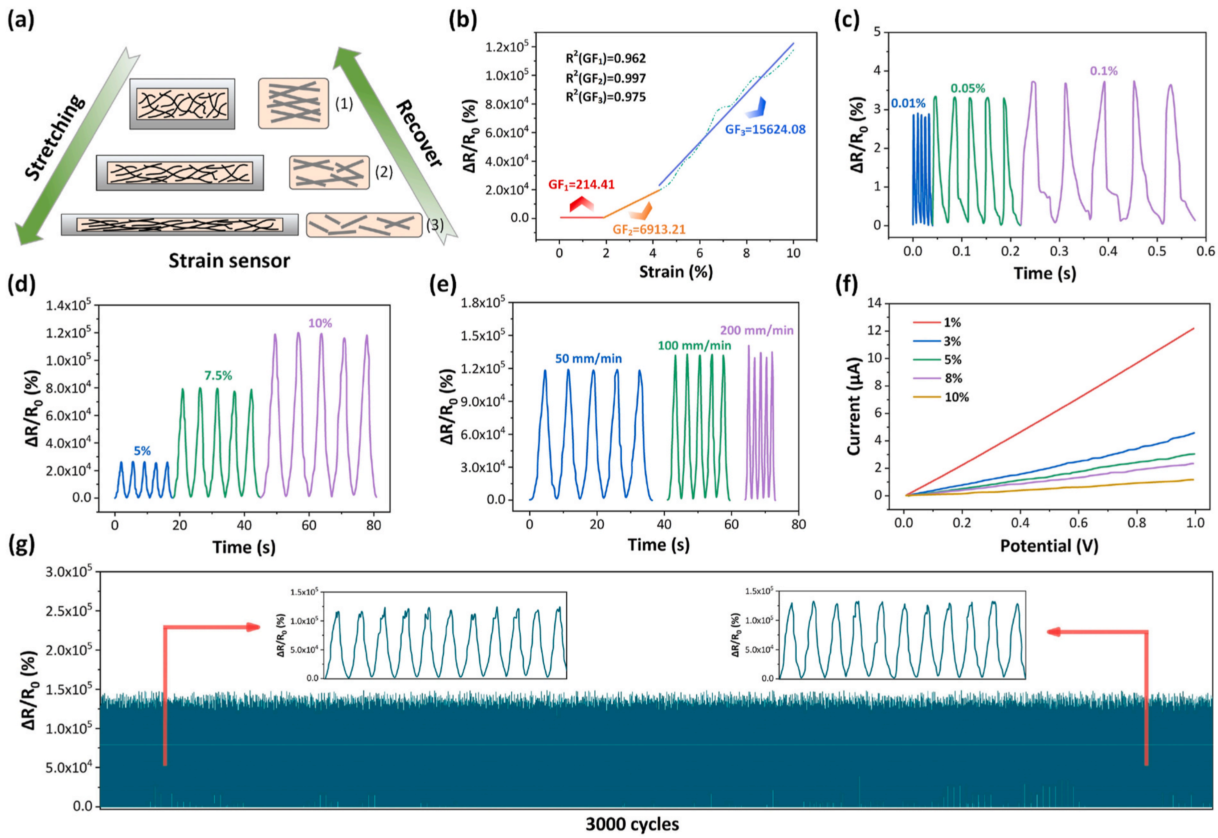


**Fig. 3.** (a) The sensing mechanism of CC-strain sensor device. (b) The relationship between $\Delta R/R_0$ and strain. (c, d) The $\Delta R/R_0$ signal of CC-strain sensor device under different strains. (e) The $\Delta R/R_0$ signal of CC-strain sensor device under different loading speeds. (f) The I/V curves of CC-strain sensor under different strains. (g) The sensing stability test of CC-strain sensor device.

(i) illustrates the picture of the CC-strain sensor device, which exhibits good flexibility.

### 3.2. The sensing performance of CC-strain sensor

Besides, we explored the sensing performance, response rate, and reliability of strain sensors for deformation by testing the electromechanical characteristics of CC-strain sensors. The sensing mechanism of the CC-strain sensor is based on the piezoresistive effect, as illustrated in Fig. 3(a). In original state, when the CC-strain sensor is not subjected to pressure, the carbon conductive channels distributed on the surface and inside of corn leaves can be very complete, and it has good conductivity in this case, as shown in Fig. 3(a1). When the CC-strain sensor is compressed under external pressure, the conductive channel formed by the carbon powder soaked inside the corn leaves can be stretched. As the conductivity between the carbon powders is achieved through contact, this will also cause some conductive channels to break, thereby increasing the resistance of the CC-strain sensor, as presented in Fig. 3(a2). Furthermore, as the pressure on the CC-strain sensor gradually increases, the conductive channels of carbon powder distributed on the surface and inside of corn leaves will continue to break, which will further lead to an increase in the resistance of the CC-strain sensor, as illustrated in Fig. 3(a3). However, when the pressure applied to the surface of the CC-strain sensor is withdrawn, the CC-strain sensor gradually returns to its initial state under its own elastic action, which also causes the resistance of the CC-strain sensor to gradually decrease. Based on this, the function of converting external pressure into self strain and converting self strain into electrical signals endows the CC-strain sensor with monitoring function. We developed the relative resistance rate ($\Delta R/R_0$) changes of the CC-strain sensor under different strains at a constant loading speed, as illustrated in Fig. 3(b). According to the results, $\Delta R/R_0$ exhibits linear characteristics in the three strain regions, and its linear coefficients are all above 0.96. When the strain is in the range of 0–1.9%, the $\Delta R/R_0$ value shows a gentle trend, and the corresponding GF value in the region is 214.41. When the strain is in the range of 1.9%–4.3%, the upward trend of $\Delta R/R_0$ value begins to increase, and the corresponding GF value in the region is 6913.21. When the strain is in the range of 4.3%–10%, the upward trend of $\Delta R/R0$ value continues to increase, and the corresponding GF value in the region is 15624.08. Thus, as the strain increases, the sensitivity of the CC-strain sensor increases, which is due to the sparsity of the conductive path inside the carbon-attached corn leaf. Furthermore, we investigated the resistance variation characteristics of the CC-strain sensor under periodic stretching cycles, as illustrated in Fig. 3(c–e). From the results (Fig. 3(c)), at low strain rates from 0.01% to 0.1%, the CC-strain sensor can display high sensitivity, which is crucial for the perception of weak signals such as expressions in dance performances. Furthermore, as the strain rate increases, the relative resistivity of the CC-strain sensor increases, exhibiting high strain sensing ability, which will help monitor the amplitude of limb movements during dance movements, as illustrated in Fig. 3(d). Also, according to the results in Fig. 3(e), the loading speed of the load will not have any additional impact on the sensing performance of the CC-strain sensor. From the I/V curves in Fig. 3(f), the CC-strain sensor exhibits good linear characteristics in the resistance of carbon-attached corn leaves under different strain conditions. The CC-strain sensor serves as wonderful reliability by using a long-term stability test, as shown in Fig. 3(g). Thus, the CC-strain sensor can be used for posture monitoring of dance athletes without losing sensing stability due to long-term operation.

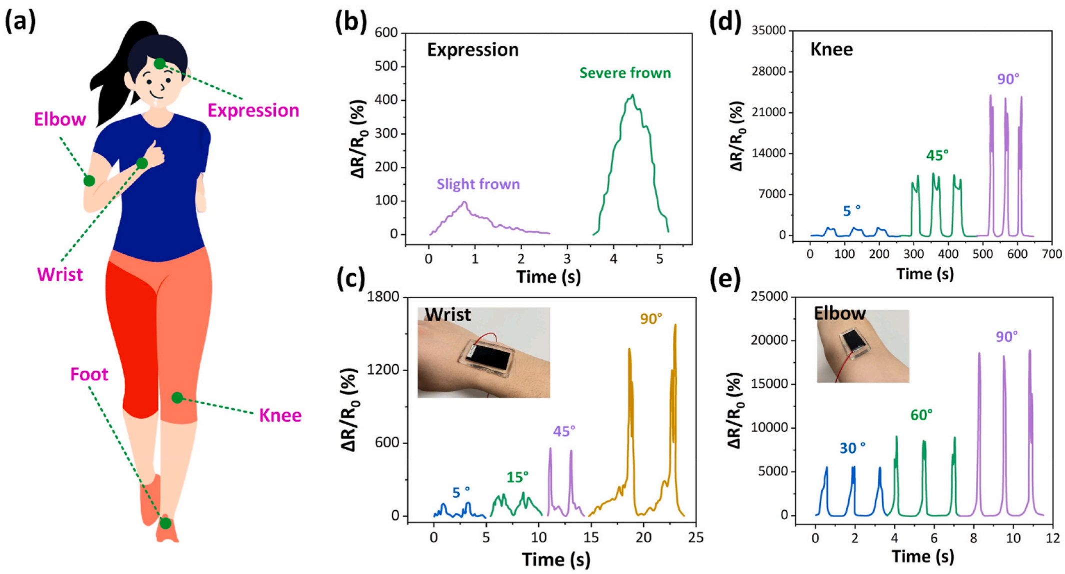


**Fig. 4.** (a) The performance photos of athlete. (b) The sensor signal of CC-strain sensor under athlete frown expression. The sensor signal of CC-strain sensor installed on (c) wrist, (d) knee, and (e) elbow at different bending angles of corresponding joints.

### 3.3. The running monitoring by using CC-strain sensor

Wearable electronic monitoring technology based on multifunctional flexible sensors is an important way to improve dance training and evaluation. In detail, when the CC-strain sensor undergoes bending deformation on its own, separation occurs between the carbon powder particles distributed on the surface and inside of the bent corn leaves, leading to the fracture of the conductive channel and an increase in the resistance of the CC-strain sensor. When the CC-strain sensor returns to its initial state, the conductive network distributed on the surface and inside of the corn leaf bend is restored, and the resistance of the CC-strain sensor will be restored. By utilizing this feature, monitoring of bending amplitude can be achieved, which has potential application value in human posture sensing. Thus, we apply a CC-strain sensor to dance teaching for evaluating the posture of running movements, as shown in Fig. 4(a). For example, we installed a CC-strain sensor on the dancer's eyebrows. During the athlete's frowning process, it drives the CC-strain sensor to deform, which in turn generates a sensing signal to provide feedback on the level of expression (Fig. 4(b)). Obviously, when the frowning expression is heavy, the sensing signal is higher. The CC-strain sensor installed at the wrist can provide real-time feedback on the degree of wrist bending, which is crucial for evaluating some athlete running movements. According to the results (Fig. 4(c)), as the curvature of the wrist increases from 5° to 90°, the $\Delta R/R_0$ value of the CC-strain sensor gradually increases. Similarly, we place the CC-strain sensor at the elbows and knees, as illustrated in Fig. 4(d and e). When the joints bend, the CC-strain sensor generates a sensing signal due to bending, and the larger the bending amplitude, the greater the value of $\Delta R/R_0$. This high-sensitivity sensing feature will contribute to motion correction and evaluation in running posture.

### 3.4. The output performance of C-TENG device

Significantly, the CC-strain sensor can also act as the triboelectric part of the C-TENG. In detail, the PDMS layer on the CC-strain sensor surface and corn leaf form the triboelectric materials. The carbon oil layer and copper foil as conductive electrodes. In this design, the corn leaf serves as positive triboelectric material and the PDMS layer works as negative triboelectric material. The operating mechanism of C-TENG for human motion energy harvesting is displayed in Fig. 5(a1-a4). In the original stage (Fig. 5(a1)), during the contact process between corn leaves and the PDMS layer, the PDMS layer can capture electrons on the surface of the corn leaf, resulting in positive charges on the surface of the corn leaf and negative charges on the surface of PDMS. When the corn leaf starts to separate from the PDMS layer, an induced current is generated in the circuit driven by the surface potential difference of the triboelectric material (Fig. 5(a2)). Until the separation distance between the corn leaf and the PDMS layer reaches its maximum, the charge in the electrode is transferred and no current is generated in the circuit (Fig. 5(a3)). When the corn leaf approaches the PDMS

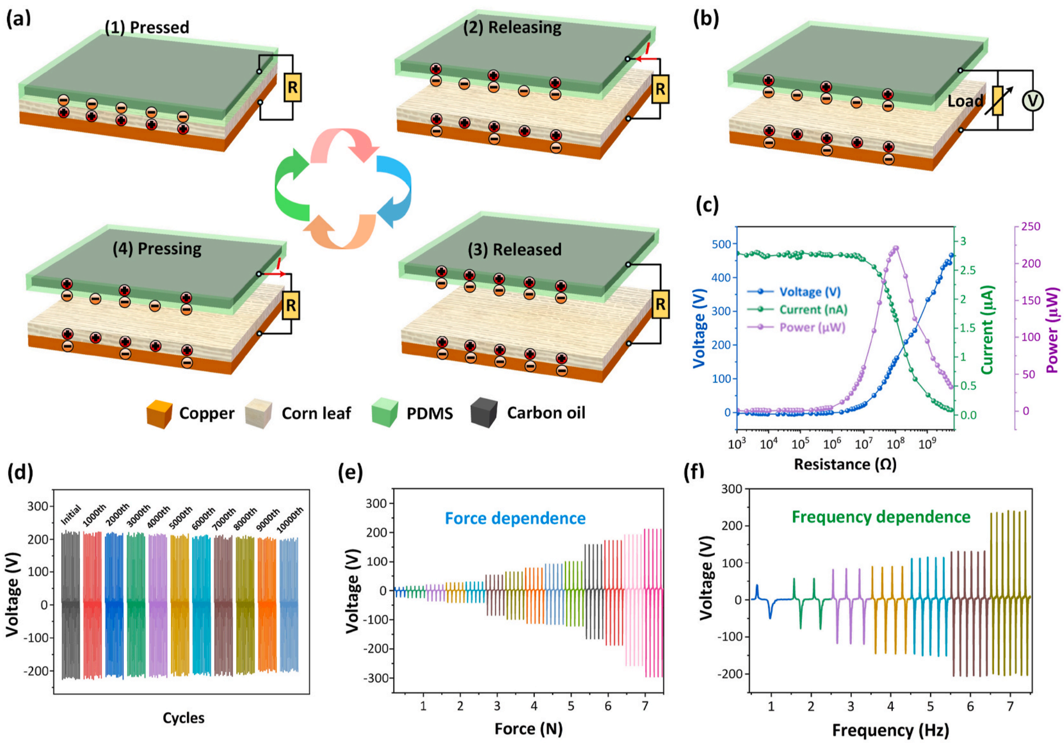


**Fig. 5.** (a) The operating mechanism of C-TENG for human motion energy harvesting. (b) The electrical output test circuit of C-TENG. (c) The relationship between electrical output of C-TENG and various load resistances. (d) The reliability testing of C-TENG. The output voltage of C-TENG under (e) different driving forces and (f) different driving frequencies.

layer again, a reverse-induced current is generated in the circuit (Fig. 5(a4)). Furthermore, the relationship between the output voltage and various loads was developed through the test system in Fig. 5(b). From the results in Fig. 5(c), the output voltage starts to grow when the resistance increases, but the trend of output current change is the opposite based on Ohm's law. Meanwhile, the maximum power of C-TENG can arrive at 222 μW (resistance: 100 MΩ). Advanced material selection endows C-TENG with superior output performance compared to previous work [35–38] according to Table S1 in **Supplement Materials**. As present in Fig. 5(d), under 10, 000 working cycles, the C-TENG can still keep stable electrical output, which indicates the C-TENG can harvest human motion energy over a long period of time. When the driving force grows from 1 N to 7 N, the triboelectric charges on the corn leaf surface and PDMS layer surface will grow, resulting in the increase of C-TENG output, as shown in Fig. 5(e). The increase in pressure applied to C-TENG will lead to the extension of wrinkles on the surface of corn leaves, providing a higher frictional surface area and improving the output performance of C-TENG. Additionally, the high driving frequency can increase the speed of charge flow between electrodes, resulting in the high output voltage of C-TENG, as shown in Fig. 5(f). Besides, considering the response of dried corn leaves to humidity, we studied the output performance of C-TENG at different humidity levels. The results in Fig. S3 of Supplement Materials indicated that as the environmental humidity increased, the output voltage of C-TENG showed a decreasing trend.

## 4. Conclusion

In conclusion, we propose a dual-function device (energy harvesting and running posture sensing), including CC-strain sensor and C-TENG. The carbon-attached corn leaf can achieve the monitoring function of slight strain and improve stability and flexibility through PDMS packaging. And the C-TENG consists of a PDMS layer and corn leaf, which can harvest various mechanical energy. According to the results, the relative resistance rate ($\Delta R/R_0$) exhibits linear characteristics in the three strain regions, and its linear coefficients are all above 0.96. Besides, at low strain rates from 0.01% to 0.1%, the CC-strain sensor can reach high sensitivity for monitoring weak signals, such as expressions in dance performances. CC-strain sensors can sense the amplitude of body movements and the degree of facial expressions in dance performances. The C-TENG device can achieve mechanical energy harvesting, providing a way to power low-power portable devices.

## Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## CRediT authorship contribution statement

**Huifang Hu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article, the manuscript entitled "A Corn Leaf Based-Strain Sensor and Triboelectric Nanogenerator for Running Monitoring and Energy Harvesting".

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e29025.

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