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A Battery-free Pressure Sensing System Based on Soft Piezoelectric Device for Tennis Training

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1. Introduction

Tennis was originated in France around the 12th century and formally invented by Major Walter Wingfield, an army officer of Wales in 1873 [1]. After that, tennis has become one of the most popular sports in the world: the International Tennis Federation (IFE) has more than 144 member nations around the world, from Zambia to Algeria [2]. More importantly, tennis is very popular among the diverse level of society and all ages of people: it is played at both a recreational and professional level and encompasses tournaments based upon ability, age, gender, and disability [3]. Nevertheless, as a competitive game, an outstanding tennis player not only needs hard-working training but also requires a great deal of skill whether it is in serving, or the groundstrokes [4]. On the other hand, with the development of fitness science, many cutting-edge technologies have been used in tennis training, which is relied on by the players to improve their skill level and minimize the injury risk [5]. To realize these goals in tennis sports, it is important to obtain the interaction between the ball and the players, which have many measurement forms such as the movement path of the ball and player, the physical contact force between ball and rackets, and velocity of rotation of the ball [6, 7].

Visual technology can be a useful tool within the area of tennis sports [6]. According to the data analysis of the recorded tennis game video, researchers are able to obtain the report of the skill features and arrange the future training plan for players. These data can be used to identify and improve the player's technique and minimize the injury potential [5]. In addition, these mediums even provide the facilities which a coach can highlight tactical awareness components to increase their cognitive understanding of tennis sport [6]. However, with the development of data analysis and artificial intelligence (AI), more precise data and diverse data sources are highly demanded. Furthermore, the calculation of video-based data analysis needs high-cost and cumbersome hardware systems and complex data processing processes, which provide chance and possibility for the other sports monitor technology [7]. On the other hand, one important application of sports monitoring is to build robotic systems, which is beneficial for the participation and promotion of sports. For the tennis automatic training machine, an urgent requirement is to obtain the interaction data between the tennis racket and ball [8]. As a result, building a physical monitor system on the tennis racket is highly demanded and necessary in real application [9]. However, with no doubt that its stronger hitting force and soft racket net will make the building of a monitoring system more difficult.

With the development of internet of thing (IoT) technology and sensing material [10, 11], the monitoring aspects of sports is expended and more monitoring system has been reported recently. Even though Tian et al. investigated a piezoelectric hard pressure sensing system towards table tennis, the similar but more useful system on the tennis racket is desirable but still unrealized now [12]. In this work, a pressure sensing system for tennis rackets is designed and verified. Soft piezoelectric thin-film devices and S-shape helical electric circuit are used for the design to fit the soft property of the racket [13]. The kinetic energy generated by the intense hitting of tennis can be harvested and used as the energy source to realize a battery-free monitoring system [14]. Different from the traditional energy harvest system concentrating on the signal transmission circuit, this work also optimized the machinal design of the circuit line and the power generation system. Based on that, the position and pressure of hits on the racket are measured in the tennis training. This design can be used to collect the training data in tennis sports and use them in the prevention of injury, training and technical assistance, and automatic machine design. After the research background introduced in this section 1, details of the design and operational circuit are shown in the next section 2. Then, the racket monitoring system is used in the real game test and it is shown that it can be used in reality effectively.

2. Methodology and theory of design

The designing methodology of the sensing system is elucidated in Fig. 1. The racket surface is separated to 3 × 3 areas. Soft sensors are place in the center of every area, which are finally connected to the wireless data transmission module. A sensor is located at the bottom of the racket to provide reference voltage. All the connecting line have an S-shape helical design. As shown in the insert of Fig. 1, the line will be transformed to state B from state A as the ball hit the racket and the net is stretched. Because the first purpose is to detect the hitting pressure and position, nine soft sensors are embedded into different positions of the racket as 3 × 3 distribution and one sensor are placed in the bottom of the racket as the initial base signal [15]. As the traditional piezoelectric sensing system, this kind of array design can obtain the variant pressure in the different positions. Nevertheless, because the net of the tennis racket is soft and has some deformation as the ball hits it, the traditional hard piezoelectric device will be damaged in this procedure [16]. Two special design is used to optimize this problem. First, the sensor is organic PVDF piezoelectric thin film, which is soft and easy to suit the racket net. Second, part of the line system in the racket system is set as helical micro coils, which is widely used in the integrated stretchable wearable monitoring system [13]. As shown in Fig. 1, while the ball has not hit the racket, the strain is released like the state A. When the ball hits the racket and a force is given to the racket, the net will be elongated and become state B. Because of that kind of design, the deformation of the racket can be well adapted and a stronger force can be added to the tennis racket.

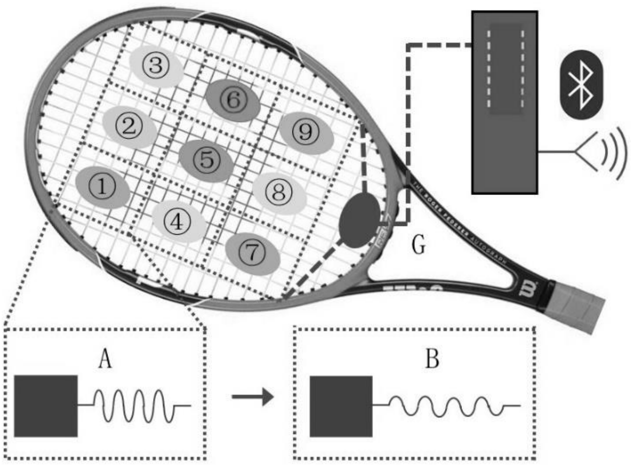


Fig. 1 Schematic illustration of the piezoelectric pressure sensing system. This system can realize the monitoring of hitting time, hitting position, and hitting pressure of the tennis ball. The electric voltage at G point is the ground of the system, where places the reference sensor to the system

Based on the piezoelectric effect, the kinetic energy of balls can be transformed as electric energy and nine sensors can measure the different signals. With the help of an energy management system, Bluetooth can transmit the massages to the laptop for the data process and collection. In this design, nine sensors are placed at nine areas and the hitting position is detected as one of the areas where the peak value appears of the nine sensors. That means for every hitting, one of nine areas can be chosen even though this result might be a little rough. To obtain a more accurate measurement of the hitting position and hitting force in the future, methods with more calculation resources or instruments can be used, such as adding more sensors to the system or developing inverse calculation algorisms to retract the hitting information.

For the piezoelectric devices, it is easy to understand that the electric voltage is proportional to the pressure of hitting driving from the energy of tennis motion. However, to benefit the future analysis, velocity of tennis ball can also be determined proportionally with the generated voltage. When the ball begins to touch the racket net, the sensors begin to generate an electrical voltage, and the elastic net starts to provide a force to the ball to decelerate the ball. The effective pressure could be measured as:

$$P_e = P - P_0, \tag{1}$$

where: P_e is the effective data used in the further calculation; P_0 is the initial pressure without hitting obtained in the sensor placed at bottom; P is the measured peak pressure from one of the nine sensors. As the velocity slowed down, the deformation of the racket net become larger. When the velocity of the ball v becomes zero, the pressure becomes to the peak value and all kinetic energy transform into elastic energy. There exists energy conservation here:

$$W = \frac{1}{2}mv^2 = Fl, \tag{2}$$

where: W is the total energy; m represents the weight of the tennis ball; v is the velocity when the ball contacts the racket; F is the resistance and l is the deformation distance. However, the force cannot be measured directly by the piezoelectric device and the measured data is the pressure P, which has the relation:

$$P = \frac{F}{S}, \tag{3}$$

S is the contact area between tennis and racket. In this design, this value can be assumed as a constant number. The deformation distance l can also be calculated by:

$$l = \frac{F}{k}, \tag{4}$$

here: k is the elastic modulus, which can also be viewed as a constant value here.

Up to now, all the relation is shown here and it can be deduced that:

$$W = Fl = \frac{F^2}{k} = \frac{(PS)^2}{k} = \frac{(P-P_0)^2 S^2}{k} = \frac{mv^2}{2}, \tag{5}$$

here, the velocity v has a linear relation with the P–P_0. The output voltage g_p of given sensor also has a linear relation with pressure P because of the relation [17]:

$$g_p = (1/C_p)S_p P, \tag{6}$$

where: C_p is the capacitance of the PVDF sensor and $S_p =$ $=\varepsilon_{33}$ represents the dielectric constant along the force direction. Considering all these parameters are kept constant in our system, the linear relation can be found among output voltage g_p, measured pressure P, and velocity of tennis ball v:

$$g_p \propto P \propto v. \tag{7}$$

In this equation, it is exposed that a stronger voltage measured from the sensor represents a higher velocity. Nevertheless, it also be noted that this relation is only a qualitative comparation and while for the precise measurement, the calibration for the environment is necessary to eliminate the change of variables among different environment.

3. Experiment and results

The circuit diagram of the tennis racket monitoring system is shown in Fig. 2. The racket is designed to have ten places to put down the sensors. Nine of them are set as a chessboard-like arrays and the last one is placed under all of them to provide the ground voltage. These nine piezoelectric thin films (PVDF) sensors (LDT1-028K) are evenly distributed as up layer (A1, A2, A3), middle layer (B1, B2, B3), and down layer (C1, C2, C3). These flexible thin film sensors are designed as square form with side length of 1cm. As a force is added to the sensors, a voltage will be generated by the sensors, which are placed at the center of the segmented areas. To make the system battery-free, four piezoelectric Lead Zirconium titanite (PZT) patches are series-connected and finally connected to the commercial energy harvesting chip (LTC3588) energy harvest chip to supply a higher power for the Texas Instrument Bluetooth communication platform based on the CC1350 chip. The hard PZT patches are designed as circle with diameter of 2.5 cm and thickness of 2 mm, which are sticked on the very thin copper plank with diameter of 3 cm. All PVDF sensors are also connected to the communication platform. As the power supplied to the system, the collected signals from nine PVDF sensors will be transmitted to the computer to compute the hitting position and hitting pressure, which are helpful to personal training guides for players. Here, a Buck-Boost converter design is used to convert the AC power to DC voltage. After a very short cold start time, the communication module is woken up and all the electrical devices are connected to a common ground to form a piezo potential.

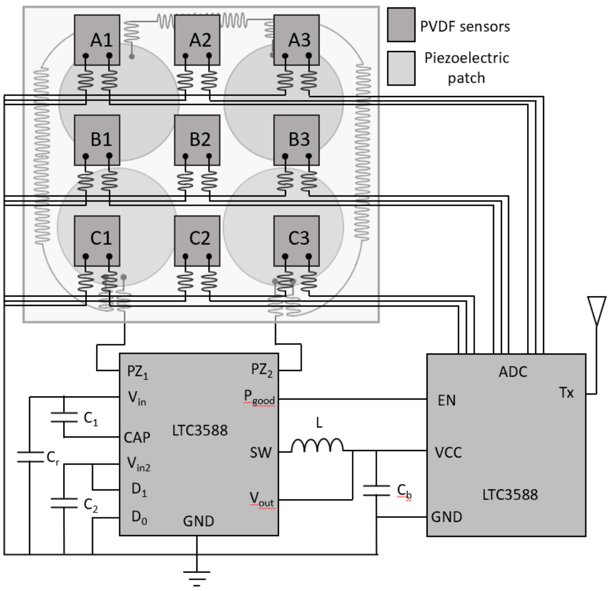


Fig. 2 Structure design of the sensing, powering, and information transmission module

The complete experimental system is shown in Fig. 3, a. Sensors are fixed on the racket by the Aluminium foil, which is flat, and makes the contact closely. Electrical signals are introduced to the interface circuits located on the racket handle. These circuits are potential to be minimized and integrated into the racket handle in the further research for commercialized application. The tennis ball used in the experiment is also shown in the picture. Main body of the sensing system frame concentrate on the frame and details of it (front side in the left and back side in the right) can be viewed in Fig. 3, b. Ten soft PVDF sensors can be viewed fixed on the net and the helical coil line is used to connect them to the edge of the racket. Based on this design, the net of the racket can undertake stronger hitting to prevent the damage. Four piezoelectric patches are also series-connected using the helical coil lines. The series connection can provide a much higher electrical voltage to the system and the voltage is managed and added to the energy management chip.

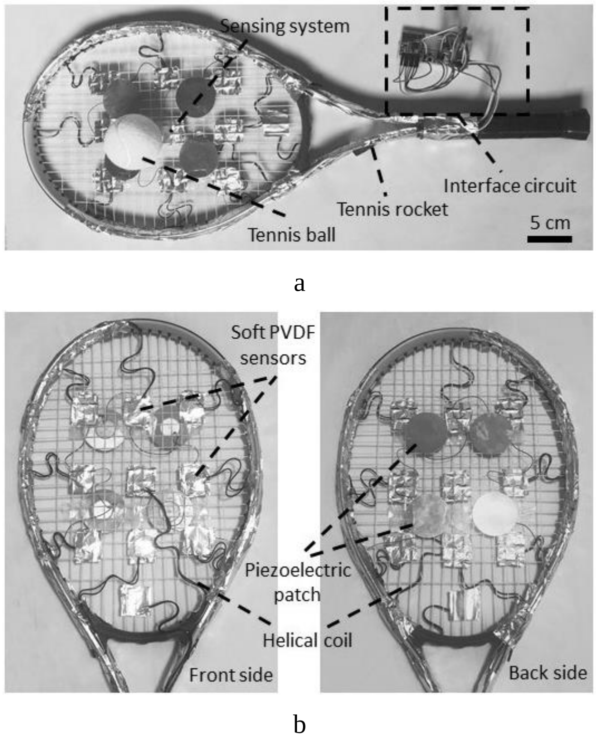
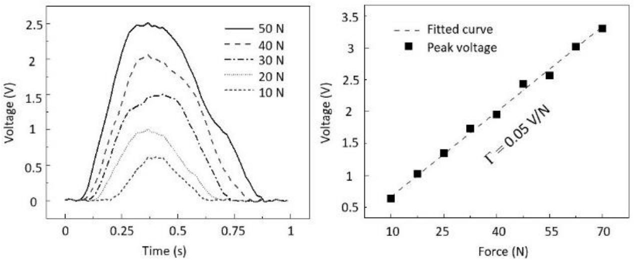


Fig. 3 a) Photo of the tennis racket piezoelectric pressure sensing system; b) Front side and back side detail of the system

Mechanical-electrical properties of the sensing system are firstly measured and the results are shown in Fig. 4. As we mentioned before, the velocity of the ball is proportional to the generated electrical voltage as well as the pressure added to the racket. It is important to investigate the relationship between force and generated electrical voltage on the racket. A force meter is used to measure the provided force exerting on the racket. An outstretched hard rob from force meter is used to support the tennis ball and to hit the rocket system. When the rob hits the racket, the maximum force added to the force meter can be recorded. A tennis ball is fixed in front of the force meter to make the contact area *S* the same in both mechanical-electrical properties test and the real application. As the force meter with a ball hit the sensing system, the generated electrical voltage could be recorded and transmitted to the computer and the maximum force would be kept and recorded. Fig. 4, a shows the measured electrical parameter from the ball directly hit one sensor under the different peak hitting force from 10 N to 50 N. After very short cold start time of the system shorter than 0.1 second, the generated voltage first become large and then decrease slowly to zero. With the growth of the maximum force, the peak voltage also becomes larger. Compared with the measured electrical signal from the hard and straight connected devices, the generated voltage data in tennis rocket monitoring system is much flat, which might because the deformation of the rocket has an offset and makes the sharp hits flatter [13]. Peak of voltage electrical response and its forces were also measured and plotted together in Fig. 4, b. It is apparent that as the force grows stronger, the generated voltage also becomes larger and the persisting time of the signal also prolongate. While fitted the data using a straight line, it can be found that the force and voltage conform to a linear relation (shown in Fig. 4, b). The growth of this linear relationship is also calculated by the mathematic method as 0.05 V/N, which means as the force grows 1 N in the test, the generated voltage becomes large of 0.05 Volt.



a b

Fig. 4 a) The induced voltage from the sensor under force with various peak hitting forces (10 N, 20 N, 30 N, 40 N, 50 N); b) The peak voltage under different peak force of the hitting. A fitting linear relation exists between them with growth rate of 0.05 V/N

In Fig. 5, the detected electric voltage of all nine sensors from a single hit is plotted. In this test, the ball is also fixed on the force meter. With precise control of hitting the B3 area with 65 N force, all detectors can get the press because of the integrity of the racket. However, as the analysis before, the B3 sensor has the strongest signal of about 3.3 V. In Table 1, the peak value from all sensors of 9 hits with the force of about 50 N is summarized and the hitting positions are marked by texture in the list. It is clear to show that the hitting position and hitting time can be distinguished and recorded as designed. Although for the flexible tennis racket, the force of one shot can be captured in the other place, it is still very reasonable to distinguish the sensor position by the strongest voltage [18].

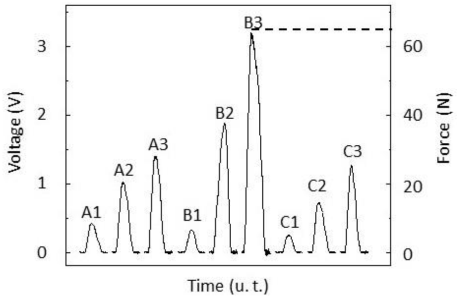


Fig. 5 Response of nine sensors with the hit point in B3 area

Then, the sensing system is used in the game test hit by the tennis ball. The tennis ball is hung in the air by a string and the racket surface is vertical with the ground to hit the ball. The distance between the ball and the ground is 1 m. After hitting the ball with the racket, the ball flew out with the initial velocity horizontal with the ground. To simulate the real game environment, different hitting positions of the racket are used. The moving distance of the ball under various situations are measured and recorded in Table 2. It is clearly shown that the contact area between the ball and racket surface can be distinguished. The contacting positions of seven hits are C1, A3, C1, B1, B3, B2, B2, respectively. Considering there exist many other influential factors on the ball's movement, the moving distance has an approximate directly proportional relationship with the hitting force, which will induce a stronger voltage in the piezoelectric system. This result shows that the battery-free pressure sensing system has a broad application capability in tennis ball training monitoring.

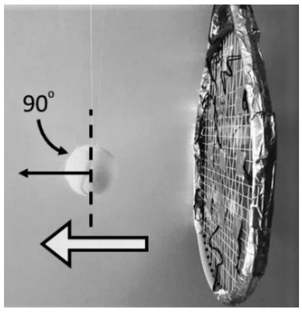


Fig. 6 Experiment setup of the tennis ball hitting test. The ball is hanging in the air and racket is vertical with the ground plane. The original velocity direction is horizontal with the ground

Table 1

Measured peak voltage intensity of installed sensors with the hit area marked in shadow

Trail number	Measured Peak voltage (V) of different sensors								
	A 1	A 2	A 3	B 1	B 2	B 3	C 1	C 2	C 3
1	2.4	1.4	0.4	1.6	0.8	0.2	0.2	0.2	0.1
2	1.6	2.7	1.7	0.7	1.8	0.8	0.3	0.3	0.4
3	0.5	1.3	2.5	0.2	0.9	1.4	0.2	0.2	0.2
4	1.4	0.6	0.2	2.6	1.5	0.7	1.4	0.7	0.3
5	0.6	1.3	0.5	1.4	2.8	1.6	0.4	1.3	0.5
6	0.2	0.5	1.3	0.5	1.5	2.7	0.3	0.9	1.6
7	1.0	0.5	0.2	1.8	0.8	0.6	2.6	1.4	0.8
8	0.3	0.5	0.2	0.7	1.5	0.6	1.5	2.8	1.6
9	0.1	0.3	0.8	0.4	0.9	1.6	0.7	1.8	2.5

Table 2

Measured peak voltage from sensors and distance of 7 hits

	Hit 1	Hit 2	Hit 3	Hit 4	Hit 5	Hit 6	Hit 7
A 1 (V)	0.8	0.6	0.3	0.6	0.4	0.7	1.0
A 2 (V)	0.4	1.0	0.2	0.4	0.8	1.2	0.5
A 3 (V)	0.2	1.5	0.1	0.1	1.1	0.4	0.2
B 1 (V)	1.4	0.3	0.7	0.8	0.7	1.3	1.5
B 2 (V)	0.9	0.7	0.3	0.5	1.2	1.9	2.2
B 3 (V)	0.4	1.0	0.3	0.3	1.8	0.7	0.5
C 1 (V)	1.8	0.2	1.2	0.5	1.0	0.4	1.0
C 2 (V)	0.3	0.5	0.2	0.7	1.5	0.6	1.5
C 3 (V)	0.1	0.3	0.8	0.4	0.9	1.6	0.7
Distance (m)	8.6	7.5	6.3	4.6	13.5	9.5	11.9

4. Conclusions

In conclusion, a battery-free pressure sensing system for tennis rackets is designed, manufactured, and experimentally used. The sensing system mainly concludes two parts: PVDF soft thin-film based sensing module and PZT piezoelectric powering harvesting module. For the sensing module, the rackets are divided into 9 blocks with a practical sensor in every area to detect the pressure. Two methods are used to realize the monitoring system for tennis ball games: the first is soft sensors technology and the second is the S-shaped line to connect the devices. With the powering system, the information can be transmitted to the personal computer and a linear relation can be found with a slop of 0.05 V/N. This design will be beneficial for the development of sport analysis and the application of the Internet of Things.

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A BATTERY-FREE PRESSURE SENSING SYSTEM BASED ON SOFT PIEZOELECTRIC DEVICE FOR TENNIS TRAINING

S u m m a r y

In this work, a battery-free position and pressure monitoring system based on soft polyvinylidene fluoride (PVDF) piezoelectric thin film with helical coils circuit design is designed and used for tennis training. The racket surface is firstly divided into block areas and the sensing transducers are placed in each of them to detect the hitting position and force in these areas. To modify the extensibility of the system for tennis training, all the devices are connected by the S-shape helical line, which has two states: curled at usual and straight at work. Four piezoelectric patches form a series system to power the energy harvest system and wireless communication module, which help to realize the battery-free and wearable functions. A linear relation between the hitting force and induced electric voltage is experiment verified with the slope of 0.05 V/N. The system is also verified in the real tennis ball game monitoring for the hitting time and hitting position, benefiting the future application of wearable devices in artificial intelligence and the Internet of Things (IoT).

Keywords: piezoelectric battery-free system, tennis training monitoring, soft pressure monitoring device, mechanics for sport application.

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