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A Lightweight Sensitive Triboelectric Nanogenerator Sensor for Monitoring Loop Drive Technology in Table Tennis Training

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Abstract: As the Internet of Things becomes more and more mainstream, sensors are widely used in the field of motion monitoring. In this paper, we propose a lightweight and sensitive triboelectric nanogenerator (LS-TENG) consisting of transparent polytetrafluoroethylene (PTFE) and polyamide (PA) films as triboelectric layers, polydimethylsiloxane (PDMS) as support layer, and copper foil as electrode. LS-TENG can be attached to the joints of the human body, and the mechanical energy generated by human motion is converted into electric energy based on the triboelectric effect, thus realizing self-power supply. LS-TENG can monitor the angle changes in elbow and wrist joints when athletes pull the loop and actively generate the output voltage as a sensing signal, which is convenient for coaches to monitor the quality of athletes' hitting in real time. In addition, LS-TENG can also be used as a power supply for other wireless electronic devices, which facilitates the construction and transmission of large motion data and opens up a new development direction for the field of motion monitoring.

Keywords: triboelectric nanogenerator; human motion monitoring; self-powered sensor; loop drive technique

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1. Introduction

In recent years, with the rapid development of big data and the Internet of Things [1,2], the Internet of Things has been widely used in the fields of intelligent public transport, energy and environmental protection, security systems, biomedical and smart home, which not only solves the pain points of many industries, but also provides more convenience for people's lives [3–10]. Internet of Things technology is also affecting the field of sports. Based on big data analysis, some wearable electronic devices have been developed to monitor athletes' sports performance and daily training, which has become an effective means to improve athletes' competitive level [11–18]. For a long time, table tennis has been popular in the Olympic Games because of its fast pace of competition and complex and changeable technology. Loop technology is recognized as the most effective and frequently used offensive ball technology in today's game [19]. The angle change in elbow and wrist determines the arc height and direction of the ball. At present, athletes use wearable electronic devices to monitor body movements to obtain movement data. However, wearable electronic devices have the problems of a short charging time and the inability to monitor the joint angle changes in table tennis players in real time, which is not conducive to the acquisition of real-time sports data of athletes. Therefore, it is very important to develop a self-powered and flexible wearable device.

Triboelectric nanogenerators (TENGs) based on triboelectrification and electrostatic effects were developed by Professor Wang Zhonglin's team in 2012 [20]. They have attracted much attention in academia because of their low cost, high efficiency, easy manufacture and self-powered sensing. In recent years, a large number of studies have provided a realistic basis for the application of triboelectric nanogenerators in more fields. It is reported that

some common items in life can be used as triboelectric materials for manufacturing TENGs, which provides great help for the collection of biomechanical energy, the detection of food quality, the provision of environmentally friendly energy, and the monitoring of human movement. For example, the latex film in a milk carton can be used to test the quality of food after being polished [21]; the waterproof function of the new nanocomposite material based on fabric can be used to collect the energy of wind and rain and sleep monitoring [22], and simple wearable devices can be attached to the human body and used in the monitoring of skating, basketball, Taekwondo and other sports scenes [23–29]. It has also been shown that: fiber/textile triboelectric nanogenerators can be used as human mechanical energy harvesters to provide mobile sustainable power for wearable electronic products [30]; new napkin-based triboelectric nanogenerators can be integrated into insoles to achieve physiological monitoring of the human body [31]; and by adjusting the weight percentage of expandable microspheres in the polydimethylsiloxane (PDMS) mixture, a sensitive triboelectric nanogenerator can be obtained, which can be used to monitor respiration and pulse [32]. Triboelectric nanogenerators can be self-powered to transmit signals without power supply, providing new ideas for monitoring joint angle changes in table tennis players.

In this paper, we report a lightweight and sensitive triboelectric nanogenerator (LS-TENG) using transparent polytetrafluoroethylene (PTFE) and polyamide (PA) films as the triboelectric layer, polydimethylsiloxane (PDMS) as the support layer, and copper foil as the electrode. This kind of LS-TENG is not only light and sensitive, but also can realize self-powered sensing. It can also fit perfectly on the elbow and wrist. Based on the triboelectric effect, it converts the biomechanical energy generated by the joint movement of athletes when they do loop technical movements into electric energy, and outputs sensing signals while providing sustained and robust power for the sensor itself. In addition, LS-TENG has good durability and flexibility, which not only guarantees the stable output of sensor signals, but also helps coaches to analyze the quality of athletes' hitting and the reasons for losing scores in competitions. All in all, the design of LS-TENG makes up for the shortcomings of some wearable devices and opens up a new path for scientific motion monitoring and big data analysis.

2. Materials and Methods

2.1. Materials

Polyamide (PA) film was purchased from Hongxing Plastic Products Factory (Shijiazhuang, China); Transparent PTFE film was purchased from Taizhou Huafu Plastic Industry Co., Ltd. (Taizhou, China); and copper foil was purchased from High Purity Metal Materials Research Institute (Hefei, China).

2.2. Methods

Preparation of PDMS support layer: First, we mixed the PDMS solution and curing agent at a weight ratio of 10:1 and stirred for 3 min to mix them evenly; then, we put the mixed solution into an ultrasonic stirrer and stirred for 5 min to eliminate bubbles; finally, the mixed solution was taken out by an injector and dropped on the mold, and the mixture was heated in a heating furnace at a temperature of 80 deg C for 10 min, to finally obtain the PDMS supporting layer with good flexibility.

The complete manufacturing process of the device comprises the following steps of: firstly, cutting the flexible PDMS into a rectangle and hollowing out the middle part; and secondly, cutting the PA film and the PTFE film into the same size according to the size of the flexible PDMS. Then, two copper foil electrodes were cut out according to the size of the PA film and PTFE film, which were closely attached to the PA film and PTFE film, respectively, to form two friction layers of LS-TENG. The PA film is used as the positive layer of LS-TENG, the flexible PDMS hollowed out in the middle part is used as the support layer to facilitate the contact and separation between the two friction layers, and the PTFE

film is used as a negative layer. The three layers are stacked one on top of the other and secured at both ends with scotch tape to form a complete device.

2.3. Characterization and Measurement

The LS-TENG is mounted on a stepper motor to simulate the stroke of a table tennis ball. The stepper motor applies an external force to the LS-TENG to cause bending and deformation, and the working frequency and amplitude are changed by manipulating the stepper motor. The performance of the LS-TENG was tested using different frequencies and amplitudes, and the sensor signals generated by the LS-TENG were collected with an oscilloscope (sto1102c, Shenzhen, China).

3. Results and Discussion

In this study, LS-TENG was used to monitor the loop technique of table tennis. Figure 1a shows the application of self-powered wearable flexible sensor in sports scenes. Its soft and flexible characteristics enable it to fit the elbow and wrist joints of the human body well. It collects the biomechanical energy generated by the movement of the human joints and converts it into electric energy, which has the ability of being self-powered. Athletes wear LS-TENG to monitor the change in joint angle. The sensor signals generated in the monitoring process are wirelessly transmitted to the oscilloscope to form motion data. Coaches judge the quality of athletes' hitting according to the sensor signals, which provides convenient conditions for table tennis competition and daily training monitoring. Figure 1b shows an optical image of a sensor that is lightweight, flexible, and capable of flexible bending to make it more comfortable for the athlete to wear. The manufacturing process of LS-TENG is shown in Figure 1c. The PDMS solution and the curing agent are fully mixed at a weight ratio of 10:1. After ultrasonic treatment for 5 min to eliminate bubbles, the mixed solution is dropped on the mold and heated to form a flexible PDMS support layer. Then, the PTFE film, the PDMS flexible support layer and the PA film are stacked in sequence from top to bottom and covered by two copper foil electrodes with the same size to obtain a complete device.

The working mechanism of operation of the LS-TENG is based on the contact-separation mode of the TENG, as shown in Figure 1d. When no external force is applied to deform the LS-TENG, the PA and PTFE membranes are in a completely separated state, in which case no electrical charge is generated or induced (state I). When the LS-TENG is deformed by an external force and the PA membrane comes into physical contact with the PTFE membrane, a frictional charge is generated on the surface of the PA membrane and the PTFE membrane based on the frictional electrical effect [33]. The electron affinity of the PTFE membrane is greater than that of the PA membrane, and therefore, the PA membrane is positively charged and the PTFE membrane is negatively charged (state II). When the external force gradually disappears, the PA and PTFE membranes begin to separate and the potential difference between the two begins to build up and increase, causing electrons to flow from the friction layer to the copper foil electrodes on both sides. From the principle of electrostatic induction it is clear that the top copper foil electrode is positively charged, and the bottom copper foil electrode is negatively charged (state III) and the two friction layers will reach a state of equilibrium (state IV) when they are completely separated. When the LS-TENG is again deformed by an external force and the two friction layers gradually approach again, the electrostatically induced charge will flow back through the external load to compensate for the potential difference (state V) until the two friction layers are back in physical contact and a cycle is completed. By repeatedly applying and releasing pressure to the LS-TENG, the repeated contact and separation of the PA and PTFE membranes will generate a sensing signal, and the device will also convert mechanical energy into electrical energy for self-powered sensing [34–36].

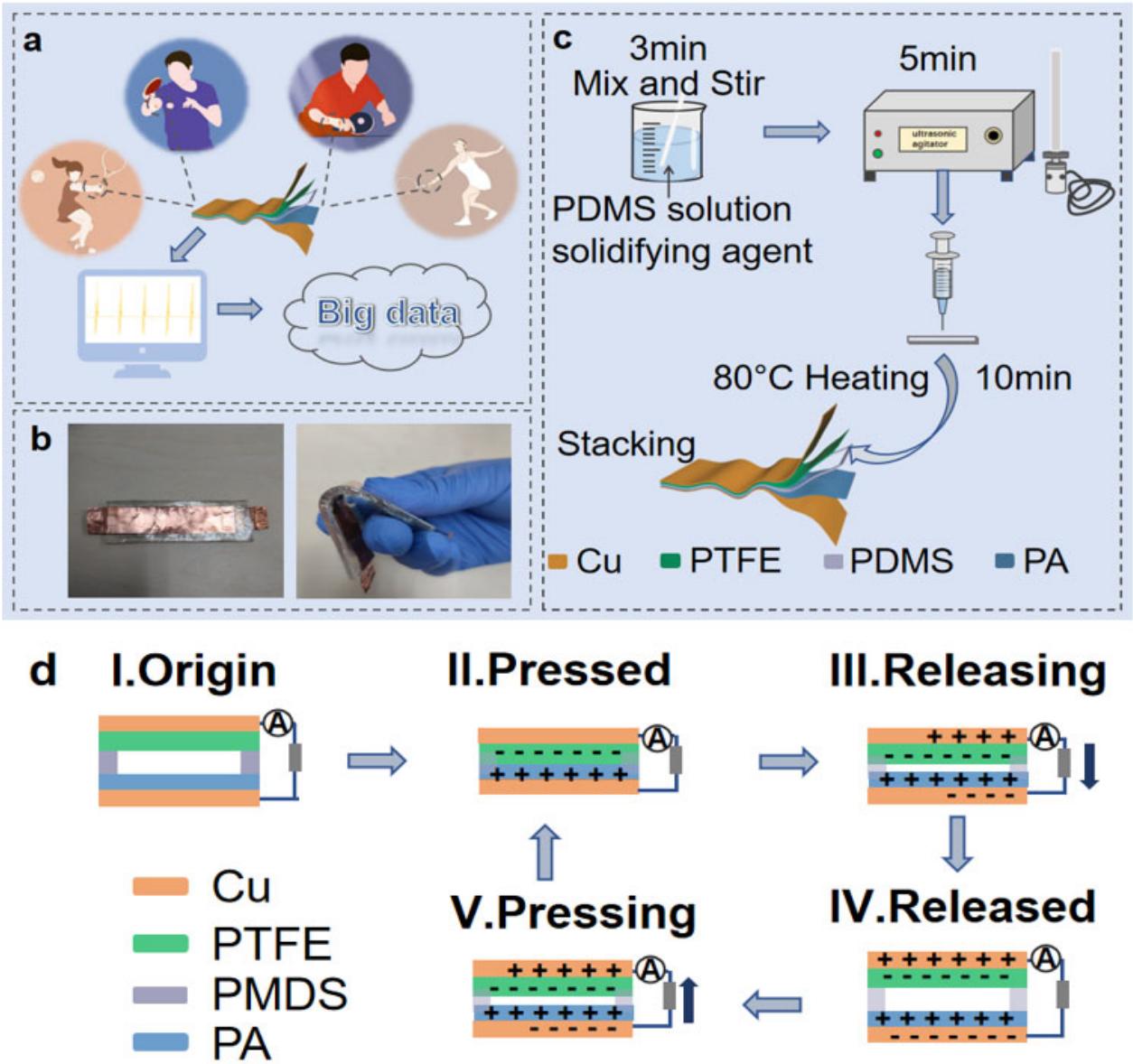

Figure 1. Design and application of LS-TENG. (**a**) Application of LS-TENG in motion scene. (**b**) LS-TENG optical image. (**c**) Preparation process of LS-TENG. (**d**) Schematic diagram of the LS-TENG.

The performance test of LS-TENG under different experimental conditions is shown in Figure 2. We fixed the LS-TENG with the size of 10 cm × 2.5 cm and the contact area of 7 × 2 cm^2 on the stepper motor. The LS-TENG is bent and deformed by the external force exerted by the stepper motor to simulate the movement of the wrist and elbow joints of athletes when using the loop technique, and the stepper motor is adjusted to control the frequency and angle of bending. Figure 2a shows the output voltage of LS-TENG at different frequencies with the same bending angle. When the frequency is 1 Hz, 2 Hz, 3 Hz and 4 Hz, the output voltage of LS-TENG is 6.48 V, 6.4 V, 6.4 V and 6.4 V. It can be seen that the output voltage of LS-TENG is basically unchanged under the same bending angle and different frequencies, which means that the output voltage is very stable. The output voltage response of LS-TENG at different frequencies is shown in Figure 2b, and the corresponding calculation formula is as follows:

$$R\% = \left| \frac{V0 - Vi}{V0} \right| \times 100\% \quad (1)$$

where $V0$ is the output voltage at 1 Hz and Vi is the output voltage at other frequencies. The responses of LS-TENG were 0%, −1.25%, −1.25%, and −1.25% at 1 Hz, 2 Hz, 3 Hz, and 4 Hz, respectively. According to the data results, when the angles are the same, the output voltage of LS-TENG is very stable and does not change with the change in frequency, which shows that the sensitivity of LS-TENG is very high. Figure 2c shows the output voltages of the LS-TENG at the same frequency (1 Hz) and different angles. When the bending angles are 6.83°, 5.26°, 4.33° and 3.21°, the output voltages are 21.8 V, 17.6 V, 15 V and 9.4 V, respectively. It can be seen that the output voltage increases as the bending angle of the LS-TENG increases. Therefore, LS-TENG is very suitable for monitoring the change in human joint angle. There is a linear relationship between the bending angle and the output voltage of the LS-TENG, as shown in Figure 2d. The Pearson correlation coefficient is 0. 98576, which indicates that there is a linear relationship between bending angle and voltage. The equation is:

$$V \approx -0.44 + 3.33 \times \text{degree} \quad (2)$$

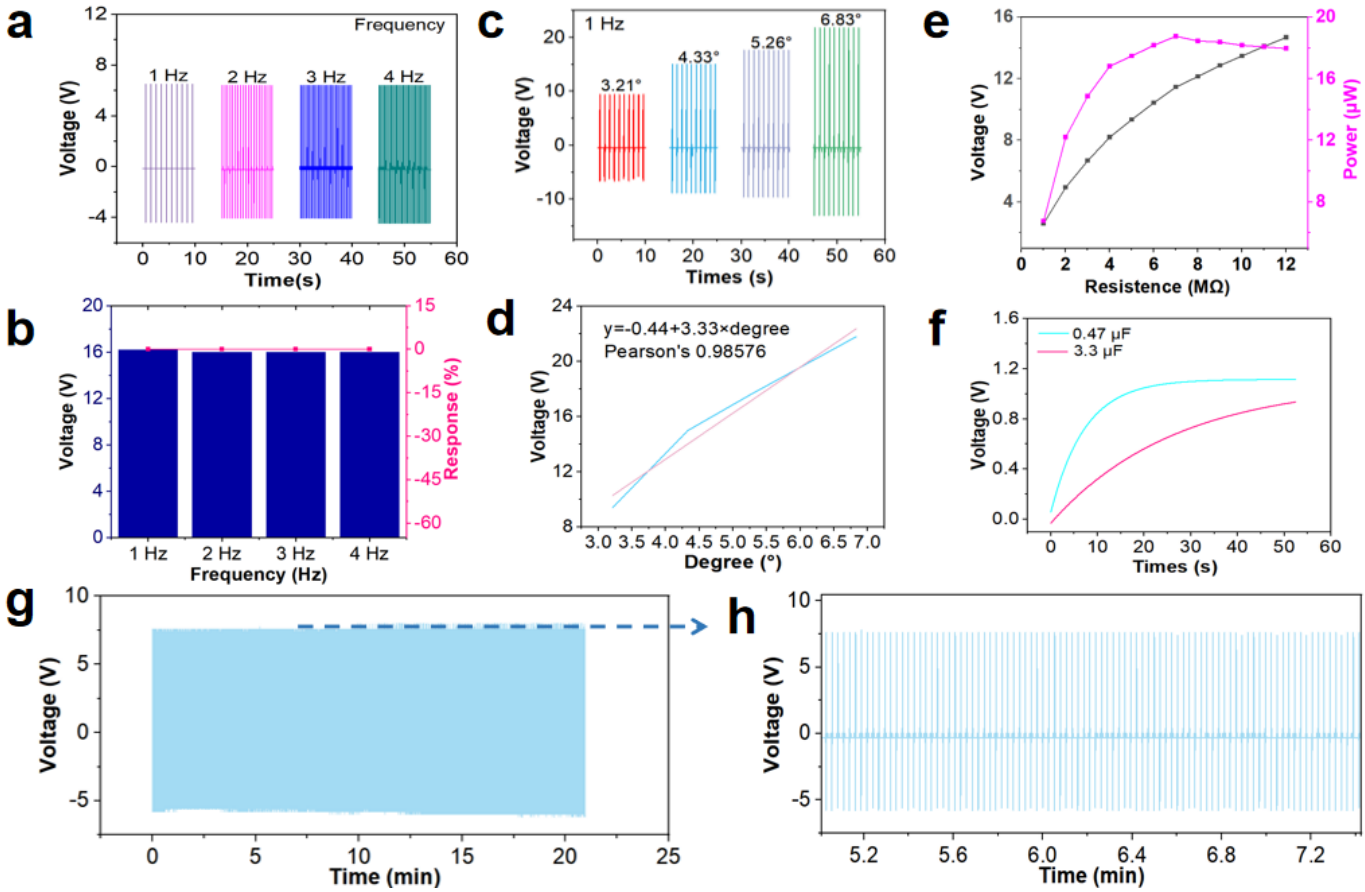

Figure 2. Performance test of LS-TENG. (**a**) Output voltage of LS-TENG at the same angle and different frequencies. (**b**) Output voltage response at the same angle and different frequencies. (**c**) Output voltage of LS-TENG at the same frequency and different angles. (**d**) There is a linear relationship between the output voltage and the bending angle at the same frequency and different bending angles. (**e**) Voltage and power of LS-TENG at different load resistances. (**f**) LS-TENG charges 0.47 μF and 3.3 μF capacitors. (**g**) Durability test of LS-TENG. (**h**) Details of LS-TENG durability test.

Figure 2e shows the output voltage and power of the LS-TENG with a size of 10 cm × 2.5 cm and a contact area of 7 × 2 cm^2 under different load resistances. It can be seen from the figure that the output voltage of the LS-TENG increases with the increase in the load resistance. When the load resistance of LS-TENG is 7 MΩ, the maximum power of LS-TENG is 18.76 μW. Therefore, the load resistance of the LS-TENG is 7 MΩ, and the power

density of the LS-TENG can be calculated to be 1.34 μW/cm^2. The LS-TENG has an electrical output capability that enables it to power other wireless electronic devices. The continuous application of external force to the device causes the two friction layers of the device to continuously contact and separate, which can charge different capacitors, as shown in Figure 2f. The LS-TENG charges a 0.47 μF capacitor to 1.2 V in 55 s, and a 3.3 μF capacitor to 0.94 V in the same time, while keeping the frequency and bend angle constant. This shows that LS-TENG can convert the mechanical energy generated by human motion into electrical energy to achieve self-powered operation. In order to pull a high-quality loop, continuous repetitive training is needed to form muscle memory. Moreover, in order for coaches to monitor the technology of athletes in the competition in real time, LS-TENG must ensure stable and continuous output of sensing signals. Therefore, the continuity and stability of LS-TENG are very important for monitoring work. We conducted a durability test on the LS-TENG. As shown in Figure 2g, the LS-TENG still maintained a stable output after a continuous 20 min cycle test, demonstrating excellent stability. Figure 2h shows the details of the endurance test, which shows that the LS-TENG can maintain the sensing characteristics of stable operation.

Loop drive technology has become the mainstream technology today, which has a far-reaching impact on the technical pattern of the world table tennis [37,38]. Loop is a strong topspin ball, and according to the direction of the ball, it can be divided into forehand loop and backhand loop. It has strong aggressiveness and stability, which is an important factor affecting the victory or defeat of table tennis matches. Loop technology is not a typical upper limb whipping action. It requires players to control the angle of the racket to make the ball rub against the racket face. Its threat mainly affects the speed, arc shape, arc height and arc direction of table tennis through the rotation of the ball, so that the opponent can make mistakes such as high ball or leakage to obtain points. The final and fundamental solution to the friction between the ball and the racket lies in the strength of the arm and wrist. If players want to deal with the incoming ball calmly in the game, they need to judge the landing point of the incoming ball before hitting the ball, so as to adjust the angle of elbow and wrist joints in order to pull out high-quality loop. When players pull the loop, they are prone to make the following mistakes: the ball is out of bounds or into the net due to insufficient grasp of the angle of the racket face; the ball is unstable due to excessive wrist force; the backswing arm is too straight or tense, and the racket sinks too low, which leads to late hitting, slow starting and leaking. Therefore, in order to monitor the quality of athletes' loop technical movements, we first need to attach LS-TENG to the elbow and wrist joints for monitoring (taking the horizontal board as an example).

Figure 3a is a schematic diagram of the forehand loop technique. The forehand loop technique requires the elbow joint on the racket side to change from extension to rapid flexion during the whole movement, and requires the wrist joint on the racket side to change from adduction to abduction. In the backswing stage, the racket arm is pulled outward, the elbow joint is slightly bent but not straight, the arm is naturally relaxed, the wrist joint is relaxed and in a straight line with the arm, and the wrist is adjusted to make the racket lean forward. In the swing stage, the racket arm swings forward and upward, the big arm drives the forearm to exert explosive force, and the forearm is quickly retracted, that is, the elbow joint is quickly rotated and flexed, and the wrist joint makes a small range of abduction movement to adjust the racket face. The action cannot be too large or too long. At the end of the swing, the arm should be fully forward and upward, that is, the elbow joint should continue to flex and the wrist joint should remain in line with the forearm. During the whole process, the angle of the elbow joint changes greatly, but the angle of the wrist joint does not change obviously.

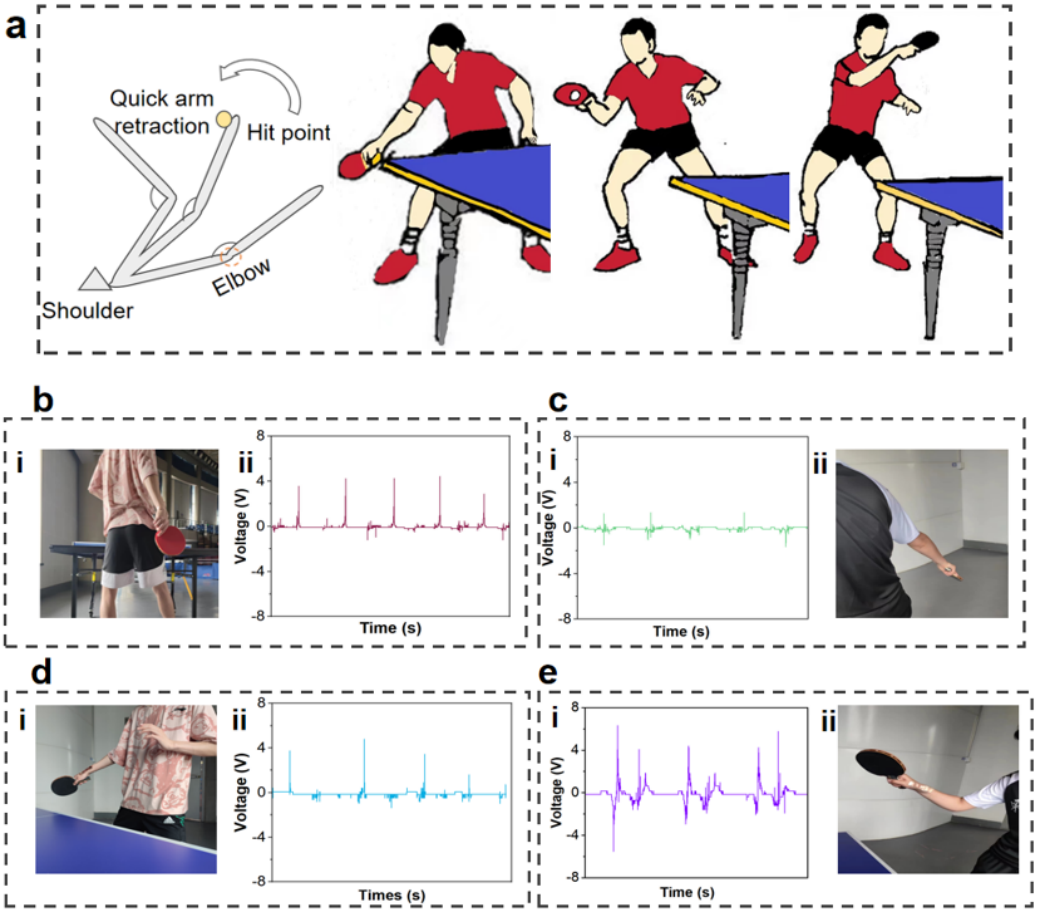

Figure 3. The application of LS-TENG in the forehand loop technique. (**a**) Schematic diagram of forehand loop technique. (**b**) Elbow state and output voltage of standard forehand loop technical action. (i) Elbow state diagram of standard forehand loop technical action. (ii) The output voltage of the elbow of the standard forehand loop technique action. (**c**) Elbow state and output voltage of the wrong forehand loop technique. (i) The output voltage of the elbow of the wrong forehand loop technique action. (ii) Schematic diagram of elbow state of wrong forehand loop technical action. (**d**) The wrist state and output voltage of the standard forehand loop technical action. (i) Wrist state diagram of standard forehand loop technical action. (ii) The output voltage of the wrist of the standard forehand loop technique action. (**e**) Wrist state and output voltage of the wrong forehand loop technique. (i) The output voltage of the wrist of the wrong forehand loop technique action. (ii) Schematic diagram of wrist state of wrong forehand loop technical action.

Figure 3(bi,cii) show photographs of the state of the elbow when the subject performs the standard and error forehand loop techniques, respectively. The output voltage of the elbow is shown in Figure 3(bii,ci). When pulling the forehand loop, the angle of the elbow joint changes greatly, so the bending angle of the LS-TENG attached to the elbow is also large, resulting in a large output voltage. By comparing the voltages in Figure 3(bii,ci), it can be seen that the output voltage of the elbow during the standard technical action is significantly higher than that during the wrong technical action. Therefore, it can be seen that the angle change in the elbow joint of the subject in Figure 3(cii) is too small, indicating that the arm is too tense, which is easy to cause the attack failure caused by the leakage of the ball. Figure 3(di,eii) show the wrist state of the subjects in the standard and wrong forehand loop techniques, respectively. The LS-TENG was attached to the wrist joint for monitoring, and the results are shown in Figure 3(dii,3ei). It can be seen from the figure that the output voltage of Figure 3(ei) is higher than that of Figure 3(dii), indicating that the bending angle of LS-TENG attached to the wrist of Figure 3(eii) subjects is larger, and the change in wrist angle is larger, which is inconsistent with the slight change in wrist angle

when pulling a forehand loop, indicating that excessive wrist force will cause instability in ball control. It can even cause sports injuries to the wrist. The above experiments confirm the conclusion in Figure 2 that the output voltage increases as the bending angle of the LS-TENG increases.

Figure 4a shows the motion diagram of the backhand loop technique. The backhand loop technique requires players to lead the racket downward to the inside of the thigh, raise the elbow joint and rotate it, bend and rotate the wrist joint reasonably and relax it properly. In the swing stage, the racket arm swings to the front of the racket side, and the elbow joint is used as the force point to drive the forearm to push the elbow. The wrist rotates fully, that is, the elbow joint stretches, the wrist joint quickly abducts and stretches, and the angle of the elbow and wrist joints increases rapidly. In the swing stage, the wrist and forearm move with the trend, the angle of elbow and wrist joints reaches its peak, and the wrist and forearm are finally in a straight line. Because the backhand is limited by the body, the angle change in the elbow and wrist joints is smaller than that of the forehand.

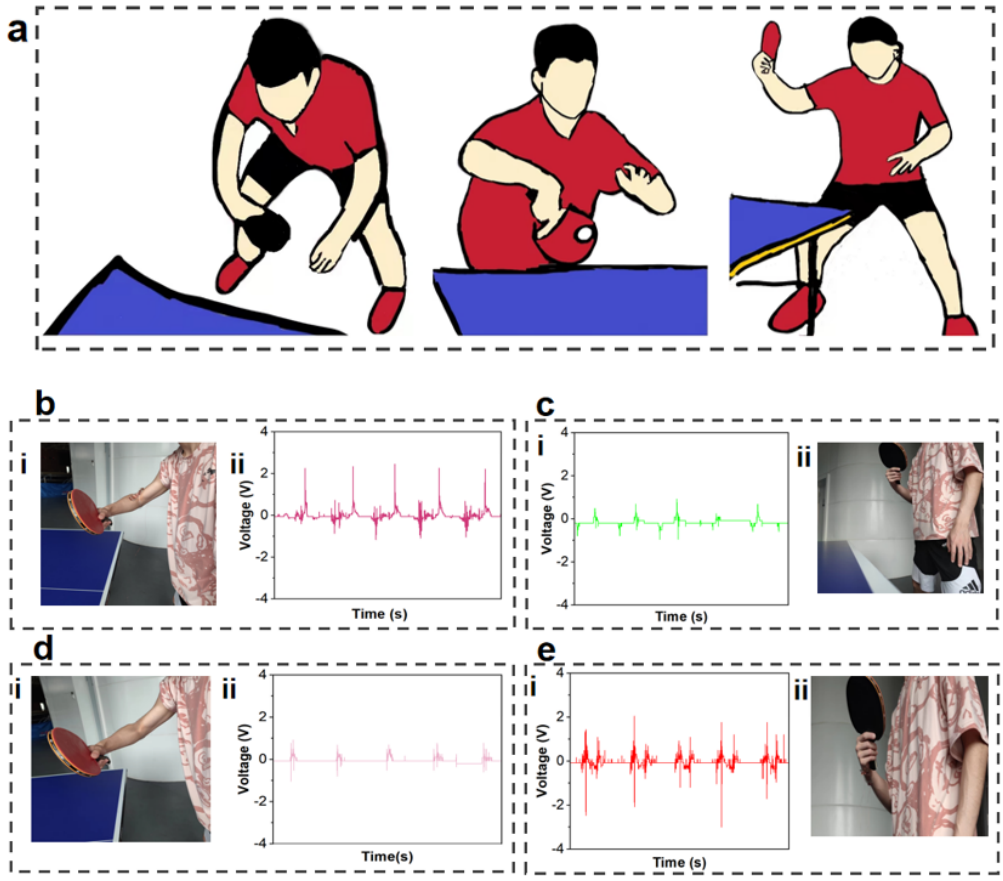

Figure 4. Application of LS-TENG in backhand loop technique. (**a**) Schematic diagram of backhand loop technique. (**b**) Elbow state and output voltage of standard backhand loop technical action. (i) Elbow state diagram of standard backhand loop technical action. (ii) The output voltage of the elbow of the standard backhand loop technique action. (**c**) Elbow state and output voltage of the wrong backhand loop technique. (i) The output voltage of the elbow of the wrong backhand loop technique action. (ii) Schematic diagram of elbow state of wrong backhand loop technical action. (**d**) The wrist state and output voltage of the standard backhand loop technical action. (i) Wrist state diagram of standard backhand loop technical action. (ii) The output voltage of the wrist of the standard backhand loop technique action. (**e**) Wrist state and output voltage of the wrong backhand loop technique. (i) The output voltage of the wrist of the wrong backhand loop technique action. (ii) Schematic diagram of wrist state of wrong backhand loop technical action.

As shown in Figure 4(bii,dii), which are the output voltages of the elbow and the wrist of the subject during the backhand loop technique, respectively, the output voltages of Figure 4(bii,dii) are smaller than those of Figure 3(bii,dii). The reason is that the backhand swing is limited by the human body, so the backhand joint angle changes less than the forehand joint angle in the process of swinging. The conclusion that the output voltage increases with the bending angle of LS-TENG is confirmed again. Figure 4(ci) shows the output voltage of the elbow when the subject performs the wrong backhand loop technique. It can be seen from the figure that the output voltage of Figure 4(ci) is far less than the output voltage of Figure 4(bii), indicating that the angle change in the elbow joint is small, and the problem of ball leakage will occur. When pulling the backhand loop, if the angle of the wrist joint changes too much, as shown in Figure 4(ei), it is easy to lose control of the ball, causing the flight trajectory of the ball to deviate. Through the observation of the output voltage of LS-TENG, we can judge the quality of the technical action of loop drive completed by athletes, which provides great convenience for coaches to better monitor the competition and training of athletes.

4. Conclusions

In this paper, a self-powered flexible wearable triboelectric nanogenerator (LS-TENG) for monitoring the elbow and wrist joints of table tennis players is introduced. The sensor is composed of PA film and polytetrafluoroethylene (PTFE) film as the friction layer, polydimethylsiloxane (PDMS) as the support layer, and copper foil as the electrode. The bending angle and frequency are monitored based on triboelectric effect and contact-separation mechanism. The sensor is very flexible and can fit well on the surface of the human body, converting the mechanical energy generated by the movement of human joints into electrical energy, not only realizing self-powered operation, but also providing power for other wireless electronic devices to construct motion data. LS-TENG can be used to monitor the quality of athletes' technical movements, and the output voltage can be used as the sensor signal of joint angle changes, which provides great convenience for coaches to better monitor the degree of athletes' mastery of loop drive technology in real time. This technology provides a new opportunity for the direction of motion monitoring and a new path for the realization of intelligence.

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