Triboelectric Nanogenerator for Sports Applications

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Progress in science and technology drives the continuous innovation of energy collection and utilization. In the field of sports, the information collection and analysis based on Internet of things have attracted particular attention. On this basis, it is considered that the stability of devices, the universality of materials, and the scientificity of application of the TENG in the future need to be improved. There is a direction for further upgrading energy collection technology to promote the high-quality development of human mechanical energy sensing in the field of sports.

wearable energy sensing body motion

1. Introduction

With the continuous progress of science and technology, the world has been entered the digital age, and great achievements have been made in the field of sports [1]. The in-depth application of the information technology drives the sports field to develop in a scientific direction. Sports data-driven, precise, and intelligent development in the sports field has become a trend. In this context, data collection technology is constantly optimized and updated, and the information collection based on the Internet of things has become more and more important [2]. In recent years, related research topics, such as sensors [3][4] and energy acquisition [5][6][7][8], have attracted great attention. The effective collection, identification, and analysis of sports information is the key to intelligent sports. It can help athletes improve their skills, formulate scientific training plans and competitive strategies [9], help sports training digitally, accurately, and intelligently, and comprehensively improve the scientific level. The emergence of the motion sensor, which can realize the measurement of motion-related parameters such as speed and acceleration [10], plays an especially important role in many aspects. With the development of science and technology society, higher requirements are put forward for sports monitoring. The operation of traditional sensors depends on external power supply, such as batteries, which brings serious environmental pollution and takes the required characteristics such as flexibility, comfort, lightweight, convenience, and wearability of unified specification [11][12]. In the research of human motion data acquisition, it is necessary to take advanced science and technology as the support, overcome various adverse conditions, update sensing equipment, optimize sensing performance, expand sensing range, and promote the high-quality development of motion information acquisition.

In 2012, Wang’s group proposed the triboelectric nanogenerator (TENG) based on contact electrification and electrostatic induction, which has been proven to be a powerful technology that can convert random low-frequency energy into electrical energy. It has unique advantages of high-power density, high efficiency, low cost, and simple manufacture [13][14][15][16][17]. TENG is considered to have potential development prospects in the direction of human mechanical energy acquisition [18][19][20] and self-powered induction [21][22][23][24]. The sensor based on the TENG shows high sensitivity and efficiency to mechanical motion [8][25][26], and can measure several characteristics at the same time, such as acceleration [27][28], pressure [29], direction [30][31], etc. In addition, such sensors can make full use of various rich and available mechanical energy sources in daily life or nature environment [16][32], such as vibration [33], human movement [34][35][36][37], eye movement [38], etc. So far, various TENGs have been successfully reported [39][40][41][42][43]. Human movement will cause changes in external environmental factors. Therefore, some triboelectric nanogenerators have certain characteristics, such as moisture resistance, flexibility, and stretchability, can be made into wearable motion sensors [44][45][46][47][48][49], which monitor various motion data of human body successfully.

In recent years, triboelectric nanogenerators have been gradually applied in the field of sports and become an important sensing means for monitoring human activities. Firstly, it is introduced the working principle of the TENGs, and then focus on the latest application progress of sensing devices based on the TENGs in monitoring human movement. Energy sensors based on the TENGs are applied to basic human activities, which can achieve the effect of monitoring human daily basic activities and body health condition. In the application of sports, especially competitive sports, the real-time movement and physical faction monitoring of athletes can be realized through intelligent training facilities and wearable devices.

2. Triboelectric Nanogenerator

As a new branch of energy conversion technology, the TENG can convert the mechanical energy into electrical energy effectively, with a self-driving system [50][51]. The operation principle of TENG is based on the coupling effect of contact electrification and electrostatic induction, and its fundamental physics model can be traced back to Maxwell's equations. The TENG has four working modes: the vertical contact-separation mode, lateral sliding mode, single electrode mode, and freestanding triboelectric-layer mode [14]. The principles of different working modes are roughly the same. It is generally believed that after two different materials come into contact, chemical bonds are formed between some parts of the two surfaces, which is called adhesion. After separation, some bound atoms tend to retain additional electrons, and some tend to release electrons, which may generate friction charges on the surface [52]. In other words, materials with different electron adsorption capacity generate electric charges through mutual friction, and the potential difference drives the transfer of electrons, thus forming an electric current.

Here researchers select the vertical contact-separation mode for detailed description. At the original position, there is no charge. When two surfaces of different materials are in contact, frictional charges will be generated on the contact surface due to the difference in the ability to adsorb electrons. Once two surfaces are separated, a potential difference will occur, causing electrons to flow from the bottom electrode to the top electrode. When the two surfaces are completely separated to the initial position, the charge will reach equilibrium. When the two surfaces are close to each other, the electrons flow from the top electrode to the bottom through the load again.

3. Research Progress of Wearable Energy Sensor Based on the TENG in the Sports Field

The TENG can be used to make wearable energy sensors to monitor human movement using the special performance. The application in the sports field has a great development prospect. Next, taking TENG's research in the field of sports as the core, this combines the previous research from the two aspects of basic human activity monitoring and sports energy monitoring.

3.1. Basic Human Activity Monitoring

The energy sensor used to monitor basic human activities is mainly integrated with the TENG, which can monitor the movement status of various parts of the human body through the combination of weaving technology with clothing [53][54][55], or direct fitting with the skin [56][57][58]. Zhu et al. developed a robust and textile-TENG energy collection [59]. By adding MoS2/GO to the friction layer, a large number of micropores are generated in the silicone rubber matrix, which provides more sites for charge generation and improves the working performance of the device. In the process of collecting energy, sandpaper is used as a template to create a rough surface to obtain a larger contact area. The device can be worn on skin or cloth (c) to harvest energy from different body movements. Sun et al. designed a highly transparent, stretchable, and self-healable ionic gel. The TENG based on this ionic gel can be used for efficient energy collection [60]. This ionic gel's fibers can be easily woven with ordinary fabrics (such as gloves) to make ITENG. The resistance of ITENG increases with the bending degree of fingers. The bending angle can be identified and distinguished by detecting the change of resistance. Because the ionic gel has good elasticity, the monitoring of the device is accurate and repeatable. In the material selection of the TENG, the reuse of waste material is a hot spot [61][62][63][64]. Bhaskar et al. proposed a recycled material-based triboelectric nanogenerator (TENG) made of plastic waste and carbon-coated paper wipes (C@PWs), and C@PW-Teng has been reshaped into a smart wristband device [65]. However, since this device has no waterproof function, the moisture in the external environment will affect its working performance. Therefore, the surface of the wrist strap needs to be wrapped with a layer of polyethylene to prevent interference in the humid environment. Minglu Zhu et al. developed a self-powered and self-functional sock (S2-sock) based on a triboelectric nanogenerator (TENG) and lead zirconate titanate (PZT) piezoelectric chips [66]. The S2-sock has diverse functions for energy harvesting and sensing various physiological signals (gait, contact force, sweat level, etc.). This proves that the S2-sock can successfully realize walking pattern recognition and motion tracking for smart home applications through changes in environmental factors and human body weight. Textile research based on TENG can not only contribute to sports monitoring in the future, but also play a huge role in medical care. X.W. Hu et al. proposed a high-output flexible ring-structure TENG (FR-TENG) [67]. Since its fabrication materials are sponge-like porous PDMS and organic flexible hydrogels, it has good tensile properties. By optimizing the concentration of deionized water, the output performance is greatly improved. On this basis, a motion monitoring and protection elastic band is made to monitor human motion data. Wearing the motion monitoring protection elastic band on the arm, the measured voltage can reflect the force of the biceps when the arm is naturally bent and the arm is bent hard. Experiments compared the output performance of FR-TENG with pure PDMS and FR-TENG with porous PDMS under different stress conditions, which further verified that FR-TENG with porous PDMS has higher sensitivity and output performance can better reflect the strength of human muscles.

3.2. Energy Monitoring of Sports

With the professionalization and commercialization of competitive sports, it is more and more difficult to improve the performance of athletes for highly developed competitive events [68], and it is increasingly necessary to improve the consciousness and refinement of training [69]. The level of science has gradually become a key factor affecting sports performance [70][71][72][73][74]. In sports, especially in competitive sports, the application of motion sensors can further quantify the athletes' sports behavior and kinematic mode, thus helping to improve athletes' skills and formulate scientific training plans and competitive strategies [75]. On the one hand, in the field of competitive sports, researchers can monitor the competitive level of athletes by improving sports venues or equipment [76][77][78][79][80]. For example, Hao et al. made a flexible self-rebound cambered TENG. The device has more than 3000 cycles' durability and excellent elasticity and stability. On this basis, a self-powered riding feature sensing system was designed [81]. The intelligent saddle can provide real-time statistical data and fall prediction for equestrian athletes and coaches. This expands the application of self-powered systems to intelligent sports monitoring and assistance. Liu and Li used cotton cloth and polydimethylsiloxane (PDMS) as triboelectric layers to design a new TENG (CC-TENG), which has the advantages of portability, flexibility, and folding [82]. On this basis, they designed a self-powered long jump monitoring system based on a series of CC-TENG arrays. This self-powered long jump monitoring system makes use of the response signal of TENG to the movement to realize the accurate measurement of the standing long jump performance. Ma et al. proposed a lightweight self-powered sensor based on the TENG, which can convert a small amount of mechanical energy into electrical signals. It is applied to the training of table tennis players to collect the information of the hitting position and speed of the balls, guide the personalized training of athletes, and achieve the purpose of improving the sports level [83]. This opens a new direction for smart sports facilities and big data analysis. On the other hand, the motion sensor can achieve the monitoring purpose through direct contact with athletes [84][85][86]. Wang and Gao designed a new wave structure triboelectric nanogenerator (WS-TENG), which can realize motion monitoring in arc state. According to this feature, it can be used for foul monitoring in race walking [87]. The self-powered race-walking monitoring system based on the WS-TENG is installed at the athlete's knee, and the electrical signal can reflect the bending degree of the athlete's knee when walking in the competition. WS-TENG will not generate an electrical signal when the athlete does not commit a foul. However, when an athlete commits a foul due to knee bending, WS-TENG will be activated to generate an electrical signal. Shi et al. made a flexible, breathable, and antibacterial electronic skin based on the TENG for self-powered sensing of volleyball receiving statistics and analysis [88]. Three sensing units are integrated on each arm, where s1 and s2 are the sweet points. Through the electric signal displayed by the volleyball impact, the judgment of volleyball receiving speed and receiving effect can be obtained in real time after processing, and the statistics and analysis results can also be obtained in the program. Several examples are listed above to fully illustrate the research progress of TENG in the field of sports.

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