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A 3D Printing Triboelectric Sensor for Gait Analysis and Virtual Control Based on Human–Computer Interaction and the Internet of Things

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Abstract: Gait is the information that can reflect the state index of the human body, and at the same time, the leg is the organ with the maximum output power of the human body. Effective collection of maximum mechanical power output and gait information can play an important role in sustainable energy acquisition and human health monitoring. In this paper, a 3D printing triboelectric nanogenerator (3D printed TENG) is fabricated by 3D printing technology, it is composited of Poly tetra fluoroethylene (PTFE) film, Nylon film, and 3D printing substrate. Based on the principle of friction electrification and electrostatic induction, it can be used as the equipment for human sustainable mechanical energy collection and gait monitoring. In order to solve the problems of energy collection, gait monitoring, and immersion experience, we conducted the following experiments. Firstly, the problem of sustainable energy recovery and reuse of the human body was solved. Three-dimensionally printed TENG was used to collect human mechanical energy and convert it into electric energy. The capacitor of 2 μF can be charged to 1.92 V in 20 s. Therefore, 3D printed TENG can be used as a miniature sustainable power supply for microelectronic devices. Then, the gait monitoring software is used to monitor human gait, including the number of steps, the frequency of steps, and the establishment of a personal gait password. This gait password can only identify a specific individual through machine learning. Through remote wireless transmission means, remote real-time information monitoring can be achieved. Finally, we use the Internet of Things to control virtual games through electrical signals and achieve the effect of human–computer interaction. The peak search algorithm is mainly used to detect the extreme points whose amplitude is greater than a certain threshold and the distance is more than 0.1 s. Therefore, this study proposed a 3D printed TENG method to collect human mechanical energy, monitor gait information, and then conduct human–computer interaction, which opened up a multi-dimensional channel for human energy and information interaction.

Keywords: TENG; 3D printing; machine learning; human–computer interaction

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1. Introduction

With the development of the fifth-generation communication technology of the Internet of Things [1–4], wearable devices are becoming more and more popular in the fields of human health and human–computer interaction [5–8]. Wearable devices can be directly worn on the surface of the human body and can obtain various state information of the human body as well as mechanical energy. It provides a wide range of applications, including sports monitoring [9–12], rehabilitation [13–15], human–machine interface (HMI) [16–19], disease diagnosis [20,21], and so on, in order to further improve the quality of human life. For example, a self-powered gesture recognition wristband that realizes full keyboard and multi-command input through machine learning is used to recognize different gestures of the human body [22]. A self-powered conductive superhydrophobic fabric machine learning glove for VR/AR gesture recognition was manufactured. This glove uses superhydrophobic textiles to realize a low-cost and self-powered gesture recognition interface [23]. Therefore, wearable devices can effectively exchange data in the fields of human health and human–computer interaction.

In 2012, a triboelectric nanogenerator (TENG) was invented by Wang's research group, and was cost-effective, highly efficient, and easily fabricated [24]. The TENG can be used as a sensing unit to acquire energy and sense information about the human body. TENG has broad application prospects in sensing fields such as soft wearables and robotics, energy harvesters, and rehabilitation or diagnostics, and it has excellent sensing performance [25–36]. It can convert human mechanical energy into electrical energy. TENG is often used as a human body monitoring sensor. For example, it is fabricated of stretchable conductive fibers (Ecoflex coating with polyaniline (PANI)) and painted wires. Based on the coupling effect of triboelectricity and enzyme reaction (surface-triboelectricity coupling effect), the wearable biosensor can not only accurately sense the movement state, but also detect glucose, creatinine, and lactic acid in sweat in real time [37]. A piezoelectric-triboelectric sport sensor (PTSS) can be used to monitor human multi-dimensional motions such as bend, twist, and rotate motions, including the screw pull motion of table tennis and the 301c skill of diving. Moreover, TENG has been used to monitor human health in many studies [38]. Gait is an effective means to monitor the human body. Different postures, walking styles, foot shapes, and other differences have different effects on gait, so everyone has different gait characteristics. Combining gait information with machine learning and human–computer interaction can develop gait passwords, and recognize the human body according to gait information. By pressing while walking, the coupling of gait and electrical signals can be realized.

With the development of 3D printing technology, a lightweight and miniaturized wearable device skeleton can be designed, which can support and protect sensors. Therefore, in this paper, we used 3D printing technology to make TENG and used a 3D printing machine to print the substrate and supporting layer, so that TENG can work normally. Through machine learning, it is possible to convert electrical signals, identify different people, calculate and count the number and frequency of steps, and make independent gait codes. At the same time, human–computer interaction technology is used to simulate the walking process of human gait. Therefore, 3D printed TENG can be used as a gait password sensor, step counting sensor, and a human–computer interaction sensor unit at the same time. Meanwhile, 3D printed TENG has the characteristics of low cost, easy manufacture, recyclability, and multifunction. It can not only convert the mechanical energy of the human body but also accurately identify the number of human steps. Further, it can be used as a unique gait creature of the human body. Therefore, it has broad potential in practical applications.

2. Materials and Methods

2.1. Materials

PTFE films (0.03 mm) and Nylon foils (0.03 mm) were bought from Taobao. PLA wires for 3D printing were purchased from Shenzhen Aurora Technique Co. Ltd. (Shenzhen, China).

2.2. Methods

Firstly, the 3D printed TENG was fabricated by a 3D printing machine, the type is JGAURORA-A6. The parameters are as follows: the Layer height was 0.1 mm; shell thickness was 1.2 mm; fill density was 100%; print speed was 50 mm/s; printing temperature was 200 °C; and bed temperature was 50 °C. The 3D substrates were printed after 30 min (Figure S1). Then, the PTFE film and Nylon film were cut into pieces. Finally, the PTFE film and Nylon film with treatment were pasted on the surface of the 3D printing substrate.

2.3. Test

The data of properties and applications testing of TENG were tested by an oscilloscope (sto1102c, micsig which was produced by Shenzhen China). The properties parts were tested by improved pulley block and step motor. In practical testing, 3D printed TENG was implanted in shoe soles, which was prepared for the performance test. For satisfying the requirements of wireless signal transport, we designed a wireless signal collection module. By integrating with this wireless signal collection module, the signal can be transported into the human–computer interaction system and gait monitoring system.

3. Results

Gait, as the password of human health, can reflect the health state of the human body when walking. At the same time, human legs are the most powerful organs of the human body, so it is of great significance to effectively collect gait energy and health information.

In this paper, TENG is used to collect human gait energy and monitor gait information. TENG has the characteristics of simple structure, economy, and portability properties. It can convert human mechanical energy into electric energy. At the same time, the electrical signal can be used as a sensing signal to sense the human body motion information. In this paper, vertical contact out mode 3D printed TENG is fabricated by 3D printing technology, the optical image 3D printed TENG is shown in Figure S1. Three-dimensionally printed TENG consists of upper and lower friction layers, which are attached to the upper and lower 3D printing substrates, respectively. The positive friction layer is Nylon, the negative friction layer is PTFE, and two copper foils are used as conductive layers to connect wires. The 3D schematic diagram is shown in Figure 1c. Figure 1a shows the schematic diagram of diversified wearable detection. At present, wearable devices can meet certain monitoring requirements, and different terminal controls can meet different sports. However, at present, most wearable devices are expensive and need to be continuously supplied by an external power supply. Although wearable devices have low power consumption, with the number of users increasing, the carbon emissions increase also. Therefore, as a sensor, TENG meets the demand for sustainable development. It can be used not only as a sensor but also as a power supply for other microelectronic devices. Figure 1b,c show the schematic diagram of energy conversion and information interaction of 3D printed TENG. Most of the mechanical energy of the human body is not utilized during walking. Three-dimensionally printed TENG can collect a part of the mechanical energy of the human body and convert it into electric energy. The electric energy is stored in the capacitor and it can charge other electronic devices, it shows potential as a sustainable energy source. At the same time, the converted electrical signals can be used as sensing signals, which can further calculate the number of steps, carry out human–computer interaction, and serve as sensing information in the Internet of Things. Figure 1d shows the sensing steps of gait information and future application. Three-dimensionally printed TENG can collect gait information, and analyze it with a computer to display human motion information, such as step number, step frequency, etc. On the other hand, we can sort out, upload, and make a personal database of everyone's action data, and use machine learning to control robots or virtual games. Therefore, 3D printed TENG has great potential in sustainable energy collection and human–computer interaction sensing. It can be used in medical care, diagnosis, sports monitoring, energy collection, identification, and other fields.

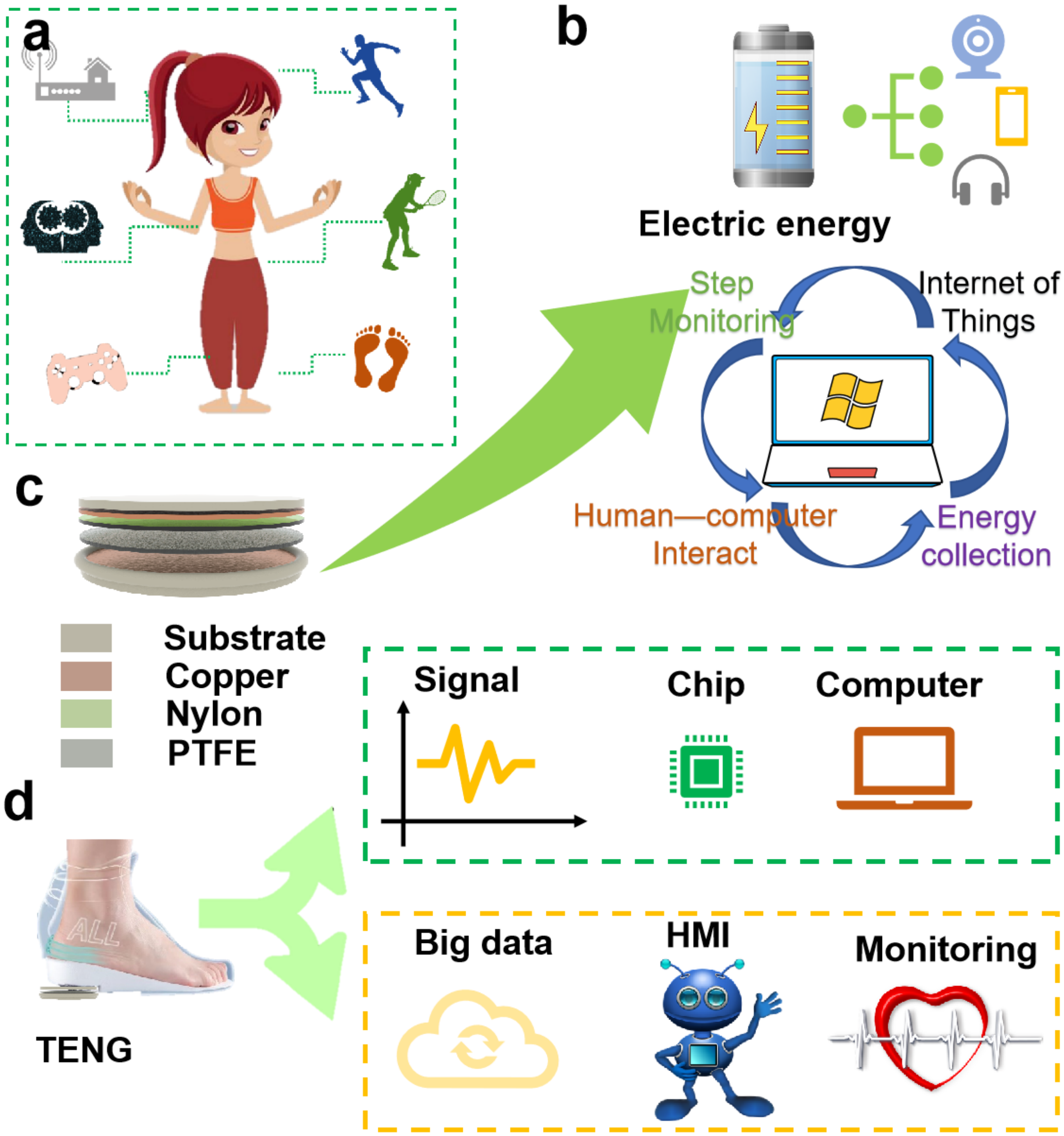

Figure 1. Intelligent health monitoring diagram based on AIoT, (**a**) monitoring diagram of diversified wearable devices, (**b**,**c**) 3D printed TENG and gait information processing based on big data, (**d**) gait monitoring process and intelligent application.

In order to monitor gait information better, the vertical contact out mode TENG is more in line with the design idea of this study [39]. Therefore, 3D printed TENG is highly coupled with gait movements which adopt vertical contact out mode in this study. Figure 2a shows the working mechanism of 3D printed TENG. When a person is in a still state, 3D printed TENG is in a pressed state, and no action potential is generated at this time, such as in Figure 2(aI). When the human body starts walking, the heel no longer presses 3D printed TENG. At this time, 3D printed TENG begins separating. Because of the different electronegativities of Nylon and PTFE, an electric potential is generated. In addition, due to friction electrification, electrons flow from Nylon to PTFE and it results in the induced current generated such as Figure 2(aII). When 3D printed TENG is completely separated, the electric charges reach equilibrium as shown in Figure 2(aIII). At this time, the foot hangs in the air. When the human body continues to walk, 3D printed TENG is pressed again. At this time, due to electrostatic induction, a reverse current is generated, as shown in Figure 2(aIV). Therefore, 3D printed TENG can be coupled with gait movement, and play the role of gait monitoring and energy recovery and reuse. Figure 2b shows the electrical potential change, which corresponds to the action change in Figure 2a. COMSOL is used to simulate electrical potential change. In the initial state in Figure 2(bI), 3D printed TENG is in the state of being pressed, at this time, the two friction layers are attached, and no potential is generated. When the two friction layers are gradually separated, as seen in Figure 2(bII), the potential gradually increases, and the induced current is generated in the circuit due to the influence of the potential. When 3D printed TENG is completely separated, the potential reaches the maximum, and the charges at both ends of the friction layers reach equilibrium, as seen in Figure 2(bIII). When 3D printed TENG is pressed, the two friction layers approach gradually, as seen in Figure 2(bIV). A reverse current is generated when friction layers touch completely and an action cycle is completed. This shows that 3D printed TENG can be coupled with gait. This has great application value in the field of energy collection and gait monitoring.

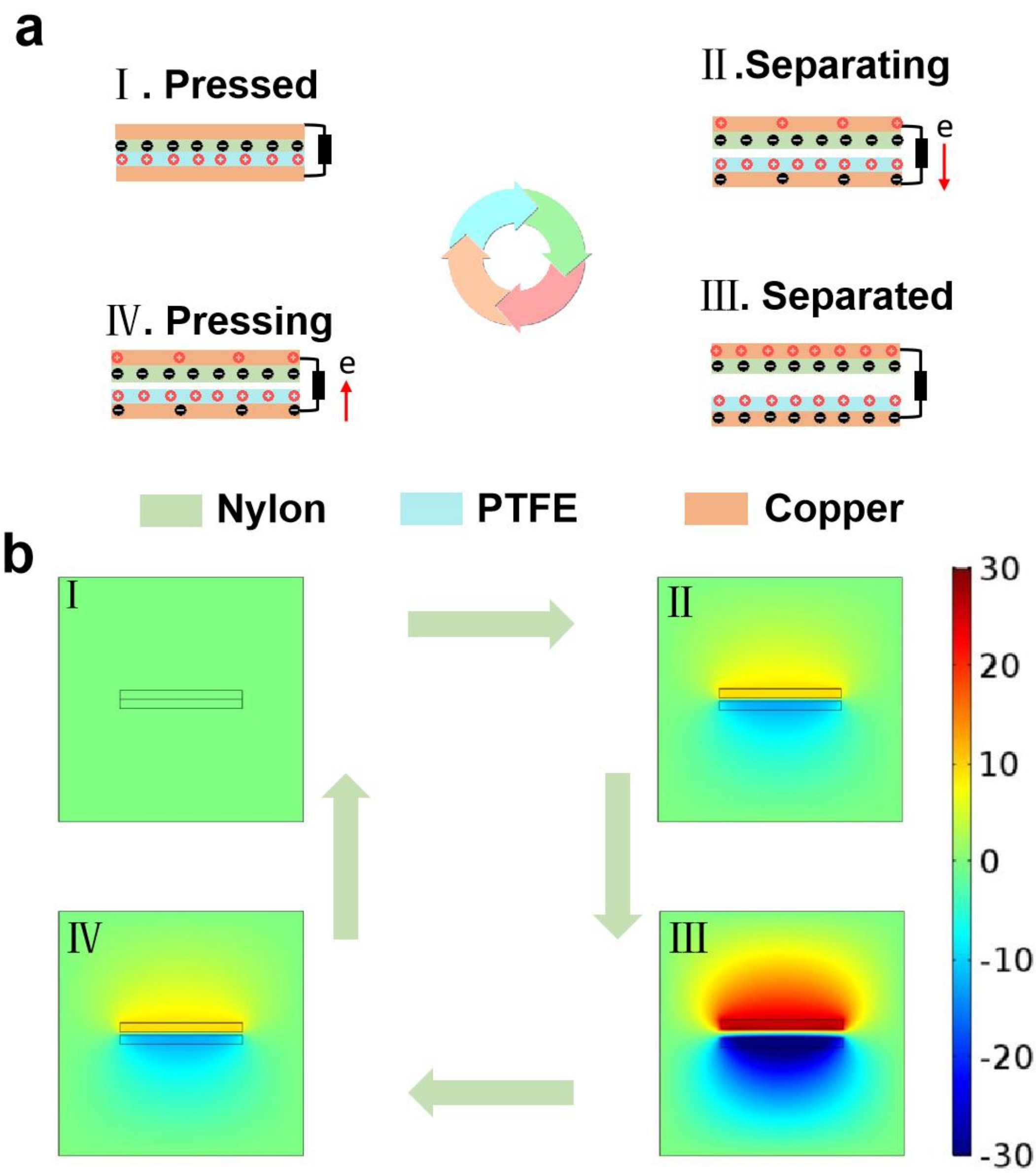

Figure 2. Three-dimensionally printed TENG working mechanism diagram and COMSOL simulation diagram, (**a**) the coupling process of 3D printed TENG and walking. (**b**) COMSOL potential simulation diagram.

Excellent electrical performance is an important index of TENG sensing equipment. Therefore, the electrical properties of 3D printed TENG are tested in this paper as shown in Figure 3a, in order to explore the electrical properties of different materials. In this paper, Nylon, PU, KAPTON, FEP, and PTFE were used as friction layers and tested by a stepping motor under the same test conditions. It was found that the combination of Nylon and PTFE has good electrical properties. At the same time, it was further found that PTFE has good electronegativity because PTFE was found in the top four voltages in various combinations. Therefore, PTFE and Nylon were selected as friction layers in this paper, and the voltage is 18 V. Figure 3b shows the voltage characteristics of friction layers with different diameters. As the diameter increases, the voltage also increases. However, since the diameter of the 3D base is 5 cm, the maximum diameter of the friction layer is 5 cm also. Figure 3c,d show the voltage characteristics and responses of different pressure tests. With the increase in pressure, the voltage also increases. When the pressure is 20.35 N, 25.81 N, 29.18 N, and 33.32 N, the voltage is 9 V, 12.4 V, 13.4 V, and 14.4 V, respectively, and the response is 0, 27.4, 32.8, and 37.5%, respectively. The test equipment is shown in Figure S2. The calculation formula of the response is:

$$R\% = \left| \frac{V_0 - V_i}{V_i} \right| \times 100\% \quad (1)$$

This shows that there is a good linear relationship between voltage and pressure. Figure 3e,f show the voltages and responses at different frequencies. When the frequencies are 1 Hz, 2 Hz, 3 Hz, and 4 Hz, the voltages are 7.2 V, 7.8 V, 7.8 V, and 7.8 V, respectively. The responses are 0, 7.6%, 7.6%, and 7.6%, respectively. This shows that 3D printed TENG can keep the same magnitude of the voltage at different frequencies, but it can be observed in the figure that the frequency of voltage increases with the frequency of the stepping motor, and the number of voltage waves increases at the same time. This performance can monitor the step frequency well. Figure 3g shows the endurance test of 3D printed TENG. Three-dimensionally printed TENG can keep a stable signal with a voltage of 6.8 V after 9000 cycles of testing, which shows that 3D printed TENG can cope with long-term work and has strong robustness. Figure 3h shows the charging capacity of 3D printed TENG to the capacitor. When the capacitance is 2.2 μF, 4.7 μF, and 10 μF, the charging voltage is 1.92 V, 1.06 V, and 0.5 V at 19 s, respectively, which indicates that 3D printed TENG can convert mechanical energy into electrical energy, which also indicates that 3D printed TENG can reuse human mechanical energy. Although the energy of individuals is few, when the number of users increases, the collection of energy also increases. The above shows that 3D printed TENG, as a gait monitoring sensor, not only has excellent sensing performance, but also has different responses to different pressures and frequencies. At the same time, it can maintain stable performance under long-term working conditions. It can also be used as a sustainable power supply to charge microelectronic devices. Therefore, 3D printed TENG has diversified functions. It can not only be used in gait monitoring but also can be used in the field of robot sensing, weight monitoring, and so on.

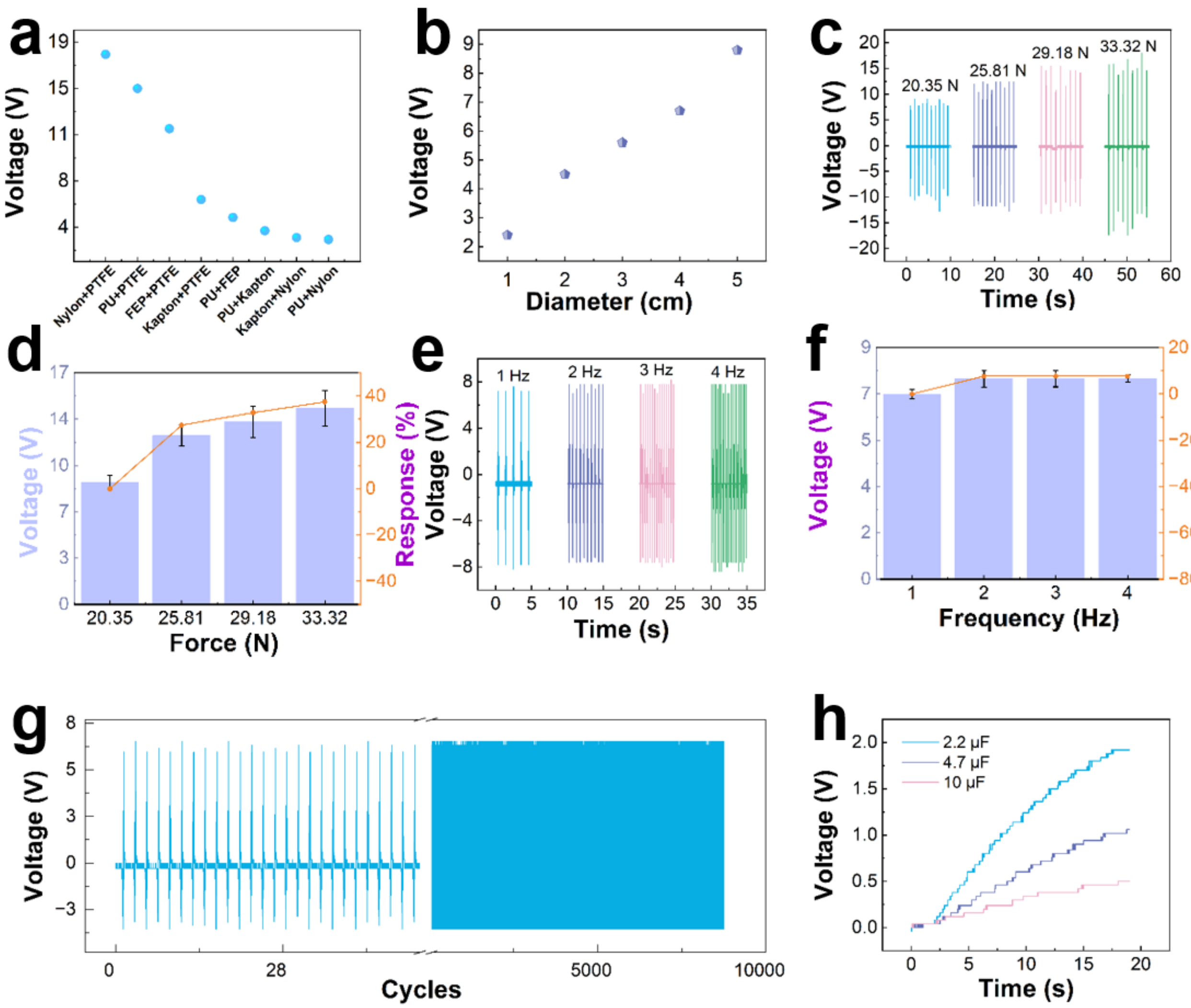

Figure 3. Electrical properties of 3D printed TENG, (**a**) voltage of different materials combinations, (**b**) voltage between friction layers in different areas, (**c**,**d**) voltage and response under different pressures, (**e**,**f**) voltage and response at different frequencies, (**g**) 9000 cycles endurance tests, (**h**) 3D printed TENG charging voltage for different capacitors.

In the era of information and digitization, there are many gait monitoring systems, but there are some errors in these gait monitoring systems. The acceleration signal of the smartphone is composed of gravity, pedestrian acceleration, and noise. However, the built-in acceleration sensor of smart phone is not accurate, and it is easily affected by the jitter of relative movement of pedestrians in the acquisition process, so the noise of the collected data is high. Therefore, 3D printed TENG is used in this paper to monitor the step frequency and step number, which has low noise and high signal-to-noise ratio, and can restore the regularity of the collected data. Therefore, it is important for this paper to monitor the step number and step frequency by peak detection. In order to monitor the number and frequency of steps more accurately, we use machine learning to process the signals. The 3D printed TENG signal is collected by the Analog-to-Digital acquisition module (Figure S3). The system proposes a technology of extracting characteristic peaks by using machine learning to analyze patterns of triboelectric signals, which provides the possibility of integration of artificial intelligence and gait monitoring. Here, we use the combination of artificial neural networks and fast Fourier transform. When the signal appears, the artificial neural network identifies it. The frequency of the characteristic peak can be accurately transformed to identify people. At the same time, the peak search algorithm is used to detect the extreme points whose amplitude is greater than a certain threshold and the distance is more than 0.1 s [40]. The system intercepts the received signal sequence every second, and the system detects the number of extreme points that meet the conditions as induction signals. Each induction signal corresponds to several steps, so it has great accuracy in monitoring the number of steps. Figure 4a shows the program diagram of the step number recognition system. In the test, firstly, 3D printed TENG collects gait signals, which are processed by the circuit composed of the Analog-to-Digital acquisition module, and the signal is transmitted to the data collection system. The data are recognized by the trained system, and the steps are recognized, calculated, and counted. Figure 4b shows the gait information machine learning process. Figure 4b shows the training data for machine learning [22]. Firstly, 300 steps of data are collected from person A, and the data are trained by a neural network. Finally, the human body is identified by visual software. When the human body steps, as shown in Figure 4c, the real-time data pass through the trained database, and the database can only identify person A and display it through visualization software. As shown in Figure 4(dI,dII), Figure 4(dI) is the gait recognition system that can recognize person A when he steps. When Figure 4(dII) person B and C step, the gait recognition system cannot recognize their step signal. This system can be used as a personal security gait password to identify a specific person, which is shown in Movie S1. At the same time, we use the peak search algorithm to monitor the number and frequency of steps, such as in Figure 4(dIII), when the software receives the data, it shows the number and frequency of the step (Movie S2). Every step generates a corresponding induction signal, the development of this application can help people better count the number of steps and avoid statistical errors. At the same time, 3D printed TENG can monitor human gait without an external power supply. It will develop a new research direction in the field of new energy and sports monitoring.

With the application of the Internet of Things and 5G technology, wearable devices can combine reality with virtual technology. However, AR-enabled wearable devices are mostly bulky, and at the same time, they have some problems, such as high cost and difficult maintenance. Frankly speaking, due to the high cost, the popularity of human–computer interaction wearable devices is few at present. TENG, as a sensing unit, solves this problem well. It is proven to be a sensitive monitoring sensor and a sensing unit for human–computer interaction. The gait man-machine interaction system based on 3D printed TENG is shown in Figure 5a. Firstly, it collects and collates the sensing signals, transmits them to the computer through wireless Bluetooth sensing, and then learns the signals through machine learning, and the computer has feedback. This system has the ability of low cost, high transmission speed, and low fault tolerance. It can solve the boredom of indoor fitness, and enhance immersion and interest in gait monitoring. As shown in Figure 5b, it shows the signal acquisition system and the process of signal transmission. When the human body steps or walks, 3D printed TENG generates a responsive sensing signal (Movie S3). The peak search algorithm is mainly used to detect the extreme points whose amplitude is greater than a certain threshold and the distance is more than 0.1 s [40]. The system intercepts the signal sequence received every second and detects the number of extreme points that meet the conditions as induction signals. Each induction signal represents an action control in the virtual game. Therefore, for every step taken, the characters in the game take a corresponding step. Figure 5c shows the actual interactive scene diagram. When the human body stands still, so does the virtual character. This is because no induction signal is generated at this time. When the human body steps, it generates a responsive induction signal. The virtual character also starts to move, as shown in Movie S4. In a word, a diversified gait monitoring system can realize immersive gait monitoring. It has made an excellent reference for medical care based on the Internet of Things.

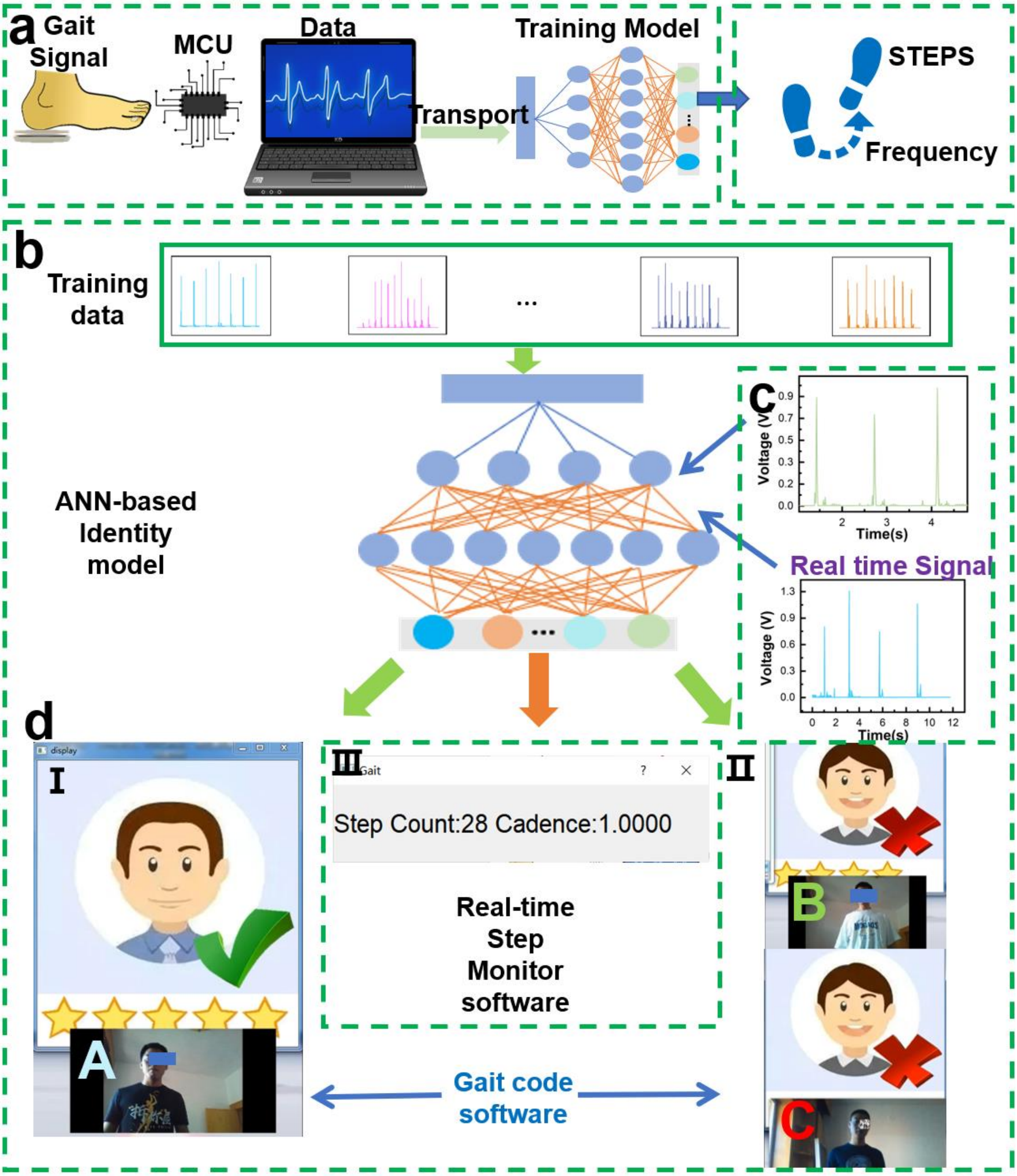

Figure 4. Gait monitoring system and gait password human identification system based on 3D printed TENG and machine learning, (**a**) gait monitoring and human identification system program, (**b**) gait information machine learning processing process, (**c**) real-time signal outputs in the trained database, and (**d**) software recognizes the numbers and frequency of steps (**III**) and identify the specific person A (**I**,**II**).

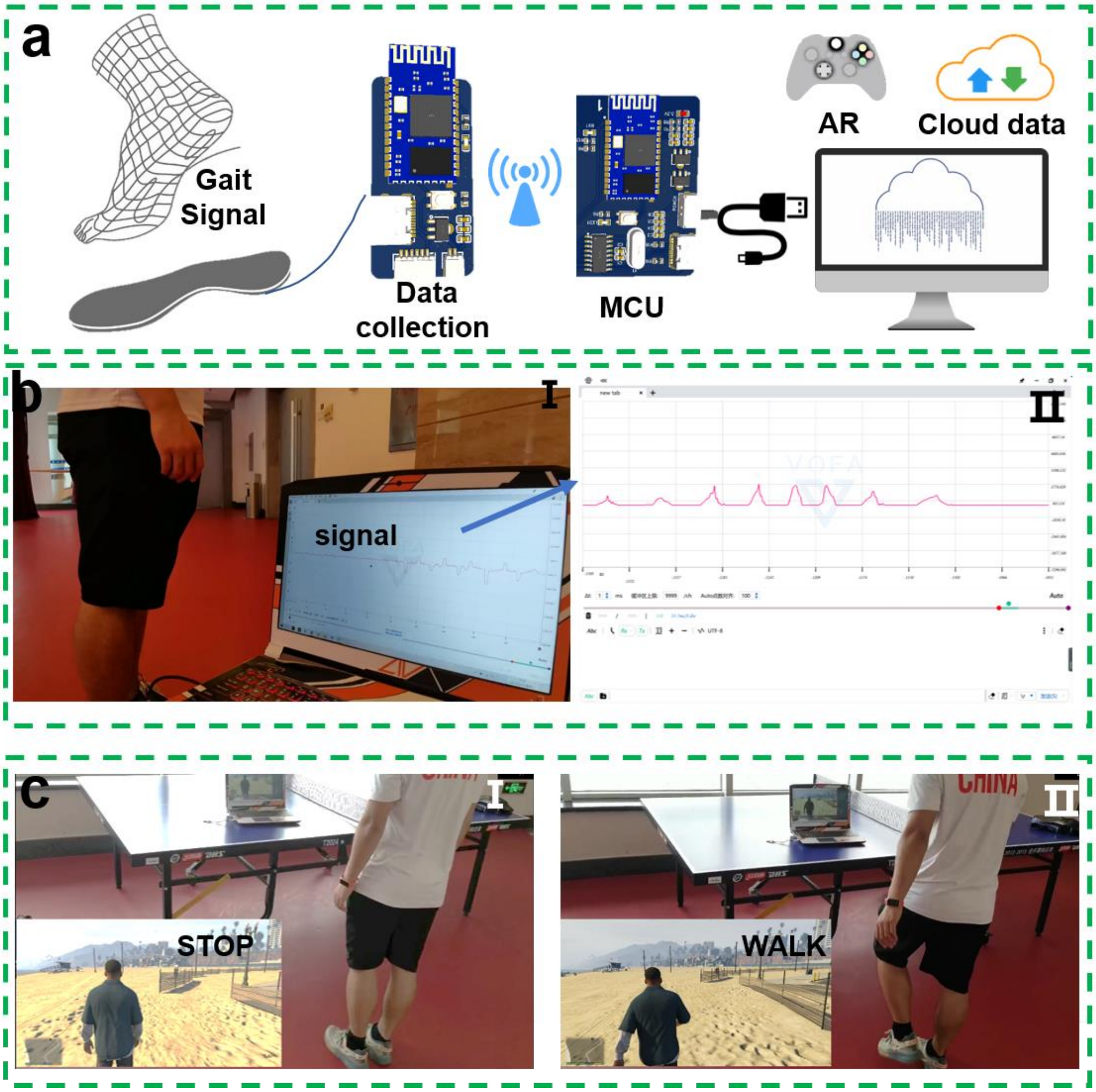

Figure 5. Human–machine interaction system, (**a**) schematic diagram of human–machine interaction system, (**b**) signal transmission process (**I**) and Detail drawing (**II**), (**c**) actual interaction scene.

4. Conclusions

To summarize, a wearable triboelectric sensing system has been specially developed for the digital robot to monitor human gait. Three-dimensionally printed TENG was fabricated of 3D printing materials. Nylon and PTFE were used as friction layers, which were coupled with gait based on friction electrification and electrostatic induction. It provides different feedback to different pressures and frequencies. At the same time, it can be used as a sustainable energy supply unit to supply power to microelectronic devices, and effectively utilize human mechanical energy for conversion. Therefore, it can charge a 2.2 μF capacitor to 1.92 V in 20 s. Long working ability is the character of 3D printed TENG. It can maintain a stable outputting voltage after 9000 cycles. At the same time, the machine learning system is used to identify and analyze the signal, and it aims to accurately calculate the number and frequency of steps. Gait information can also be used as a unique password to identify a specific person. As the sensing unit of the human–computer interaction system, 3D printed TENG also couples real human actions with virtual games. It provides an entertainment and immersion experience during the gait monitoring of users. Generally speaking, the proposed 3D printed TENG gait monitoring and human–computer interaction system provides a low-cost, energy-saving, and universal solution. In the future, the self-powered sensor will have a broad application prospect. Three-dimensionally printed TENG can design the structure that is actually needed, such as ergonomic devices and aerodynamic devices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141710875/s1, Figure S1: The optical image of 3D printed TENG; Figure S2: Commercial manometer test; Figure S3: The Analog-to-Digital acquisition module; Movie S1: The Human body recognition system; Movie S2: Gait monitoring system; Movie S3: Wireless transmission system; Movie S4: Man-machine interaction system.

Author Contributions: Y.M. and L.C. put forward to the concept of the study. Y.Z. wrote the manuscript. C.J. and F.S. made the visualization. C.H. and K.W. made the software. Y.L. finished proof. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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