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OPTIMIZATION OF TECHNICAL ABILITY OF SOCCER SHOOTING BASED ON PHYSICS ANALYSIS

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Shooting is an effective means of scoring in soccer games, and the variation of soccer ball flight trajectory can enhance the offense. This paper constructed a kinetic model of soccer ball flight by analyzing the force of the flying soccer ball, numerically calculated five kinds of flight trajectories using MATLAB software, and verified the validity of the kinetic model through actual tests. Finally, ten athletes were instructed by the kinetic model on the technique of fixed-point straight-line shooting for one month. The results showed that the five trajectories calculated by the kinetic model nearly coincided with the actual flight trajectories, which verified the validity of the model. The upward rotation of the soccer ball would raise the position of the highest point of the trajectory, and the downward rotation would lower the position of the highest point of the trajectory; the greater the rotation speed was, the greater the change was. After the guidance assisted by the kinetic model, the hitting rate of fixed-point straight shot significantly improved, and the stable hitting rate could be maintained at different shooting distances.

Keywords: soccer, force analysis, shot, flight trajectory

1. Introduction

As the number one ball sport globally, soccer is popular worldwide [1]. The game is highly competitive, and winning places in world-class competitions helps to increase international influence, so countries are gradually focusing on the development of soccer [2]. In the process of soccer confrontation, the ball can be scored by sending it into the opponent's goal in a non-foul way. Among different scoring methods, shooting is the most common means of scoring, especially in free kicks with few obstacles, and excellent shooting techniques can bring more advantages [3]. In soccer, except for the goalkeeper, players are not allowed to touch the ball with their hands, and they need to use their lower limbs to control the ball in most cases, which is more skillful, and the higher the skill level is, the higher the scoring rate is when shooting at goal. In daily training, players need to work on their shooting skills [4]. The traditional training mode is to conduct repetitive shooting training with the help of a coach, and players adjust their technical movements when shooting according to the coach's experienced guidance and their feeling during the training. Although it is not ineffective, it is

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less efficient in improving shooting techniques. In order to improve the shooting technique more effectively, the scientific analysis of ball flight motion is introduced in the training process, from which the factors affecting the ball flight are obtained as a guiding basis for the training of shooting technique. Nakashima et al. [5] studied the three-dimensional kinematics of batting baseballs toward the same field, center field and opposite field and estimated the effect of ball rotation on trajectory and flight distance. The results of their study showed that due to the horizontal action of Magnus force, the trajectory of batting balls in the same and opposite field is curved and the flight distance tends to be shorter than that in the center field. Hong et al. [6] measured the aerodynamic forces acting on a rotating soccer ball in a wind tunnel test. The results showed that air- and motor-type rotating balls exhibited a very strong dependence of the rotation parameter (Sp) on the drag force during rotation. Konishi et al. [7] performed Particle Image Velocimetry (PIV) on a ping-pong ball in flight to confirm whether the Magnus force becomes negative in actual flight. The results showed that the mean velocity field of the ball was asymmetric during rotation, which indicated the Magnus effect, and that the Magnus force became zero when the spin parameter was 0.65, indicating the appearance of a negative Magnus force. In this paper, the kinetic model of the soccer ball during the flight was constructed by analyzing the force of the flying soccer ball, the five flight trajectories were numerically calculated using MATLAB software, and the validity of the kinetic model was verified by actual tests. The model was used to guide the shooting technique of soccer players.

2. A kinetic model of soccer flight

In soccer, athletes generally use their lower limbs to change the motion of the soccer ball. The player shots by swinging the lower limbs to apply an external force on the soccer ball using the instep in contact with the ball [8]. Under the action of the external force, the soccer ball changes its original state of motion; when the soccer ball breaks away from the contact of the instep, the flight trajectory is approximately parabolic before it hits the ground and rebounds (if there is no another player to apply external force during the flight), but the mass and volume possessed by the soccer ball itself during its flight cannot ignore the forces other than gravity [9]. Figure 1 shows the force analysis diagram of the soccer ball during flight. The soccer ball is subjected to vertical downward gravity, vertical upward air buoyancy, air resistance along the opposite direction of velocity, and the Magnus force generated by rotation. The gravitational force on the soccer ball depends on its mass. The buoyancy force depends on the mass of air displaced by its volume. The air resistance depends on the maximum cross-sectional area of the sphere orthogonal to the direction of ball flight velocity and the fluid velocity (relative to the sphere) orthogonal to that cross-section. The

Magnus force is generated due to the rotation of the sphere in the fluid, whose magnitude is influenced by the rotation velocity and whose direction is influenced by the rotation direction.

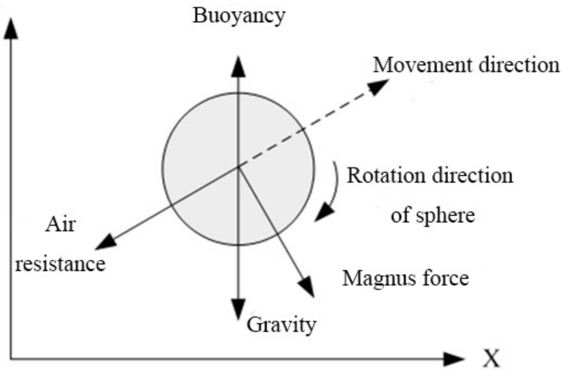

Fig. 1. Force analysis of the soccer ball during flight

After the force analysis of the soccer ball during flight, a kinetic model of the soccer ball flight was constructed according to Newton's second law [10], in which the gravitational force on the soccer ball is much greater than the buoyancy force, so the buoyancy effect was ignored for ease of calculation when the model was constructed. The model is:

$$\begin{cases} m\dfrac{d^2\mathbf{r}}{dt^2} = mg + \mathbf{F}_D + \mathbf{F}_M \\ \mathbf{F}_D = -\dfrac{1}{2}C_d \rho S v^2 \dfrac{\mathbf{v}}{v} \\ \mathbf{F}_M = \dfrac{1}{2}C_m \rho S v^2 \dfrac{\boldsymbol{\omega}\times\mathbf{v}}{|\boldsymbol{\omega}\times\mathbf{v}|} \end{cases}, \qquad (1)$$

where m is the mass of the soccer ball, which is fixed under normal circumstances, $\mathbf{r}$ is the position vector of the soccer ball in space, g is the acceleration of gravity, $\mathbf{F}_D$ is the air resistance, $\mathbf{F}_M$ is the Magnus force [11], C_d is the air resistance constant, C_m is the Magnus coefficient, S is the maximum cross-sectional area of the soccer ball, v is the magnitude of the soccer ball flight speed, $\mathbf{v}$ is the soccer ball flight speed vector, and $\boldsymbol{\omega}$ is the rotation vector of the soccer ball.

3. Example analysis

3.1 Experimental environment

The kinetic model of soccer ball flight was solved by MATLAB [12] to obtain the simulated trajectory of soccer ball flight, and trajectory was used to guide the soccer ball shooting technique. The kinetic model was solved in a laboratory server with the Windows 7 system, I7 processor and 16 G memory. The validation of the kinetic model and the guidance of the goal-scoring technique with the kinetic model were performed in an indoor soccer field.

3.2 Experimental setup

The constructed soccer flight kinetic model is a system of second-order differential equations, which cannot be solved directly to obtain analytical solutions but can be solved by using numerical analysis. The initial conditions need to be given when solving the numerical solution of the kinetic model. Although the kinetic model is not very complex, the amount of computation required is not small, and it is inefficient to rely entirely on manual computation, so the Runge-Kutta algorithm [13], which comes with the MATLAB software, was used to solve the numerical solution.

(1) Validation of the soccer flight kinetic model

The main purpose of constructing a kinetic model of the soccer ball flight was to analyze the physics of the soccer ball flight trajectory to optimize the shooting technique of the player; therefore, the soccer flight kinetic model was validated before being applied to guide players. The relevant initial conditions of the kinetic model are shown in Table 1. Five trajectories were used to verify the validity of the kinetic model. In the five trajectories, the flight environment, specifications, initial velocity magnitude, direction and starting point of the soccer ball were the same, and the only difference was the direction of rotation and the velocity magnitude of the soccer ball. The reason for setting different rotation directions and velocities is that adding rotation techniques to the soccer ball is helpful to improve the diversity of the soccer trajectory. In addition to the initial conditions mentioned above, the setting of the corresponding axes was also required. The midpoint of the goal line was taken as the origin O, the axis perpendicular to the goal line was taken as the x axis, and the direction toward the other side of the goal was regarded as the positive direction of the x axis; the goal line was taken as the y axis, and the axis that was perpendicular to the ground and passed through the origin was taken as the z axis. For the sake of discussion, the five trajectories were confined to the xOz plane; the direction of rotation of the top-spin ball was rolling in the negative direction of the x axis, and the direction of rotation of the backspin ball was rolling in the positive direction of the x axis, and the axis of rotation was parallel to the y axis. The soccer flight starting point was at (0 m, 0.1 m) in the xOz plane.

Table 1

Initial conditions for the five trajectories used for verifying the validity of the kinetic model

Track number	Flight environment	Soccer specifications	Initial speed	Initial rotation speed	Direction of rotation	Flight starting point
1	25 °C and one atmospheric pressure in the indoor soccer field	The mass of the soccer is 0.42 kg; the maximum cross-sectional area is 0.03 m^2	The velocity is $20\sqrt{2}$ m/s; the direction forms a 30° angle with the x axis	60 rad/s	Topspin	0.1 m above the ground
2				30 rad/s		
3				0 rad/s	No rotation	
4				30 rad/s	Backspin	
5				60 rad/s		

In the indoor soccer field, the soccer ball was launched using a soccer ball launcher according to the initial conditions shown in Table 1. Air resistance constant C_d was 0.4, and Magnus force C_m was 5.55. The flight trajectory of the soccer ball was recorded using a high-speed camera [14], and the actual flight trajectory was compared with the simulated trajectory. The comparative experiment of every kind of flight trajectory was conducted thrice.

(2) Optimization of players' shooting techniques with a soccer flight kinetic model

Ten athletes were randomly selected from the varsity team of Nanjing Agricultural University to verify the optimization effect of the soccer flight kinetic model on the shooting technique. The average age of the ten athletes was 18 ± 1 years old, their average height was 1.75 ± 0.01 m, and they had not suffered any trauma in the last three months. All ten athletes had some experience with soccer, but did not develop in depth, and had an understanding of basic techniques of fixed-point shots. The athletes' fixed-point straight shot technique was optimized by the soccer flight kinetic model.

① Testing before training

Firstly, the athletes were tested to shoot in a straight line at a fixed point before receiving training. A circular plate with a radius of 0.1 m was hung in the center of the goal. Then, the athlete shot in a straight line at a fixed point that was 5, 10 and 15 m away from the goal, and the angle of the kick was kept at 45° as much as possible when shooting (a small piece of tape was pasted on the surface of the soccer ball, the line between the center of the ball and the tape was in the xOz plane and formed an angle of 45° with the x axis; a small piece of tape was also pasted on the back of the shoe; the athlete made the two pieces of tape touch as much as possible when kicking the ball). The athlete shot 20 times under every distance, and the scoring rate was recorded.

② Training of straight-line shot at a fixed point

During the previous scoring rate test, strain gauges of the same size were also installed when pasting the tape to the back of the shoe [15] to record the contact time between the back of the foot and the ball and the contact force when kicking the ball.

During the training process, in addition to the regular physical training, the contact force and contact time of every athlete when kicking the ball at a fixed point under different distances in the way described in the previous section were recorded, and the average contact force and average contact time of every athlete when kicking the ball at different distances were calculated to obtain the average impulse of every athlete when kicking the ball at a fixed point under different distances. The average impulse was taken as the standard impulse of corresponding individuals during training.

Next, the initial velocity of the soccer ball flight if the player kicked the ball according to the standard impulse was calculated according to $F \cdot t = m \cdot v$ (2). Then, the flight trajectory that hit the suspended round plate at different distances was calculated by the constructed kinetic model. The actual trajectories of the soccer ball captured by the high-speed camera were compared with the calculated trajectories, and the technical shooting movements of the players were guided according to the difference to make the actual flight trajectory of the soccer ball close to the calculated trajectory as much as possible.

Individualized technical instruction was provided for every athlete at different shooting distances in the manner described above. After one month of training, the scoring rate was tested again according to the way conducted before training.

3.3 Experimental results

Due to the limitation of space, only number 3, i.e., the simulated and actual trajectories of the soccer ball flight with no rotation, are shown here, see Figure 2. It was seen from Figure 2 that the flight trajectories under the same initial conditions captured by the high-speed camera roughly overlap with the simulated trajectories at the naked eye. Table 2 shows the errors and average errors between the simulated trajectories of each trajectory and the actual trajectories of the three repeated experiments. It was seen from Figure 2 that the flight trajectories were nearly approximate to parabolic, but the trajectories were not parabolic as can be seen from the force analysis of the flying soccer ball. Based on the average error and actual trajectory in Table 2, it was confirmed that the kinetic model could effectively simulate the soccer ball flight trajectory.

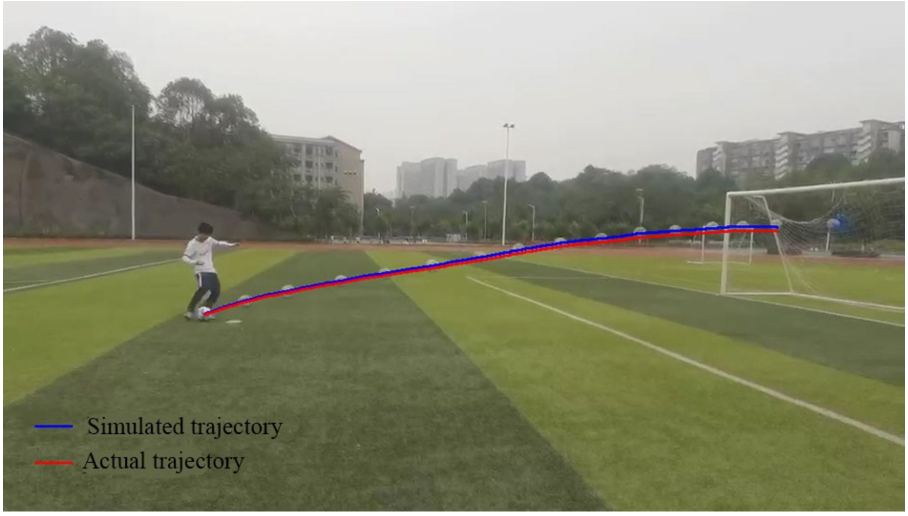

Fig. 2. A flight trajectory under the soccer flight kinetic model in the simulation experiment and the actual trajectory

Table 2

Deviation of the five trajectories calculated by the kinetic model from the actual flight trajectories

Track number	Deviation of the first actual trajectory from the simulated trajectory/%	Deviation of the second actual trajectory from the simulated trajectory/%	Deviation of the third actual trajectory from the simulated trajectory/%	Average deviation/%
1	0.78	0.87	0.76	0.80
2	0.69	0.71	0.73	0.71
3	0.76	0.75	0.76	0.76
4	0.78	0.77	0.76	0.77
5	0.75	0.78	0.79	0.77

When a soccer ball rotates during its flight, it is subjected to a Magnus force. The magnitude and direction of the Magnus force were influenced by the rotational speed and direction of the soccer ball. When the soccer ball rotated upward, the Magnus force generated an upward component force, which canceled out part of the gravity, so the highest point of the trajectory was higher, while the backward component force generated by the Magnus force reduced the horizontal speed of the soccer ball together with the air resistance, making the distance of the landing point decrease; when the soccer ball rotated downward, the Magnus force generated a downward component force, which increased the downward acceleration in the vertical direction of the soccer ball; as a result, the highest point of the trajectory was lower, and the hang time decreased, leading to the decreased horizontal distance of the flight.

To sum up, providing a spin for the soccer ball when shooting can increase the flight trajectory diversity of the ball and enhance the aggressiveness of the shot: when facing the wall, the player can provide an upward spin for the soccer ball to make it fly higher in order to cross the wall of man; when the player is close to the goal and there is no obstruction in the middle, he can provide a downward spin for the soccer ball, which not only enhances its horizontal speed but also reduces the goalkeeper's reaction time.

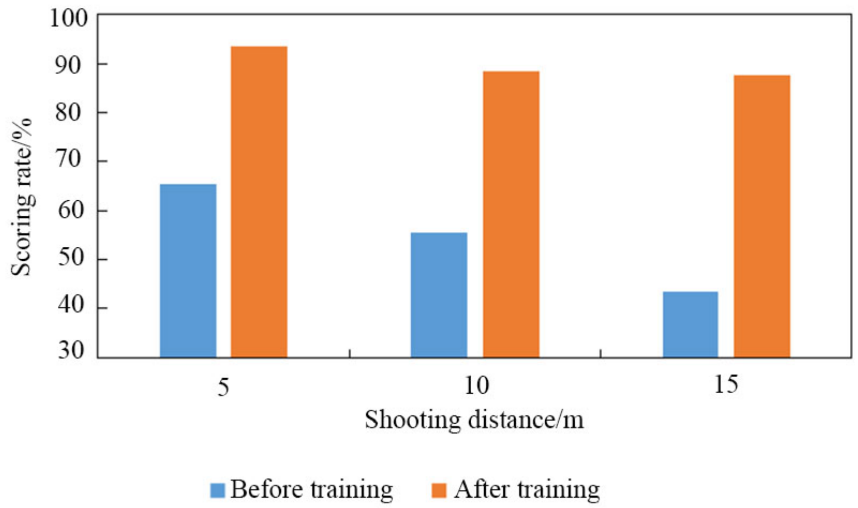

Fig. 3. Scoring rate of athletes before and after training at different shooting distances

Figure 3 shows the scoring rate of the athletes kicking the circular plate hanging in the center of the goal at different shot distances before and after receiving the instruction of the soccer flight kinetic model. When the shooting distance was 5 m, the scoring rate of the athletes before receiving training was 65.5%, and the scoring rate after training was 93.5%; when the shooting distance was 10 m, the scoring rate of the athletes before training was 55.5%, and the scoring rate after training was 88.5%; when the shooting distance was 15 m, the scoring rate of the athletes before training was 43.5%, and the scoring rate after training was 87.5%. It was seen from Figure 3 that the scoring rate of the athletes after training was significantly higher for the same shooting distance. The horizontal comparison of the scoring rate under different shooting distances showed that before receiving training, the scoring rate of the athletes decreased significantly with the increase of the shooting distance; after training, although the scoring rate of the athletes also decreased with the increase of the shooting distance, the degree of decrease was significantly smaller than before training. The above results demonstrated that guiding the shooting technique with the soccer ball flight kinetic model could not only improve the scoring rate but also keep the scoring rate stable.

4. Conclusion

In this paper, a simple force analysis was conducted on the soccer ball in flight to construct a kinetic model of the soccer ball in flight. In the experiment, five kinds of flight trajectories were numerically calculated using MATLAB software; moreover, the actual test was conducted using a ball launcher under the same initial conditions to verify the validity of the kinetic model. Then, the fixed-point straight line shooting technique of the ten athletes was guided by the kinetic model for one month. The results are as follows. The flight trajectories calculated by the kinetic model nearly overlapped with the actual trajectories under the same initial conditions, which verified the validity of the kinetic model. Rotation of the soccer ball during flight could significantly affect the flight trajectory. The highest point of the trajectory raised when the soccer ball rotated upward; the faster the rotation was, the higher the highest point was. The highest point of the trajectory was lowered when the soccer ball rotated downward; the faster the rotation was, the lower the highest point was. After the guidance assisted by the kinetic model, the scoring rate of the athletes significantly improved, and the scoring rate kept stable under different shooting distances.

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