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A novel three-axis force sensor for advanced training of shot-put athletes

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Abstract

This paper presents a novel three-axis force sensor for measuring the throwing forces of shot-put athletes. The shot-put sensor has been designed and fabricated with almost the same size and weight as the standard shot for open males. Instead of using a common shot, the shot-putters can use this shot-put sensor to make their throws. The sensor can simultaneously detect applied forces along three orthogonal directions with reasonably high accuracy. With the help of a commercially available high-speed photography system, field tests have been performed. The experimental results show that each phase of the throwing motion can be clearly identified by analysing the force curves and it is easy to distinguish between good throws and faulted throws. In this manner, the shot-put sensor serves as a powerful tool for coaches and sports scientists to make scientific researches on shot-put techniques. It also provides an intuitive and reliable guidance for the shot-put athletes to improve their skills.

Keywords: Force sensor; Shot; Shot-put; Shot-put sensor

1. Introduction

There are now increasingly intense competitions in professional sports. Sports science and scientific training are becoming more and more important for cultivating excellent athletes. Shot-put is one of the most popular athletic events in track and field. This century-old athletic event has a good effect on increasing the strength of the upper limbs and the fingers. How shot-put athletes exert force on the shot plays an important role in improving the final throwing distance. By analysing the force data, coaches and sports scientists can diagnose faulted throwing attempts and direct the shot-put athletes to improve their skills. Shot-put athlete training that depends only on the naked eyes and personal experiences of the coaches has become a thing of the past.

The recent evolution in computer-based instruments is opening the way to the research on shot-put techniques. The relationship between the angle of release and the velocity of release in shot-put was studied in [1]. High-speed videography was used to record the attempts of throwers. In [2], the constraint relations among four release variables in shot-put were investigated. A 200 Hz video motion analysis system was used to determine the initial release angle, speed, height and horizontal distance for each throw. In [3], the influence of Earth rotation on the range of the male hammer throw and shot-put was compared with that of air resistance, wind, air pressure and temperature, altitude and ground obliquity using computer modelling for typical release heights and optimal release angles.

These solutions, though effective in getting the aforementioned kinematic data, cannot provide enough kinetic data such as the throwing force of the shot-putters. In order to get the first-hand kinetic data, various sensors and measuring equipments have been developed and used in some athletic events [4–6]. A three-axis force measuring system for parallel bars has been developed in [4]. Measurement of applied force and deflection in the javelin throw has been done in [5]. A six-axis force measuring platform for weight lifting has been developed in [6]. But in the shot-put, there still lacks good methods or instruments for measuring the forces applied on the shot by athletes.

This paper describes a novel three-axis force sensor for advanced training of shot-put athletes and for research on shot-put techniques. The sensor has almost the same size and weight as the standard shot for open males and can simultaneously

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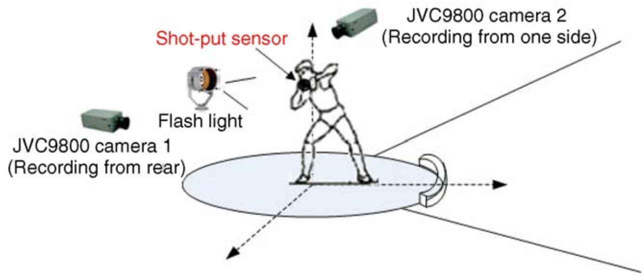

Fig. 1. Force sensing system for shot-put training.

detect applied forces along three orthogonal directions. System overview, sensor design and some experimental results are presented in the rest of this paper.

2. System description

Fig. 1 shows the proposed force sensing system for measuring the applied forces of the shot-put athletes. It consists of two JVC9800 high-speed cameras, a flash light and a shot-put sensor. Considering that the body of the athlete will turn during the throwing motion, stereo filming method is used to record the video data. Camera 1 is mounted right behind the athlete, while camera 2 is mounted on one side of the athlete. Each camera is 15 m away from the edge of the putting circle. In this way, best video images can be captured.

The shot-put sensor is designed to measure the forces applied by the athletes during the full throwing motion. It is 129 mm in diameter and 7.2 kg in weight, almost the same as the standard shot for open males (Ø110–130 mm, 7.26 kg).

In order to synchronize the video data and the force data, a flash light is used to provide the synchronizing signal. The data-acquisition switch on the shot-put sensor also controls the power supply of the flash light. When the button switch is pushed, the shot-put sensor starts force measuring. At the same time, the flash light is instantaneously powered on and flashes once. The light from the flash is then recorded by the cameras as the synchronizing signal.

3. The shot-put sensor

3.1. Principle of sensor

The shot-put sensor is a strain gauge sensor that can simultaneously measure forces along three orthogonal directions. A 3D model of the sensing element is shown in Fig. 2. This type of structure is made of high-quality alloy structural steel. The simplified analysis model of this sensing element is a flat sheet with a rigid centre under a concentrated load, as shown in Fig. 3. In this scenario, some key mechanics parameters of the sensing element have to be calculated, such as the maximum deflection and the maximum stress. These parameters play a crucial role in the optimum structural design of the sensing element [7].

The maximum deflection and the maximum stress of the flat sheet under a concentrated load all emerge at the edge of the rigid centre, which can be, respectively, expressed as:

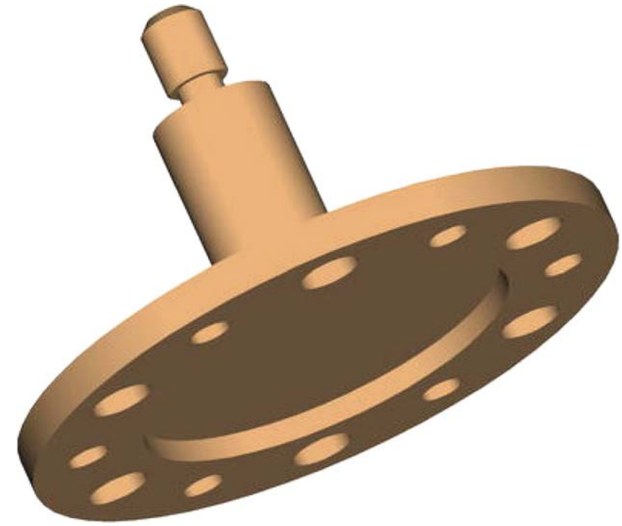

Fig. 2. 3D model of the sensing element.

$$w_{\max} = \frac{3(1-\mu^2)}{4\pi}\frac{FR^2}{Eh^3} \times \left[1 - \left(\frac{r_0}{R}\right)^2 \frac{1-(r_0/R)^2 + 4In^2(r_0/R)}{1-(r_0/R)^2}\right] \quad (1)$$

$$(\sigma_r)_{r=r_0} = \frac{3F}{2\pi h^2}\left[-\frac{2In(r_0/R)}{1-(r_0/R)^2} - 1\right] \quad (2)$$

where μ is the Poisson's ratio of the material of the sensing element and E is the Young's modulus of the material of the sensing element.

Fig. 4 shows the principle of the shot-put sensor and how the force applied by the athlete is measured. When the athlete exerts a force on the lower shell of the sensor, the acceleration difference between the upper shell and the lower shell makes the upper shell exert a reacting force on the sensing element. A 1 mm gap is kept between the lower shell and the upper shell for restricted deformation of the flat sheet. The flat sheet of the sensing element is very sensitive to load changes from the rigid centre. The load changes can cause elastic strains in the flat sheet. These elastic strains will then be transferred to the strain gages pasted on the surface of the flat sheet. Three Wheatstone

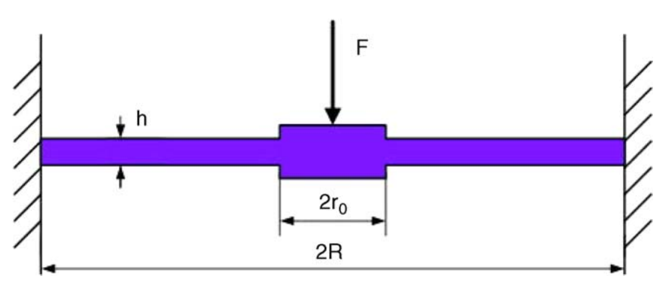

Fig. 3. Simplified analysis model of the sensing element under a concentrated load. F denotes the concentrated load, h denotes the thickness of the flat sheet, r_0 denotes the radius of the rigid centre, R denotes the radius of the flat sheet.

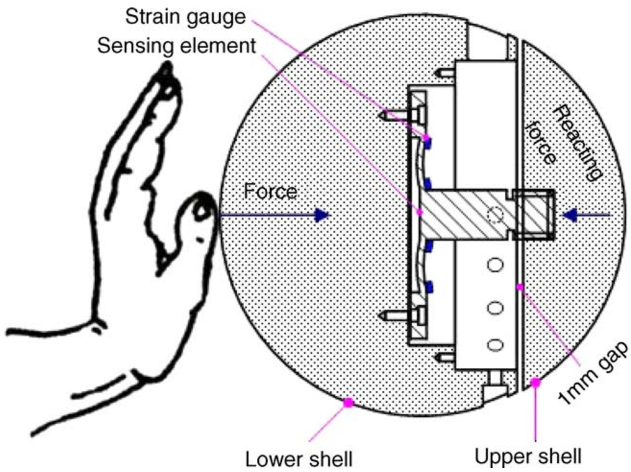

Fig. 4. Principle of force measurement.

bridges composed of the strain gauges convert the strains into raw electrical signals for the forces F_x (x-direction force), F_y (y-direction force) and F_z (z-direction force), respectively. A specially designed layout of the strain gages can assure very small couplings among those raw electrical signals.

3.2. Fabrication of sensor

Fig. 5 shows the structural model of the proposed shot-put sensor in an exploded view. Owing to very limited inner space, each part of the sensor has to be carefully designed with emphasis on size and mounting position. The overall structure has to be very firm in order to withstand the intense collision when the sensor falls onto the ground.

The upper shell is connected with the sensing element via a screw joint. The lower shell is connected with the sensing element via screw fastening. The other parts are all installed inside the shells, including data-acquisition and processing circuits, battery, mass balances, etc. The two mass balances are added into the structure in order to keep the sensor's weight at around 7.26 kg. And these mass balances can also compensate for deviation of the mass centre of the structure.

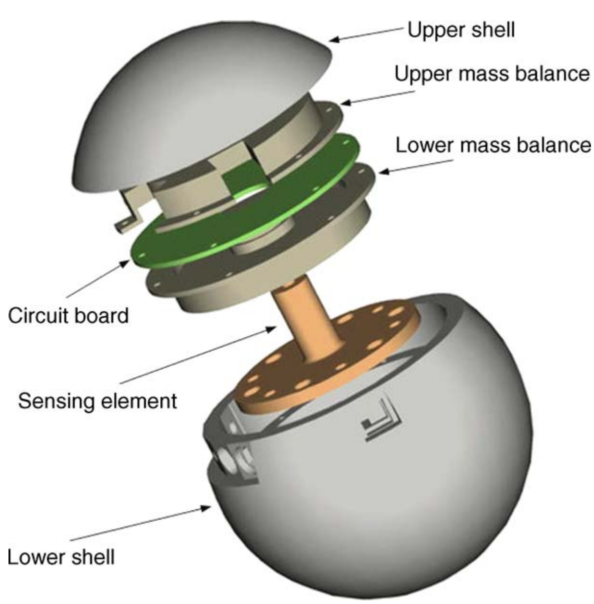

Fig. 5. Exploded view of the shot-put sensor.

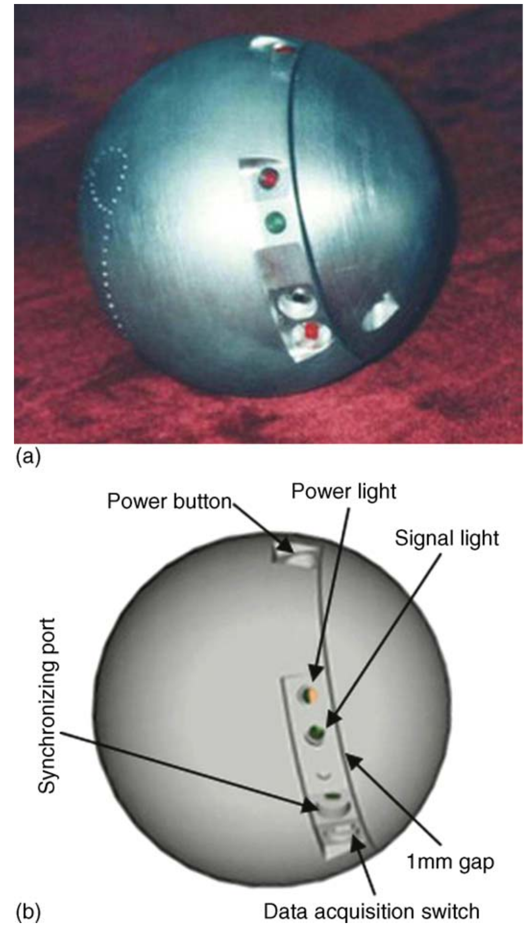

Fig. 6. Fabricated shot-put sensor: (a) prototype and (b) schematic.

Fig. 6 shows the photograph of the fabricated shot-put senor. Compared with the schematic, it is easy to identify the control buttons, ports and leds of the sensor. Fig. 7 shows the photographs of the shot-put sensor in contrast with the standard shot for open males. It can be seen that they are almost of the same shape. The Universal Serial Bus (USB) 1.1 port is used to transfer stored sensor data to PC or laptop. The hand position is marked on the surface of the lower shell for the shot-putters to locate where they should put there hands. The measuring range of each component force is 100–400 N. The measuring accuracy is 2% full scale (FS). The overload capacity can reach 200% FS.

The fabricated sensor has to be calibrated before it is brought into use by shot-putters. The calibration was performed by stepwisely increasing the external loads from 100 to 400 N. Fig. 8 shows the characteristics of the shot-put sensor for external loads. According to the practical loading situation, both F_x and F_y have two opposite directions. F_x and F_y are used to represent the negative x-direction force and the negative y-direction force, respectively. F_z only has a positive z-direction. The calibration results show that the sensor has a high sensitivity and a high linearity in each direction.

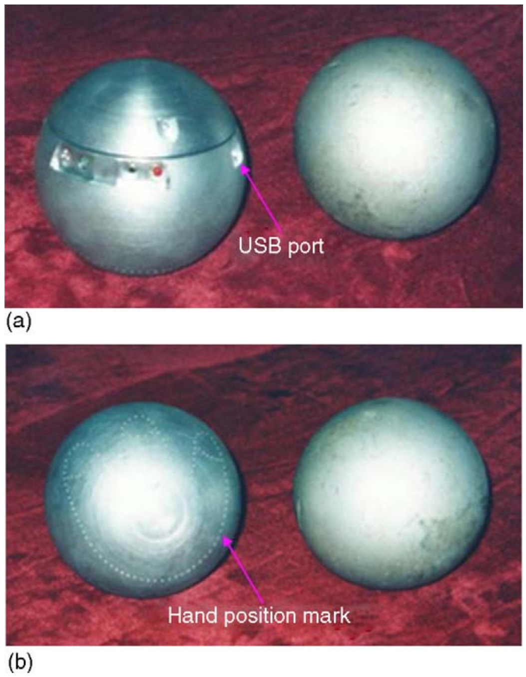

Fig. 7. Fabricated shot-put sensor in contrast with the standard shot for open males: (a) displays most buttons and ports and (b) displays the hand position mark for shot-putters.

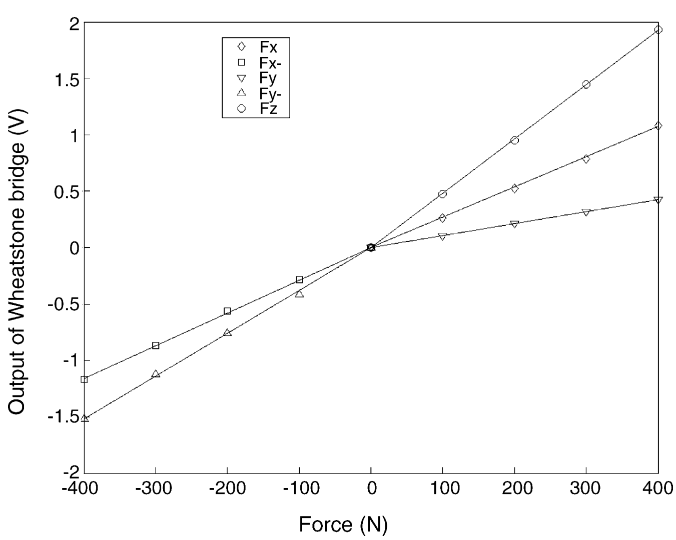

Fig. 8. Characteristics of the shot-put sensor for external loads (bridge output vs. each component force).

3.3. Data processing system

The data processing system of the shot-put sensor is shown in Fig. 9. The raw output signals of the three Wheatstone bridges are processed by the conditioning circuits before being transmitted to the 8-channel ADC AD7888. The MCU AT89C52

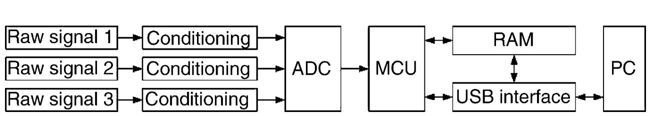

Fig. 9. Block diagram of the data processing system.

acquires the digital outputs of the ADC from 3 standalone channels, performs some calculations and stores the data into the 512 kb RAM. According to the capacity of the RAM, the sensor can continually measure up to 20 throws. Each measurement routine costs a time of 5 s, which has been proven long enough for a normal throw. During the 5 s measurement time, 512 samplings are taken. When all the measurement routines are finished or the RAM is full, the stored data can then be sent to upper PC for further processing and analysis.

4. Experimental results

There are now two throwing techniques in shot-put, i.e. the glide technique and the spin technique. The glide technique can raise the release speed by prolonging the time during which the shot moves with the shot-putter's hand. The final throwing distance can then be improved. The spin technique has evolved from the glide technique. Rotational motions are added to the thrower's body in the spin technique. Although some elite shot-put athletes have achieved good performances by using the spin technique, there is no scientific explanation for its rationality. The glide technique still remains the most popular.

The shot-put sensor was first used by the student athletes of Hebei Normal University, Shijiazhuang, China. For some practical reasons, several female shot-put athletes have been chosen to do the experiments, though the sensor was originally designed for male athletes. The glide technique was adopted by all of them to make their throws. Each camera runs at a speed of 50 fps to snap every motion of the athletes. The experiment field should be lawn or plastic cement playground and the landing area should be covered by thick sponge cushions in order to protect the sensor from fatal crashes.

Fig. 10 shows the typical experimental results of a successful throw. According to the glide technique, a complete throwing motion can be divided into four phases, i.e. the preparation phase, the glide phase, the transfer phase and the release phase. Judging from the curves, it can be seen that force changes in x-direction and y-direction are very small during the throwing process. So only F_z is chosen for the latter analysis.

In the preparation phase, F_z gradually increases owing mostly to trunk bend and knee bend. In the glide phase, F_z has no obvious changes. In the transfer phase, the athlete moves into a so called power position that is achieved when the front foot touches down and the athlete has both feet in contact with the throwing circle in preparation for the delivery of the throw. Great forces are applied on the shot-put sensor in this phase. So F_z increases rapidly and reaches its peak value at the end of the transfer phase. In the release phase, the shot-put sensor begins to leave the hand. F_z then begins to decrease until the sensor flies out. When flying in the air, the sensor has no force applied. So the curve of F_z remains a straight line. When the senor falls onto the ground, a drastic collision occurs and leads to a sharp crest on the curve of F_z.

Fig. 11 shows the experimental results of some faulted throws. In (a), there is a small straight line in the release phase. It takes too long to stretch the body and the shot-put sensor can-

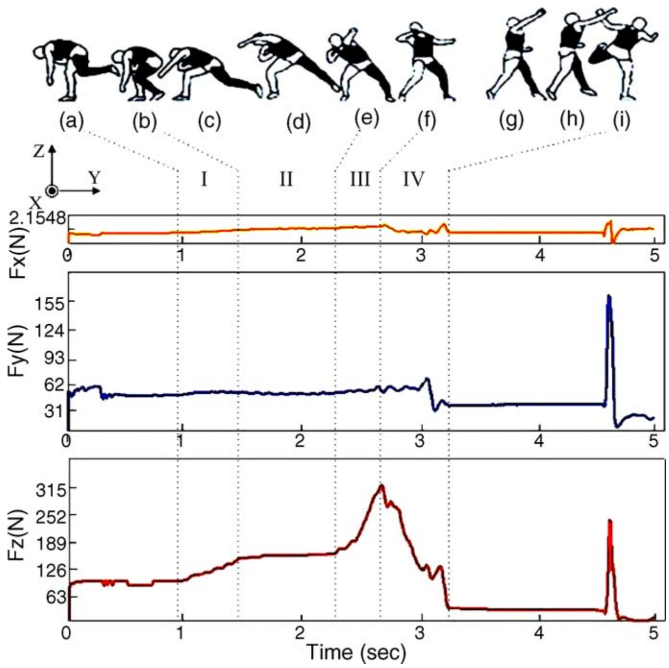

Fig. 10. Typical experimental results of a successful throw made by a professional shot-put athlete. I (a and b) is the preparation phase, II (b–e) is the glide phase, III (e and f) is the transfer phase and IV (f–i) is the release phase.

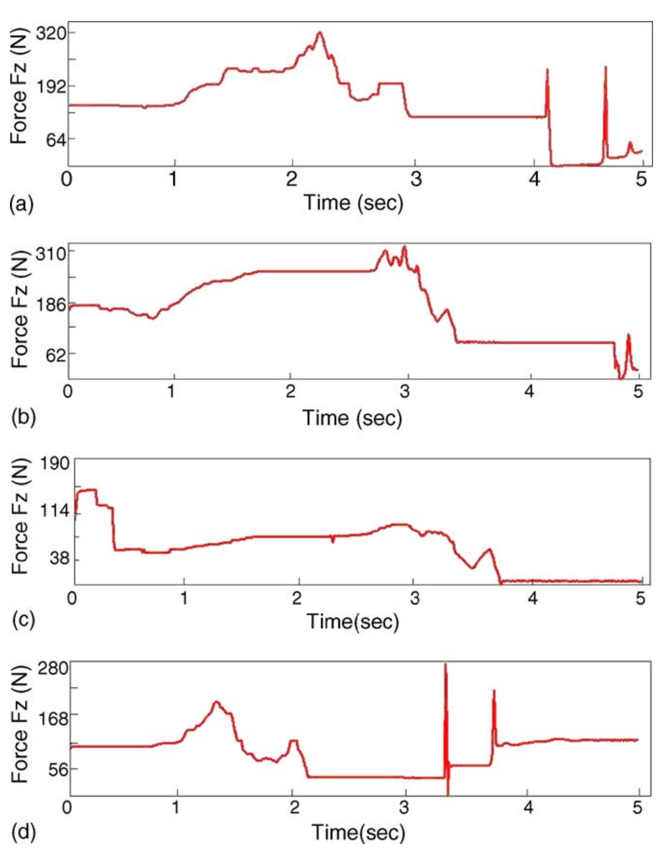

Fig. 11. Experimental results of some faulted throws (F_z only). (a) Improper motion in phase IV, (b) improper motion in phase III, (c) improper motion in all the phases and (d) throw in situ with no glide.

not get maximum release velocity. In (b), there are no obvious changes from the glide phase to the transfer phase. It indicates that the athlete failed to link the two phases smoothly. In (c), the force curve tends to be flat in all the phases, which proves that the athlete has poor break-out forces and the overall throwing motion was too slow. In (d), F_z has no changes until the transfer phase, which means that the athlete has made the throw in situ with no glide.

5. Conclusions

We have developed a novel three-axis force sensor for measuring the forces applied on shots by shot-put athletes. The shot-put sensor has almost the same size and weight as the standard shot for open males and can simultaneously detect applied forces along three orthogonal directions. The measuring range of each component force is 100–400 N. The measuring accuracy is 2% FS. The overload capacity can reach 200% FS. With the help of a commercially available high-speed photography system, field tests have been performed. The experimental results show that it is easy to distinguish between good throws and faulted throws. The shot-put sensor thus provides a new way to train shot-put athletes and to make scientific research on shot-put techniques.

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