Research Article

A Self-Powered Sport Sensor Based on Triboelectric Nanogenerator for Fosbury Flop Training

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Due to the high efficiency of low-frequency mechanical energy harvesting, wearable and flexible self-powered sport sensor based on triboelectric nanogenerators (TENGs) have become the hot research topic. Thus, we report a flexible and wearable cotton fabric (CF) coated with carbon oil- (CO-) based TENG (CC-TENG) with low processing costs, good electrical properties, and long working life. Meanwhile, we use a piece of flexible, microfibre-woven CF as the substrate for the CO. Moreover, the fibre surface characteristics of the cotton fabric provide higher surface roughness, which can make the TENG device work better. In detail, the CO layer serves as the triboelectric material and conductive electrode. According to the results, the CC-TENG shows good reliability, and the electric energy generated by CC-TENG can drive low-power electronic devices. Significantly, CC-TENG device can be applied to fosbury flop training to obtain training data and motion information monitoring, which will promote the wearable intelligent sports device.

1. Introduction

One of the world’s most ancient sports, athletics has its roots in ancient Greece. Additionally, it acts as a benchmark for evaluating the overall caliber of a country’s sporting endeavors and institutions [1]. Aside from that, it is the sport that won the most gold medals at the Olympic Games in recent history. As a result, countries that excel in athletics are more likely to enjoy a competitive advantage over their counterparts. In the world of athletics, the high jump has a long and illustrious history [2]. It was not until the 18th century that the men’s high jump was included as an official event in the first modern Olympic Games, cementing its status as a sport with its origins in the United Kingdom. The high jump, scissors, tumbling, prone, and deadlift are just a few of the five diverse high jump techniques that have emerged over time [3]. Today, the fosbury flop is a jumping event at the World Sports Championships, and it is also utilized in physical education as one of the athletics learning events in the sport of track and field [4]. An example of an athletic event where the arc running technique is used is the fosbury flop, which is one of the most technically difficult events to master owing to the combination of periodic and nonperiodic movements [5]. With advances in science and technology in the 1990s, the fosbury flop technique was enhanced and further investigation was carried out. Consequently, the fosbury flop reached new heights and performance improved considerably as a result of this. Research on running and take-off tactics has been and continues to be groundbreaking.

As its core component, the research progress of sensor directly affects the development process of wearable technology [6, 7]. Traditional rigid sensors are poor in skin affinity, flexibility, wearing comfort, and so on, so they are not suitable for human wearing [8]. Flexible sensors, which are made of flexible materials, have unique advantages in the application of wearable devices and have become the mainstream research content of wearable devices [9]. At present, wearable sensors are mainly used in medical, sports, and military fields. With the continuous progress of materials and preparation technology, its application field will be further expanded. Wearable sensors are used in sports monitoring devices. The sensors can be integrated into athletes’ smart bracelets, hair bands,
sportswear, and socks. They can not only collect athletes’ routine indicators such as exercise duration, body temperature, respiration, and heart rate during daily exercise but also monitor their speed, endurance, and explosive power during training in real time. Thus, we can more scientifically understand the physical condition of athletes in sports and formulate a reasonable training plan. Wearable sensors can be roughly divided into flexible pressure sensors, flexible biosensors, flexible optical fibre sensors, flexible temperature, and humidity sensors according to their sensing mechanisms [10–13]. However, traditional wearable sensors usually face the problem of continuous power supply; therefore, it is very meaningful to develop new self-powered wearable sport sensors.

Triboelectric nanogenerators (TENGs) are a new and exciting technology that has the potential to dramatically improve the efficiency of the sustainable mechanical power that we use on a daily basis [14–19]. Blinking, breathing, walking, clapping, wind, and tidal energy are just a few of the micromechanical energies that have been proposed for use in TENGs [20, 21]. Other than for powering small mobile devices and detecting movement and pressure, these TENGs are also employed as self-contained power sources for charging small mobile devices and other small electronic devices. Nonetheless, by bringing two polarity-opposite frictional electric materials into contact, these TENGs have the ability to generate electricity (contact charging) [22]. As a result, in order to achieve high output performance, it is vital to select triboelectric materials with care and to increase the surface interfacial interaction between them on the device [23]. Furthermore, the development of future wearable technologies, such as sensors and flexible screens, is critical. These gadgets, which can be worn on the body, can also be used to generate and store electricity. For self-powered wearable electronics, TENGs in particular offer a number of advantages, including being lightweight and delivering a significant amount of power, mechanical stability, material freedom, and cost-effective device architectures, all of which are desirable characteristics for TENGs in particular [24–29]. Also noteworthy is the fact that wearable fibres composed of interlaced microfibres can have a high surface roughness, which increases the contact area between active components and, as a result, increases the TENGs’ high effectiveness [30]. The coating of conductive metals, carbonaceous compounds, or dielectric polymer films onto microfibre network fabrics or flexible substrates has lately resulted in the development of a large number of flexible and wearable transducers [31–36]. These TENGs can produce output, but it takes a long time and a lot of money to create the fibres and flexible substrates mentioned above. As a result, the application of TENGs on a wide scale and in real time may be hindered by the manufacturing process. Graphene layers (i.e., carbonaceous materials) applied to flexible substrates, for example, were reported by Kim et al. as transparent and flexible transient electrochemical nanosystems [37]. The manufacture of graphene layers, on the other hand, is time-consuming and expensive and requires the use of high-temperature chemical precipitation processes. These graphene layers can only be applied to flat surfaces and cannot be used in conjunction with microfibrous fibre frameworks. To be able to use them in real-world situations, it is important to improve the way stretchy TENGs are made and to make the devices more powerful.

In this work, we report a flexible and wearable cotton fabric (CF) coated with carbon oil- (CO-) based TENG (CC-TENG) with low processing costs, good electrical properties, and long working life. Besides, the CC-TENG device can be used to fosbury flop training to obtain training data and motion information monitoring. Meanwhile, we use a piece of flexible, microfibre-woven CF as the substrate for the CO. In energy storage systems, CO is a popular conductor because of its low price and ease of production, as well as precise control over conductivity. Under normal environmental circumstances, this organic polymer likewise exhibits robust behaviour. Moreover, the fibre surface characteristics of the cotton fabric provide higher surface roughness, which can make the TENG device work better. In detail, the CO layer serves as the triboelectric material and conductive electrode. Following that, the structural material characteristics and mechanical stability of the CO-coated cotton fabrics were thoroughly examined. According to the results, the CC-TENG shows good reliability, and the electric energy generated by CC-TENG can drive low-power electronic devices.

2. Experimental Information

The deposition of polyaniline on a CO@CF surface is schematically illustrated in Figure 1(a). The famous in situ polymerization of aniline precipitates a conductive polymer (i.e., CO) on the CF, and the experimental section details the growth process in detail. As shown in Figure 1(a), cotton cloth with a skeleton of interlaced microfibres was cut from a used laboratory apron and soaked in the CO solution for several hours before being washed. As a result, the successful growth of CO nanostructures on the CF was achieved. As an triboelectric material with a positive electrical tendency, CO@CF was also employed as the upper and lower electrode of the TENG. Additionally, the TENG’s negative triboelectric material was polytetrafluoroethylene (PTFE) film. Figure 1(b) depicts the construction of the TENG based on the CO@CF platform (CC-TENG). The experiment section discusses the CC-TENG fabrication method in detail. Figure 1(c) depicts the fabricated CC-TENG device. Figure 1(d) illustrates the CF before and after CO coating, demonstrating the material’s superior mechanical flexibility and colour difference. Following the deposition of CO, the white CFs became utterly black, showing conductive polymer (i.e., CO) had effectively grown on every microfibre of the CF. In this work, the digital oscilloscope FNIRSI-1014D was used to measure the $V_{OC}$ of CC-TENG. The current amplifier SR-570 measures the $I_{SC}$ of CC-TENG. Besides, the Keithley 6514 electrometer was used to measure the transferred charge of CC-TENG.

Figures 2(a) and 2(b) illustrate the scanning electron microscope (SEM) images of the CF layer coated with CO layer. As indicated previously, SEM pictures of the CFs reveal an interwoven network of microfibres with diameters ranging from 10 to 12 μm. Additionally, the SEM image of each fibre at high magnification verifies the absence of material and the absence of nanotopography. Thus, the TENGs’ high surface roughness and surface charge density are obtained by forming CO nanostructures on the CF’s microfibre backbone. Figure 2(c) shows the energy dispersion X-ray (EDX) of the CO layer. The results
Figure 1: The following diagram illustrates the deposition and design processes for CO on the CF and CC-TENG devices. (a) CO deposition on the surface of CF. (b) CO@CF-based TENG device design. (c) CC-TENG device’s photographic images. (d) CFs taken before deposition and after deposition.

Figure 2: (a, b) The SEM image of the CF layer coated with CO layer. (c) The EDX elemental analysis of CO layer fabricated in CF layer surface. (d) The FTIR spectrum of CO layer.
show that the CO material on CF is dispersed and mixed with elements C, N, and O, which indicates that it is a good coating. Additionally, the FTIR spectra in Figure 2(d) are consistent with those of normal CO. The FTIR spectrum demonstrates unequivocally that the two prominent distinctive peaks at 1503.1 and 1572.1 cm⁻¹. Stretching vibrations (N-H and C-N) of aromatic amine groups were also detected at 3195.2 and 1282.2 cm⁻¹, to match C-H bending vibrations, both in and out of the plane at 1153.6 and 741.5 cm⁻¹. As a result, it is obvious that CO normally precipitates in each CF.

3. Results and Discussion

In previous work, a more in-depth examination was carried out into the influence of the length of time that CO was deposited on the impedance of CO@CFs and the voltage level efficiency of CC-TENGs. A further in-depth examination was conducted into the influence of the length of time that CO was deposited upon the impedance of CO@CFs and the voltage level efficiency of CC-TENGs. As a consequence, a variety of CO@CF specimens were produced at varying coating
Figure 4: (a) Analyses evaluate the TENG device’s durability through 5000 cycles with a 10 N exterior compression force. (b–e) The CO@CFs normalized resistance under different extreme conditions, including bending, rolling, folding, and squeezing cycles, respectively. (f, g) The output voltage and current of CC-TENG, before and after 10000 cycles of extreme deformation.
durations, and their weight growth as a function of exposure time was studied, as shown in Figure 3(a). An increase in growth thickness might explain this as the polymerization/deposition time increases. As an additional measure and to compute an average value, the electrical resistivity of these CO@CFs formed at different deposition times was measured using the 2-point probe approach at seven to eight locations and averaged. Figure 3(a) also illustrates the variation in sheet resistance of CO@CF with polymerization/deposition time: the sheet resistance of CO@CF prepared at deposition times from 2 h to 30 h was $2.496 \pm 0.372 \, \text{M}\Omega$, $2.208 \pm 0.3 \, \text{M}\Omega$, $0.804 \pm 0.108 \, \text{M}\Omega$, $0.216 \pm 0.06 \, \text{M}\Omega$, $21.48 \pm 6.24 \, \text{K}\Omega$, $12.6 \pm 4.56 \, \text{K}\Omega$, and $9.36 \pm 2.52 \, \text{K}\Omega$, respectively. This demonstrates that as deposition time increases, the sheet resistance of CO@CF reduces considerably. Due to the fact that the quantity of formed CO on the CF rises with the length of time spent depositioning, this is the case. Additionally, the effect of CO deposition period on the PW-electrical TENG’s output efficiency was studied, as illustrated in Figures 3(b) and 3(c). As depicted in Figure 1(b), a CC-TENG was created utilizing CO@CFs generated at varied deposition times. As the deposition time increases, the output voltage and current of CC-TENG can increase, which is ascribed to the enhanced growth thickness of CO layer as well as the sheet resistance of CO.

Figure 5: (a) The output voltage/current of CC-TENG with various external load resistance. (b) The output power density of CC-TENG under a series of external load resistance. (c) The equivalent circuit diagram mode of CC-TENG for temperature driving sensor. (d) The charging curves of the capacitors from 3 $\mu$F to 120 $\mu$F. (e) Charging and discharging curves of 30 $\mu$F for powering the temperature sensor. (f) The picture of an athlete high jump.
layer. However, when the deposition time continues to increase, the output voltage and current of CC-TENG will decrease. And this may be due to the long deposition time, which can increase the growth thickness of CO layer as well as an additional and randomly distributed lump-like CO architecture on the surface of cotton microfibrous network. The as-formed lump-like CO architectures on the surface and/or in between the fibrous networks can be expected to reduce the surface roughness of CO layer, which can lead to the reduction in the contact area between the triboelectric materials as well as the output performance of CC-TENG. An additional set of experiments was carried out to investigate the effect of an exogenous shock of 0.5 N to 30 N on the achievement of the optimal CC-TENG configuration (devised with CO@CF and fabricated over an eight-hour deposition time), and output electrical qualities including such $V_{OC}$ and $I_{SC}$ were measured during the investigation, as presented in Figures 3(d) and 3(e). The results show that raising the exterior compressive stress from 0.5 N to 30 N causes an increase in the highest $V_{OC}/I_{SC}$ ratios of CC-TENG when the exterior compressive force is increased. Because of the high compressive force, the region of contact between PTFE and CO@CF is increased. As a result, the surface charge density of these electrode material can be improved, potentially improving the output performance of the CC-TENG. In order to bolster the precious thesis, the surface charge density of the CC-TENG materials was further examined, as shown in Figure 3(f). These findings demonstrate unequivocally that the external compressive force strongly influences the of CC-TENG devices. Additionally, the CC-TENG values at various compressive stresses follow the same trend as the $V_{OC}/I_{SC}$ values. As a consequence of the foregoing research, it is possible to conclude that CC-TENGs exhibit a relatively large electrical output under high compressive stresses, due to the significant surface region of the electric friction materials. However, the $V_{OC}$ and $I_{SC}$ results were calculated at a compressive load of 10 N and remained constant at a compression force of 20 and 30 N. This is largely due to the fact that the friction charge on the active material surface is sufficiently big when compared to the delivered tensile stress to overcome the frictional resistance. To put it another way, a pressure stress of 10 N leads in the generation of the greatest amount of triboelectric charges on the triboelectric material surface, as measured by the friction electron count. This occurs when the applied compressive force reaches a value of 20 or 30 N. It has been found that these friction charges do not keep adding up, though.

The CC-TENG’s electrical output is practically saturated at the relevant compression forces. It is critical for device applications that require a pragmatic response that the proposed CC-TENG device has long-cycle activity, mechanical deformation stability, and reliable output performance. So the electrical stability and longevity of the CC-TENG device were first confirmed through durability testing. So the CC-TENG’s output voltage was tested for 5000 cycles at 5 N and 5 Hz external compression frequencies, as shown in Figure 4(a). The results indicate that the CC-TENG’s voltage amplitude is nearly steady even after a long time of cyclic compression operation. Therefore, it is desirable for realistic industrial applications that the CC-TENG has a consistent output (i.e., long life) during a large number of compressions. As demonstrated in this experiment, in addition to being a self-powered source of energy, the CC-TENG device can also be used to directly power a range of low-power mobile devices. In order for the power generated to be stable, the CO@CFs in Figures 4(b)–4(e) exhibit the normalized variation of twisting, tumbling, folding, and compressing cycles. (i.e., $ΔR/R_0 × 100%$). Figures 4(b)–4(e) additionally include insets depicting CO@CFs under twisting, tumbling, folding, and compressing. The $ΔR/R_0 × 100%$ value gradually rises from 0% to 34%, 0% to 29%, 0% to 26%, and 0% to 16% as the number of twisting, tumbling, folding, and compressing cycles increases from 0% to 2000. Although CO@CF has been subjected to 2000 cycles of diverse mechanical delamination, a minor rise in electrical resistance (i.e., $<26Ω/sq$ or $<35%$ of standardized variation) may still be observed. The sheet resistance of CO@CF remained practically constant after 1700 cycles of twisting, tumbling, folding, and compressing. CO@CF exhibits a virtually steady thin layer resistance under a variety of mechanical deformations due to its high degree of mobility and connection between CO and cotton microfibres. The output electrical voltage or current changes of the CC-TENG with the associated CO@CFs were also tested during 2000 twisting, tumbling, folding, and compressing cycles, as well as during 2000 twisting, tumbling, folding, and compressing cycles, as shown in Figures 4(f) and 4(g). Similarly, the CC-TENGs and related CO@CFs exhibited nearly comparable electronic signal performance both during 10000 cycles of varied mechanical displacements were applied.

As a result of CC-TENGs’ exceptional resilience and durability, flexible electronic applications may take advantage of them more readily. Aside from short-circuit and open-circuit circumstances, the adequate power of nanogenerators is a significant aspect in device applications. Various external load resistances (RLs) vary from 100 MΩ to 1 GΩ were utilized to explore the power of the CC-TENG. The power of the CC-TENG is determined by measuring the power of the TENG. The production performance was evaluated under a variety of RLs. Exterior compression frequencies and forces is set as 5 Hz and 5 N. CC-TENG $V_{OC}/I_{SC}$ values increased/decreased as the RL climbed from 100 MΩ to 1 GΩ, both of which are exhausted at extremely high load internal resistance (i.e., between 100 MΩ and 1 GΩ), as indicated in Figure 5(a), respectively. In addition, the output power density of the CC-TENG was estimated using the product of the observed $V_{OC}$ and $I_{SC}$ values at different RL, as shown in Figure 5(b). An internal short circuit condition in the proposed CC-TENG can result in lesser electrical output battery capacity due to a lack of electrical power density. According to our tests, the CC-TENG’s output power density was 13.5 W/m² when the medium load resistance was 80 MΩ. When used in practical applications, components such as rectifiers and capacitors will be used to power low-power electronic equipment, resulting in a steady and high-power output. An example of the CC-TENG circuit is given in Figure 5(c), which charges a capacitor through the use of a bridge rectifier in order to deliver power to a variety of temperature sensor. As shown in Figure 5(d), the rectifier-connected CC-TENG
Figure 6: (a, b) The scene photo of fosbury flop. (c–e) The output voltage signal of CC-TENG 1 under different steps, such as 4 steps, 8 steps, and 16 steps. (f–h) The output voltage signal of CC-TENG 2 under different steps, such as 4 steps, 8 steps, and 16 steps.
device is shown with voltage versus time curves for various capacitors from 3 μF to 120 μF. As illustrated in Figure 5(e), the 30 μF capacitor’s charge/discharge curve is exhibited when driving a temperature sensor via the CC-TENG. The CC-TENG generates the power, which is then utilized to control the temperature sensor display. The CC-TENG gadget that has been proposed does not require an external power supply and is more efficient when it comes to powering portable electronic gadgets. CO@CF has the capacity to construct a TENG (double electrode) that is high in performance, flexible, and durable and to utilize it as a source of electricity to run small electronic devices such as cell phones. From the research described above, it is undeniable right that this conclusion has been reached. When employing the two-electrode vertical touch separating mode, as well as the one-electrode CO@CF configuration, it is possible to produce CC-TENGs.

Fosbury flop is a track and field event with complex technology, which has high requirements for athlete speed, jumping, and the ability to quickly and effectively control all links of the body. The run-up speed is the key technical link in the pole hugging high jump technology. The take-off process is to make the body obtain a good body posture at the moment of completing the take-off and leaving the ground, achieve a better take-off effect, and take off fully, so as to cross the crossbar smoothly. However, in the previous training, it mainly depends on manual monitoring, which has large error and is difficult to respond to high jump information in real time. Therefore, we propose a fosbury flop sensor technology based on CC-TENG device, as shown in Figures 6(a) and 6(b). In detail, two CC-TENGs are installed on the jump bar and in athletes’ shoes, respectively. The CC-TENG 1 device located in the athlete’s shoes can monitor the run-up steps of the movement. The CC-TENG 1 device located on the jump bar can monitor for collisions. Usually, the best approach is between 8 and 12 steps. Considering that CC-TENG is only installed in one shoe, the best number of steps should be 4-6 steps. Therefore, we developed the effect of fosbury flop under different run-up steps, as shown in Figures 6(c)–6(h). From the results, when the number of run-up steps is low or high, it will lead to the failure of fosbury flop. Thus, the fosbury flop training system based on the CC-TENG can realize the analysis of athletes sports state and data acquisition, which will promote the development of intelligent sports.

4. Conclusion

In summary, we report a flexible and wearable cotton fabric (CF) coated with carbon oil- (CO-) based TENG (CC-TENG) with low processing costs, good electrical properties, and long working life. From the results, the maximum values of $V_{OC}$ and $I_{SC}$ can arrive at 420 V and 54 μA under force applied of 5 N. Furthermore, the output power density of CC-TENG can reach 13.5 W/m$^2$. The electrical output function of CC-TENG maintains a constant level of performance over a lengthy period of time, ensuring long-term durability and resilience even after 10000 cycles of mechanical deformation. Finally, the CC-TENG device can play the role of self-powered fosbury flop sensor for physical training.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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