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Portable Referee System for Volleyball Game Based on Pressure Monitoring and Self-Powering Communication

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1. Introduction

Volleyball is a sport played in major competitions such as the Asian Games and Olympics. Measuring player performance and skills is essential [1, 2], and several studies continue to enhance volleyball performance, including physical movement analysis [1], medical support [2], and mental guidance [3]. The flexibility of volleyball has led to its growth in different areas, including the development of beach volleyball [4]. Monitoring player performance in attacking, smashing, receiving, and spiking is critical [5, 6], and parameters measured from these actions can guide training, analyze skills, referee the game, and build movement models such as endurance, flexibility, and power during sports [8, 9].

The wearable system is the most applicable method for sport monitoring. Different sensors can be designed in the wearable form and integrated into the system [10]. Materials synthesis, mechanical design, and electronic innovation have been developed to improve wearable systems and collect various data [11, 12]. The close connection between the measured sample and sensor enables precise measurements and individual monitoring [13]. Among wearable devices, piezoelectric sensors are useful in measuring pressure and providing power simultaneously, essential for monitoring force and movement during sports [14]. With the application of minimized piezoelectric sensors, the monitoring can be less cumbersome and more functional [15]. Piezoelectric sensors have been used in many areas, but their use in volleyball is still unreported.

An automatic referee system can be useful in promoting and advancing sports [16]. In volleyball, referees can be four to six people, which wastes human resources and hinders its spread. Referee actions are based on personal judgment, leading to uncertainty [17], and training a referee can be costly in terms of time and number of games for internship. Machine-based referee systems can be useful to replace human referees, and video-based analysis has been designed [18]. However, videos are ineffective in monitoring actions from certain angles [18]. Wearable devices using piezoelectric systems can monitor all contacts between the ball and the human, enabling automatic referee systems. Mechanical pressure can produce electric charges proportional to force, and contact time, position, and force information can be extracted to judge the game [10]. The power from these electric signal can also enable the work of device without battery which promotes the integration of devices and their use in the Internet of Things (IoT) system. Even though the embedded piezoelectric sensing system has been widely used in human signal capture and actuation [19] , only limited reports can be found in the real game referee [20]. However, referring is a very important application for human sensors. Considering the limit of video-based referee systems and battery-integrated sensing systems, the piezoelectric sensing system can work as the sensor and power source at the same time, which is beneficial to the future referring system. Here, we used volleyball game monitoring as an example to show the possibility.

This paper presents a sports monitoring framework based on hard piezoelectric Lead Zirconium Titanate (PZT) patches and soft piezoelectric polyvinylidene fluoride (PVDF) thin films. The system has two monitoring parts that work together to gather information. The first is the volleyball system, which has eight PZT patches to power the system and collect information. The second is a specially designed pressure monitoring system on a glove, using PVDF thin films as sensors and PZT pads for power. We measured the sensitivity of pressure for every system and the time delay first, which is essential for referees as every system has its delay [21]. Then the framework is applied to a volleyball referee, which is a three-second contact foul. The violation is crucial in the volleyball game, has a close connection with hand movement, and is a suitable choice for verifying our framework for future automatic referee systems. The framework can also be used in other action referees with different rules [22].

In section I, the background and motivation of this work are introduced and in section II, the framework system design and working circuit for different models are shown. Where in Section III, the photos of fabricated devices, the experiment setup, the delay time of different systems, and some results are shown. In section IV, the primary results of the three seconds contact referee are discussed and statistical results of the referee are measured. In the last section, the paper is concluded, and the future possibility of the monitoring framework is discussed. Overall, the framework provides a novel and possible approach for monitoring and improving the performance of volleyball players, as well as potentially revolutionizing the way the game is refereed.

2. Design of the sensing system

The demonstration of the sensing systems is shown in Fig. 1, a. This system sensing has two sensing parts on the glove and ball, respectively. Piezoelectric sensors are placed on gloves and balls to monitor pressure. When force is applied to the sensor, it generates electrical energy that is collected by circuits [23]. Based on the working mechanism of piezoelectric sensing, the generated energy is proportional to hitting force and ball speed [14]. For the glove part, the soft sensors are attached to the tip of the fingers to better capture the pressure distribution. The information is transmitted through a Bluetooth module to the personal computer for collection and analysis, which is powered by a hard piezoelectric pad in the center of the hand [24]. The hard pads are used on the ball for sensing and powering, as they provide a larger piezoelectric effect than soft sensors. The eight pads are evenly placed on the volleyball surface, series-connected, and connected to the power management circuit and data transmission circuit. The captured pressure information on glove and ball is transmitted to a personal computer to make a judgment. In the expanded 2D view of the volleyball surface, the sensor distributions are even, with a distance of 12 cm between them [25]. Considering most human hands have a length larger than 15 cm, the 12 cm distance is enough to ensure at least one sensor is covered when a hand covers the surface (Fig.1, b).

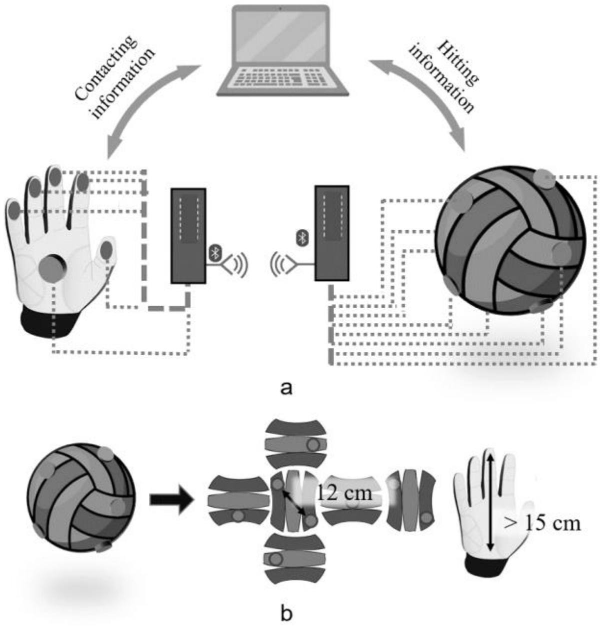

Fig. 1 Schematic illustration of the sensing system: a - general view of the system, b - demonstration of positions of the sensors on volleyball and an expanded view on a 2D plane with its comparison with the glove

The circuits modules and used chips are presented in Fig. 2. The systems on the glove and the volleyball use the same sensing chip, which includes a communication antenna to transmit information and an energy management circuit to collect the energy from piezoelectric material for powering. On the other hand, the system on the glove uses a soft sensing film to capture the contact information and a hard patch to provide the power. All films are series-connected and connected to the signal input port of the sensing chip. The voltage from each sensor is added together to show a superposition voltage. A sensor is also located at the back of the hand to provide the reference voltage. For the system on the volleyball, eight patches are evenly distributed on the volleyball surface and series-connected, which collect the kinetic energy from hitting and use the energy as both the source and target signal. The output of the eight patches is connected to the energy management circuit and sensing circuit with a separation design. When there is a hitting on the ball, the patches record the hitting signal and collect the energy simultaneously. Compared with the electrical power collected from flexible PVDF film, the hard patches can collect more energy in this application. First, the PZT hard patch we use is more sensitive than the PVDF film. Second, for the soft background in use, such as a volleyball surface or a human hand, the deformation of it can cancel out some force on it and absorb some energy, while a hard sensor is better for power collection. The system on glove and volleyball can work separately in the volleyball game, but they are used together for better judgment.

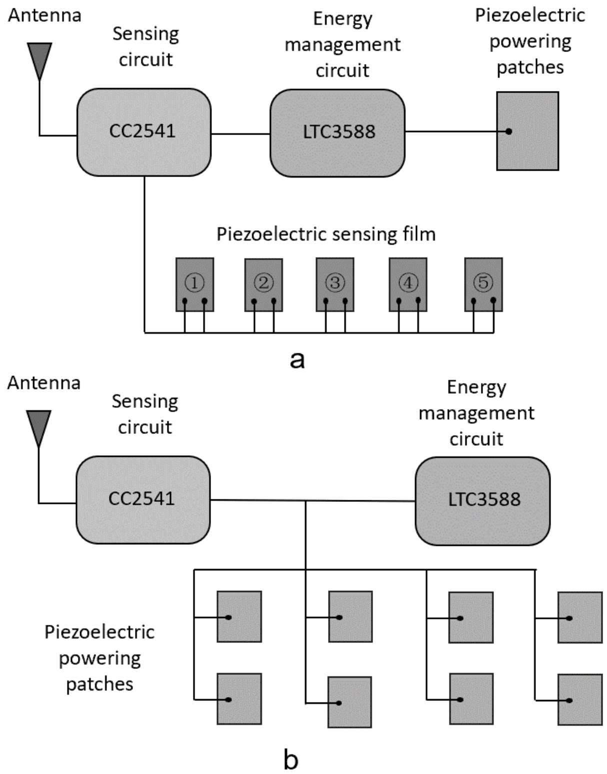

Fig. 2 Applied circuits modules of the sensing system: a - on the glove, b - on the volleyball

3. Experiment and results

The fabricated systems on gloves and on balls can be viewed in Fig. 3, a and c, respectively. The interface circuit is on the breadboard outside; soft sensors are on the tip of fingers, and the hard pad is in the palm. The sensors are positioned at the required locations and covered with a metal film or hard paper pad to protect them from electromagnetic interference and ensure even pressure distribution. Without this protection, the duration of PZT pad might be shorter because these components are fragile in use. Because of the flexibility of the hand, more room is needed for the movement of the hand and the circuit also needs to move special designs. To accommodate it, a specially designed S-shaped circuit line is employed, as shown in Fig. 3, b. This design allows for more robustness in movement, with two stages: straight and bending. As the bending stage, the line structure shows a bigger curvature to obtain enough room to put the lines and offset the stretching influence on the monitoring. The used soft sensor is LDT1-028K from TE Connectivity Company, which is a 28-um laminate made of piezoelectric polymer polyvinylidene fluoride sandwiched by sheets of polyester (Mylar). And the used hard pad is from Chironal company. All circuit elements are assembled on a breadboard. Considering the device is only the early-stage demonstration and the referee action is still simple, only five positions on glove are chosen to put the pressure monitoring

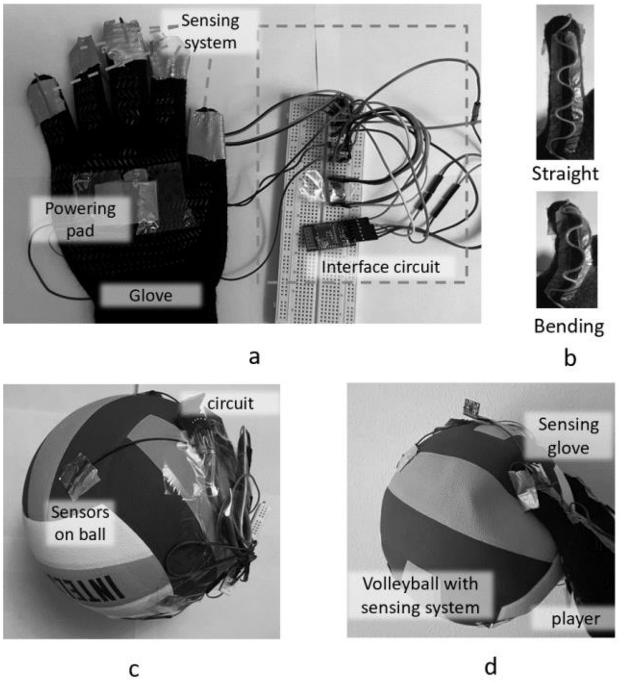

Fig. 3 Experimental setup: a - photo of the piezoelectric pressure sensing system on a glove, b - demonstration of the two stages of S-shape line design, c - photo of pressure sensing system on the ball, d - the measuring setup of the system with a player to play the ball

devices but it is enough for the game referee. For the volleyball side, eight sensors are set on the surface. Because the sensors are series connected together to the common ground, the pressure on any position of the volleyball will be captured easily. The fabricated system on ball is shown in Fig. 3, c and the measuring of the system can be viewed in Fig. 3, d. The player wears the glove when patting the ball and the analysis is based on the captured signals on both two systems considering the time duration of these pressure.

Before applying the system in a refereeing capacity, the sensitivity and time delay are measured, as presented in Fig. 4. To measure the piezoelectric sensitivity, sensors are pressed with varying forces controlled by the force meter (HP-100). In tests, the tip of the force meter is set to push the sensor with different forces in continuous wave mode or pulse wave mode. The electrical signal generated is recorded by the laptop after transmission from the Bluetooth module. According to the property of the piezoelectric material, the added force and generated electric signal is linearly related, which is also proved by our measurement, shown in Fig. 4, a and b. The results demonstrate that the measured electric signal intensity increases as the added force gradually grows from 10 N to 50 N, with the soft and hard sensors exhibiting different growth rates. The sensitivity of the sensors is calculated from the fitting line in Fig. 4, with values of 0.056 V/N and 0.032 V/N for the soft and hard sensors, respectively. This means that a 1 N increase in force results in a voltage increase of 0.056 V and 0.032 V for the soft and hard sensors, respectively.

The time delay between when a force hits the sensor and when the computer collects the data is a crucial parameter in our systems. When a force is added to a sensor in this system, there will be a time delay before generated electrical voltage being recorded and transmitted to the computer. To demonstrate this delay, we plot the added force and the resulting electrical signal on the same axis. The force meter is also used to excite the device with a transient

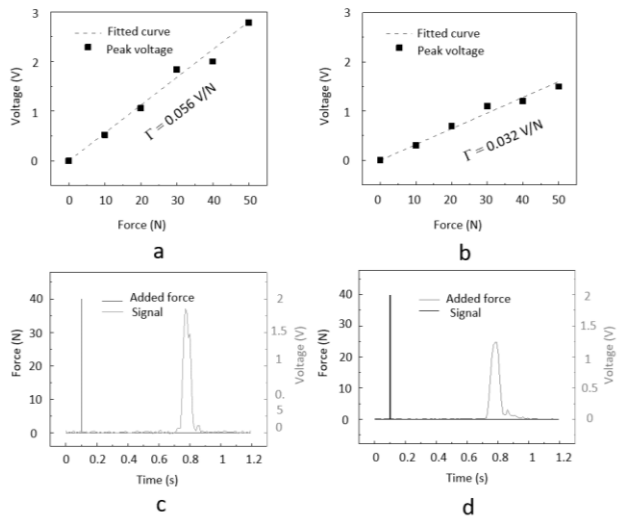

Fig. 4 Generated voltage under various peak values hitting force from: a - hard piezoelectric, b - soft film; and system time delay measurement test for: c - sensors on ball, d - sensors on a glove in the calibration

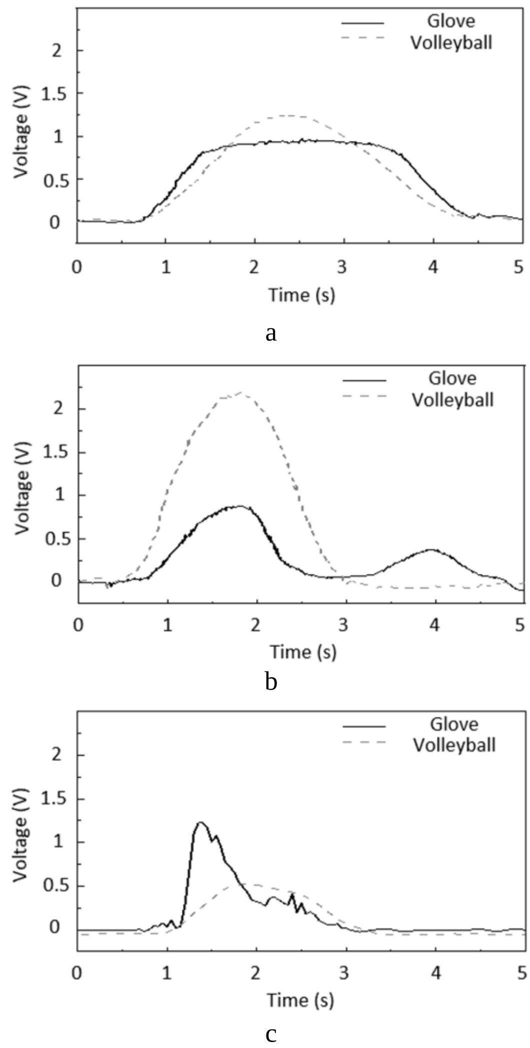

Fig. 5 Output electrical signals from system on glove and volleyball for a - three second contact, b and c - non-three second contact

signal of 10 ms duration and 40 N amplitude, and then the system measures the generated voltage. The initial voltage is near zero and then rises quickly to a value larger than 1 V, lasting for about 0.15 ms. The deformation and displacement of the sensor background on the ball and glove may offset part of the force and influence the generated voltage [24]. The time delay can be extracted, as the time between the force hitting the sensor and the appearance of the signal in measurement, which is around 0.7 s for both systems. This delay is critical in our system, as many sports referees rely on accurate timing of events. The similarity of the delay between the two systems ensures that our system will be beneficial to referees. When a volleyball hits the glove, the electrical signals generated by the glove and ball will have a similar time delay before being collected by the computer.

Then the designed system was tested in real volleyball games using a basic and commonly occurring foul action, which is three second holdings of the ball, as an example to be distinguished by the referee system. At the start of a game, the ball is given to a player who must pass it out within three seconds. During the experiment, a volunteer passed the volleyball to another volunteer who wore the glove with our system on their left hand. The demonstration of the experiment measurement is similar to the Fig. 3, b, where the player will play the ball wearing the glove with our systems. As different actions of the player, the pressure on ball and glove will be changed and an electric voltage will generate. Here, we did 15 times pass and the electrical signals generated by both the glove and volleyball systems were captured and plotted together in the same timeline. The first three results are shown in Fig. 5, a to c. The measured signal raised and then went down to nearly zero after reaching its peak, indicating that the sensors measured pressure also raised and then went down over time.

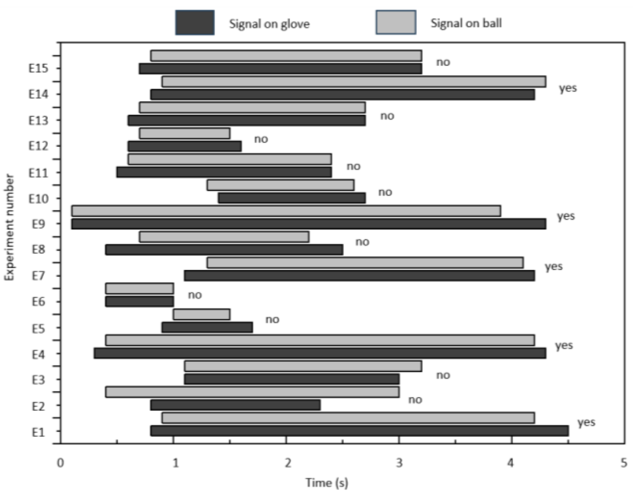

Fig. 6 Measured signal duration from systems in 15 experiments with judgement of three-second contact (yes or no)

The framework system was used to distinguish whether the three-second contact had occurred. The start time and end time of the signal on the glove and ball were extracted from the measured electrical signal, and the duration of the contact was then calculated to help the referee make a judgment. The measured signal duration from 15 experiments and the judgment of whether the player broke the rule and contacted the volleyball for more than three seconds based on the system are shown in Fig. 6. For numbers E1, E4, E9, and E14, both the system on the ball and the system on the glove judged that the player had broken the rule because the duration of the signals was longer than three seconds. However, for number E7, only one of the sensors had a longer contact time than three seconds, but we still judged it as a foul because one longer duration was enough to determine that the contact time had exceeded three seconds.

It should be noted that the duration time of the glove signal was often much longer than the contact length of the ball signal. This might be due to the more complex actions of the hand and the fact that the glove might have more pressure sources than the ball. Another reason could be that the ball has more cushion effect than the hand, making the pressure measurement have a slightly weaker signal.

Although our framework is the first volleyball referee system, it can monitor these simple actions, and the complexity of the system can be improved in the future. More sensors could be added to the system to realize complex action monitoring, and the system can be minimized and integrated for future demonstrations [10].

The more complex signal can also be obtained from the system on glove, such as the black line signal plotted in the Fig. 5, c. That might have two reasons. Firstly, the pressure on the hand when playing the game might have complex diversification to realize the manipulation of the ball. Secondly, the sensors are series-connected, which means the measured signal are added together as the output. The pressure on different fingers has the time-dependent variety and when they are overlayed together, the signal might be complex.

4. Conclusions

In summary, we have designed, produced, and verified a portable volleyball game referee framework system that utilizes the piezoelectric effect to power the circuits and sense pressure. The framework employs both soft PVDF thin film sensors and hard PZT pad devices in various positions to improve sensing accuracy. Specifically, eight sensors are placed on the surface of the volleyball, which is divided into eight parts evenly, while soft sensors are fixed on the tip of the finger and hard pads are located in the center of the glove. Additionally, we have incorporated a special S shape line design to ensure that the circuit has enough room for movement. The sensitivity tests indicate that the hard patches have a sensitivity of 0.056V/N, while soft sensors have a sensitivity of 0.032V/N. Furthermore, the time delay for data transmission of the glove part and volleyball part is approximately 0.7 seconds, where the similarity is beneficial for the referee's judgment. Finally, the framework system has been applied to the three-second contact rule judgment, demonstrating that it can make judgments easier than relying solely on human judgment. This framework also has potential applications in automatic referee systems and training guidance for other sports.

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J. Wu, Z. Fan

PORTABLE REFEREE SYSTEM FOR VOLLEYBALL GAME BASED ON PRESSURE MONITORING AND SELF-POWERING COMMUNICATION SYSTEM

S u m m a r y

Sports refereeing has traditionally relied on human judgment, which can be prone to errors. However, the development of automatic referee systems has the potential to address this issue, improve training, and promote sports in the future. In this study, we present a novel and portable referee framework system specifically designed for volleyball games, which utilizes piezoelectric sensors to detect pressure and simultaneously harvest energy for powering the system. The system consists of two parts: a wearable glove and a device mounted on the volleyball. The glove part has five sensors fixed on the fingertips and the volleyball has eight sensors evenly distributed on its surface. The collected contact data from the sensors is wirelessly transmitted to a personal computer. Our experimental results demonstrate that the framework can accurately capture a three-second contact and detect foul actions in a volleyball game. These findings highlight the potential of wearable sensors for sports and other monitoring applications.

Keywords: portable piezoelectric sensing system, automatic volleyball referee, energy harvest, mechanics for sport application.

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