Correlations Between Stroke Structural Characteristics and Stroke Effect of Young Table Tennis Players

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Abstract

Background: A perfect stroke is essential for winning table tennis competition. A perfect stroke is closely related to reasonable stroke structure, which directly affects the stroke effect. The main purpose of this study was to examine the correlations between the structural characteristics of stroke and the stroke effect.

Methods: Forty-two young table tennis players were randomly selected from China Table Tennis College ($M_{\text{age}} = 14.21 \pm 2.13$; $M_{\text{height}} = 1.57 \pm 0.14$ m; $M_{\text{weight}} = 46.05 \pm 6.52$ kg, right-hand racket, shake-hands grip, no injuries in each joint of the body). The high-speed infrared motion capture system was used to collect the data of stroke structural characteristics, and the high-speed camera was used to measure the spin speed of the stroke. The influence of striking structural characteristics on striking effect was examined.

Results: The time duration of backswing and forward motion were significantly correlated with ball speed ($r = -0.403, p < 0.01$; $r = -0.390, p < 0.01$, respectively) and spin speed ($r = -0.244, p = 0.027$; $r = -0.369, p < 0.01$, respectively). The linear velocity of right wrist joint was positively correlated with ball speed ($r = 0.298, p < 0.01$) and spin speed ($r = 0.238, p = 0.031$). The angular velocity of right elbow joint and right hip joint were positively correlated with ball speed ($r = 0.219, p = 0.013$; $r = 0.427, p < 0.01$, respectively) and spin speed ($r = 0.172, p = 0.048$; $r = 0.277, p = 0.012$, respectively). The angular velocity of right knee joint had a significantly negative correlation with placement ($r = -0.246, p = 0.026$). The angular velocity of right ankle joint had a significantly positive correlation with the ball speed ($r = 0.443, p < 0.01$).

Conclusions: The time allocation of the three phases of backspin forehand stroke had an important impact on stroke effect, especially the ball speed and spin speed. The ball speed of the stroke was mainly affected by the translation of the right wrist joint. The spin speed of the stroke was mainly affected by the translation of the right wrist joint. The placement of the stroke was mainly affected by the rotation of the right knee joint.

Background

Table tennis is a skill-based confrontation sports and has the characteristics of fast ball speed and fast spin speed, which requires table tennis players to master perfect techniques and tactics. The technique is the basis of tactics, and only with strong and stable techniques can flexible tactics be formed [1, 2]. The rationality of technical action is the essential basis for table tennis players to reach a high skill level and win a game. Unreasonable and unstable technical action not only affects the application of technical and tactical combination, but also increases the incidence of injuries in daily training and competition [3].

The structural characteristics of stroke refer to the changes of kinematic parameters of human body joints during a whole stroke. The kinematic parameters that describe the changes of human body posture mainly include the displacement, angle, and changes (such as linear velocity and angular velocity) of human body joints [4, 5].

The stroke structure of table tennis is the way in which each part of the stroke is made up and the order each part is combined [6]. Although different table tennis players may have different stroke structures, there is still similar law in the stroke structure [7]. A whole stroke of table tennis can be divided into three phases: backswing racket, swing forward, and restoration [7, 8]. A reasonable stroke structure plays an important role in better use of techniques and improving stroke effect of young table tennis players [6].

Young table tennis players (especially in the enlightenment stage) are in the cognition, formation, and fixation stage of technical actions, so it is particularly crucial for them to cultivate correct and stable technical actions [9, 10]. Scientific training and monitoring methods of technical actions can effectively promote players' competitive level, prevent and reduce the occurrence of sports injuries, and further improve the stroke effect of young table tennis players [11].

The five elements of table tennis technical actions are speed, spin, power, placement, and trajectory, in which the speed, spin, and placement are the keys to win a game. The control of placement and trajectory is also very important in today's table tennis competition [12]. For table tennis, the ball speed and spin speed of stroke are two dominant factors that determine the outcome of a competition, and also the two main technical parameters to describe the stroke effect [13, 14].

When striking the ball, the faster the racket movement, the faster the ball speed [15]. Increasing the rotation angle of the hip joint helped to improve the racket speed of swing [16]. At present, the D40 plus (mm) plastic ball was designated for table tennis training and completion. As the increased diameter and mass of the D40 plus plastic ball, the air resistance also increases, which reduces the ball speed and rotation accordingly. Therefore, it has a negative impact on the improvement of stroke effect [17, 18].

There was a significantly positive correlation between the ball speed and the swing speed of the end of the racket. If the racket speed was increased before striking the ball, the ball speed will also be increased after the stroke [15]. When striking the ball with forehand, the angles of many body joints changed, and the best racket speed would be achieved by using the ordered rotation of the hip joint, upper body, shoulder joint, and forearm. The angular velocity of shoulder internal rotation and shoulder adduction had a significant impact on the racket speed [19]. Without considering the rotation of the ball, the racket speed was increased with the increase of the amount of energy transferred from the shoulder joint to the forearm [20]. When striking topspin ball with backhand, the mechanical energy of the swing racket was mainly transmitted by the force and torque of the shoulder joint [4]. Therefore, when striking the ball, the mechanical energy would be transferred from the lower limbs of the body to the upper limbs by changing the angle and angular velocity of the body joints, and the swing racket speed and ball speed could be enhanced. Thus, the stroke effect could also be improved [21].

The methods used to analyze sports techniques are qualitative and quantitative, of which the quantitative method is most used. Quantitative method involves collecting and analyzing objective data. For table tennis, the data often concerns identifying the main structural characteristics of a stroke, such as position, angle, range of motion, speed, phases of the stroke, etc. This data collection can be achieved by motion capture and computer analysis of images [8].

Motion capture technology uses the principle of computer graphics to track, measure, and record the three-dimensional motion of the main joints of human body in the form of images through multiple cameras arranged in space, and has been widely used in film production, mechanical control, simulation training and teaching, human posture research, ergonomics and other fields [22, 23 24, 25, 26, 27]. High-speed motion capture system can not only capture the trajectory of a flying ball, but also calculate the ball speed, which is widely used in the monitoring of sports training [21, 28, 29].

In this study, the structure characteristics of backspin forehand stroke of young table tennis players were collected using a high-speed infrared motion capture system, and the correlations between the stroke structural characteristics and stroke effect of young table tennis players were examined combined with the stroke effect data. Thus, the factors that affect the stroke effect of young table tennis players can be analyzed, which helps to improve the rationality of stroke action structure and also improve the stroke effect of young table tennis players.

Methods

Participants

This study was approved by the ethics committee of Shanghai University of Sport. Participants were randomly selected from China Table Tennis College. The inclusion criteria included: table tennis player, 12 to 18 years of age, right-striking arm, shake-hands grip. Forty-two young table tennis players ($M_{\text{age}} = 15.21 \pm 2.13$; $M_{\text{height}} = 1.57 \pm 0.14$ m; $M_{\text{weight}} = 46.05 \pm 6.52$ kg) who met the inclusion criteria were chosen to attend this study. The average training time for them was 6.09 ± 2.63 years, and the table tennis technical grade of them has been to the same level [31]. All subjects were informed of the study procedure and provided written informed consent before the experiment.

Instruments

(1) High-speed infrared motion capture system (Qingtong Vision Technology Company, Shanghai, China) was used to collect the real-time data of body joints' spatial position and joint angle during the stroke. The sampling frequency was 120 frames per second.

(2) Radar speed detector: SPEEDSTER radar (BUSHNELL Company, the United States) was used to measure the ball speed of the stroke.

(3) High-speed camera: Miro R111 (the United States) was used to measure the spin speed of table tennis. The focal length was 70mm, the exposure time is 330 μ s, and the sampling frequency was 4500 fps.

(4) Serving machine: V-989H Serving machine was manufactured by Nittaku Company, Japan. The parameter settings used for the study were: the serving machine's upper wheel speed was set at level 3

(10 levels in total, the higher level the faster speed), the bottom wheel speed at level 7, and the service frequency was 40 balls per minute.

Experimental equipment layout

The layout of experimental equipment was shown in Fig 1.

In Figure 1, there are twelve infrared high-speed cameras arranged around the measurement area of 4x3 meters on steel consoles 4 meters above ground level, and the cameras are connected to the PC through USB hubs [25]. The speedometer allocated approximately 3½ - 4 meters away from the table tennis player (directly facing the player). The high-speed camera was set up on one side of the net, about 40cm from the sideline and 90 centimeters above ground level. The measurement setup is located at the training hall of China Table Tennis College of Shanghai University of Sport, China.

Marker placement

Before the experiment, participants were required to wear tight-fitting clothes, and 38 reflective spherical markers (diameter: 16 mm) were attached to the body surface of each participant's trunk, shoes, and all limbs, as shown in Figure 2. The marker locations included: wrist joint, elbow joint, shoulder joint, hip joint, knee joint, ankle joint, etc. The spatial position and angle of the marked body joints were recorded by an infrared camera at a frequency of 120 Hz [32].

Calibration of spatial coordinate system

During the real-time data collection of body joints' movement, the spatial coordinates of body joints were collected based on the spatial coordinate system. The spatial coordinate origin was located on the ground and the right side of the ball net, shown in Figure 3. The joint angle was described based on the human body coordinate system. In this study, the hip joint was taken as the root node of the human body, and the other joints take their parent node as their joint center.

Calculation of spin speed

Each experimental ball was marked with T-mark on its surface using a black marker. After each stroke, a series of continuous images of the ball flying over the net were captured using the high-speed camera. Then, using the computer processing software of the high-speed camera, the number of frames required for the T-mark on the surface of the ball to rotate around (360 degrees) when flying over the net was observed and calculated. Finally, the spin speed of the ball flying over the net was calculated by dividing the sampling frequency of the high-speed camera (4500 fps) by the number of frames required for the ball to rotate around. See equation (1).

$$\frac{4500}{x_2 - x_1}$$

Equation Spin speed (r) =

Note. The number of frames in the starting position of the T-mark on the ball was x_1 , and the number of frames after the T-mark rotated one turn was x_2 . The sampling frequency of the high-speed camera (4500 fps).

Corner area

During the experiment, in order to evaluate the stroke effect of players, five rectangles with a different area of 20 cm by 20 cm to 60 cm by 60 cm were drawn at the two bottom corners of the table tennis table on each side, as shown in Figure 4. The player scored 5 points if the ball placement was in the rectangle of 20 cm by 20 cm, 4 points in the rectangle of 30 cm by 30 cm, 3 points in the rectangle of 40 cm by 40 cm, 2 points in the rectangle of 50 cm by 50 cm, and 1 point in the rectangle of 60 cm by 60 cm. The size of the rectangle area represents the accuracy of players' stroke. The larger the rectangular area, the lower the accuracy and the lower the score. The higher the score, the better the stroke effect.

Outcome measures

The stroke structural characteristics of players were assessed using the position, angle, linear velocity, and angular velocity of body joints movement. The stroke effect was assessed using the ball speed, spin speed, and placement of stroke. These outcome measures were shown in Table 1.

Three-phase division of stroke

In this study, a whole stroke was divided into three phases, that is, backswing phase, forward phase (including swing racket to hit the ball and follow-through), and recovery phase.

Selection of body joint

In this study, a total of 6 joints on the right side of the body (playing side) were selected to be observed, that were: the upper limb three joints (right wrist joint, right elbow joint, and right shoulder joint) and lower limb three joints (right hip joint, right knee joint, and right ankle joint).

Experimental protocol

In this paper, the data such as the changes of spatial position and joint angle of body joints were collected during a stroke using the high-speed infrared motion capture system. The stroke ball speed, spin speed, and placement of the ball were simultaneously collected using the high-speed camera. The specific experimental protocol was shown in Figure 5.

(1) Calibration of high-speed motion capture system

Before the data collection, the calibration of high-speed motion capture system should be finished using an L-shaped ruler. The T-shaped wand was moved and rotated slowly in the three-dimensional measurement area. The T-shaped wand was also moved at the edges of the experiment site and the camera field of views in order to help the software improve lens distortion. Calibration was refined until no untracked rays were present around the measured markers using default reconstruction settings.

(2) Attachment of markers to the body surface of players

During the experiment, players were required to wear tight-fitting clothes, and 38 reflective markers were attached to the body surfaces of players.

(3) Construction of 3D mannequin

After finishing the attachment of markers, players were required to stand statically in the T-pose position (Figure 6) in the camera field of views until the completion of 3D human model construction by the motion capture software.

(4) 5 minutes' warm-up exercise

Participants were required to warm up for 5 minutes before formal data collection in order to adapt to stroke with tight-fitting motion capture clothes.

(5) Data collection

During the experiment, the serving machine served backspin ball (five balls for each player), and the young table tennis players were required to stroke the ball with forehand and repeated for five times.

Data processing

All statistical analyses were conducted by the Statistical Product and Service Solutions (SPSS 22.0, SPSS Inc.). Descriptive statistics analysis was conducted on all study variables. Pearson product-moment correlation was computed to assess the strengths of the association between stroke structural characteristic variables (spatial position and joint angle of main body joints) and stroke effect (stroke ball speed, spin speed, and placement). Statistical significance was defined at 5% ($p < 0.05$).

Results

In order to examine the stroke structural characteristics and stroke effect of young table tennis players, descriptive statistical analysis was conducted on the position and angle changes of upper and lower limb three joints as well as the changes of these variables such as linear velocity and angular velocity of body joints movement, respectively.

Stroke structural characteristics

Position changes of the upper and lower limb three joints movement

The descriptive statistical analysis results of the position changes of the upper and lower limb three joints in the three phases of backspin forehand stroke were shown in Table 2.

For each phase of the backspin forehand stroke, the position changes of the upper limb three joints movement from large to small were right wrist joint, right elbow joint, and right shoulder joint. The position changes of the right wrist joint movement in the three phases of the stroke were: 674.12 ± 128.47 mm in the backswing phase, 910.42 ± 121.30 mm in the forward phase, and 571.59 ± 118.93 mm in the backward phase (Table 2), of which the change in the forward phase was the largest, followed by the backswing phase and, finally, the backward phase.

In the backswing phase of the backspin forehand stroke, the position changes of the lower limb three joints movement from large to small were as followed: right hip joint (209.06 ± 74.65 mm), right knee joint (155.59 ± 124.40 mm), and right ankle joint (120.89 ± 115.77 mm). In the forward phase of the stroke, the position changes of the lower limb three joints movement from large to small were as followed: right knee joint (207.78 ± 104.30 mm), right hip joint (203.80 ± 80.19 mm), and right ankle joint (149.23 ± 152.00 mm). In the backward phase of the stroke, the position changes of the lower limb three joints movement from large to small were as followed: right knee joint (195.98 ± 110.13 mm), right ankle joint (175.68 ± 116.33 mm), and right hip joint (175.00 ± 107.95 mm) (Table 2).

Angle changes of the upper and lower limb three joints movement

The descriptive statistical analysis results of the angle changes of the upper and lower limb three joints in the three phases of backspin stroke with forehand were shown in Table 3.

In the backswing phase of the backspin forehand stroke, the angle changes of the upper limb three joints movement from large to small were as followed: right elbow joint ($39.64 \pm 27.34^\circ$), right wrist joint ($32.24 \pm 13.86^\circ$), and right shoulder joint ($16.29 \pm 11.01^\circ$). In the forward phase of the stroke, the angle changes of the upper limb three joints movement from large to small were as followed: right wrist joint ($34.70 \pm 15.39^\circ$), right elbow joint ($33.73 \pm 20.41^\circ$), and right shoulder joint ($23.74 \pm 15.90^\circ$). In the backward phase of the stroke, the angle changes of the upper limb three joints movement from large to small were as followed: right wrist joint ($35.08 \pm 14.25^\circ$), right elbow joint ($29.50 \pm 25.06^\circ$), and right shoulder joint ($21.79 \pm 14.61^\circ$) (Table 3).

In the backswing phase of the backspin forehand stroke, the angle changes of the lower limb three joints movement from large to small were as followed: right hip joint ($81.42 \pm 16.07^\circ$), right knee joint ($28.72 \pm 14.12^\circ$), and right ankle joint ($27.91 \pm 9.20^\circ$). In the forward phase of the stroke, the angle changes of the lower limb three joints movement from large to small were as followed: right hip joint ($126.08 \pm 20.21^\circ$), right ankle joint ($45.51 \pm 15.75^\circ$), and right knee joint ($25.22 \pm 17.35^\circ$). In the backward phase of the stroke, the angle changes of the lower limb three joints movement from large to small were

as followed: right hip joint ($50.60 \pm 19.58^\circ$), right ankle joint ($28.70 \pm 11.70^\circ$), and right knee joint ($15.53 \pm 12.48^\circ$) (Table 3).

Changes of the linear velocity of the upper and lower limb three joints movement

The descriptive statistical analysis results of the changes of the linear velocity of the upper and lower limb three joints movement in the three phases of backspin forehand stroke were shown in Table 4.

For each phase of the backspin forehand stroke, the linear velocity variation of the upper limb three joints movement from large to small was right wrist joint, right elbow joint, and right shoulder joint. The linear velocity changes of the right wrist joint movement in the three phases of the stroke were: 0.96 ± 0.46 m/s in the backswing phase, 2.40 ± 0.85 m/s in the forward phase, and 0.89 ± 0.40 m/s in the backward phase, of which the change in the forward phase was the largest (Table 4). During the three phases of the whole stroke, the linear velocity of each upper limb joint was increased at first and then decreased at the end. In the backward phase of the stroke, the linear velocity change of the right shoulder joint was the smallest, which had a positive impact on maintaining the stability of the upper body.

In the backswing phase of the backspin forehand stroke, the linear velocity changes of the lower limb three joints were in the following order: right hip joint, right knee joint, right ankle joint, and the largest change of linear velocity was 0.29 ± 0.11 m/s in the right hip joint. In the forward phase, the variation of linear speed of the lower limb three joints was in the following order: right knee joint, right hip joint, and right ankle joint. Among them, the linear speed of the right knee joint was the fastest, which was 0.53 ± 0.24 m/s, and the linear speed of the hip joint was 0.52 ± 0.18 m/s, which was close to that of the right knee joint. In the backward phase, the linear velocity variation was in the following order: right knee joint, right hip joint, and right ankle joint, of which the biggest variation was the right knee joint, which was 0.30 ± 0.18 m/s, followed by the right hip joint and right ankle joint (Table 4).

Changes of angular velocity of the upper and lower limb three joints movement

The descriptive statistical analysis results of the changes of angular velocity of the upper and lower limb three joints movement in the three phases of backspin forehand stroke were shown in Table 5.

In the backswing phase of the backspin forehand stroke, the angular velocity changes of the upper limb three joints were in the following order: right elbow joint, right wrist joint, and right shoulder joint, of which the largest change of angular velocity was the right elbow joint ($58.61 \pm 52.03^\circ/\text{s}$), followed by the right wrist joint ($45.10 \pm 36.31^\circ/\text{s}$) and the right shoulder joint ($22.68 \pm 17.90^\circ/\text{s}$). In the forward phase, the angular velocity changes of the upper limb three joints were in the following order: right wrist joint ($92.48 \pm 101.20^\circ/\text{s}$), right elbow joint ($89.11 \pm 59.83^\circ/\text{s}$), and right shoulder joint ($63.07 \pm 47.17^\circ/\text{s}$), of which the change of the right wrist joint was the largest. In the backward phase, the angular velocity changes of the upper limb three joints were in the following order: right wrist joint ($53.40 \pm 66.31^\circ/\text{s}$), right elbow joint ($46.56 \pm 42.27^\circ/\text{s}$), and right shoulder joint ($34.90 \pm 28.09^\circ/\text{s}$), of which the change of the right wrist joint was the largest (Table 5).

In the backswing phase of the backspin forehand stroke, the angular velocity changes of the lower limb three joints were in the following order: right hip joint, right ankle joint, and right knee joint, of which the largest change of angular velocity was the right hip joint ($115.41 \pm 42.00^\circ/\text{s}$), followed by the right ankle joint ($39.15 \pm 16.74^\circ/\text{s}$) and the right knee joint ($37.85 \pm 17.15^\circ/\text{s}$). In the forward phase, the angular velocity changes of the upper limb three joints were in the following order: right hip joint ($327.63 \pm 65.17^\circ/\text{s}$), right ankle joint ($120.05 \pm 47.78^\circ/\text{s}$), and right knee joint ($65.52 \pm 46.60^\circ/\text{s}$), of which the change of the right hip joint was the largest. In the backward phase, the angular velocity of the right hip joint was the largest ($76.98 \pm 33.11^\circ/\text{s}$), followed by the right ankle joint ($44.75 \pm 22.23^\circ/\text{s}$) and, finally, the right knee joint ($24.49 \pm 21.29^\circ/\text{s}$) (Table 5).

Time duration of the three phases of backspin stroke with forehand

The descriptive statistical analysis results of the time duration of the three phases of players' backspin stroke with forehand were shown in Table 6.

The time duration of the three phases of players' backspin stroke with forehand was 92.98 ± 28.10 frames in the backswing phase, 47.18 ± 8.55 frames in the forward phase, and 82.39 ± 22.84 frames in the backward phase, respectively. During the whole stroke, the backswing phase's time duration was the longest, followed by the backward phase and the forward phase, which made the body fully expanded to make a good preparation for the stroke and good preparation for the next stroke (Table 6).

Stroke effect of backspin stroke with forehand

The descriptive statistical analysis results of the stroke effect (ball speed, spin speed, and placement) of players' backspin forehand stroke were shown in Table 7.

The ball speed of players' backspin stroke with forehand was 10.34 ± 2.09 m/s, the spin speed was 106.78 ± 17.29 r/s, and the placement score was 2.93 ± 1.33 points (table 7). According to the placement score, the young players had a general ability to control the placement of backspin forehand stroke (mainly in the 40*40cm corner area).

Correlation analysis between stroke structural characteristics and stroke effect

Pearson bivariate correlations were calculated to examine the relationships between the stroke structural characteristics and stroke effect. These results were presented in Table 8.

As shown, there was a significantly negative correlation between the time duration of the backswing phase and the ball speed ($r = -0.403$, $p < 0.01$) and spin speed ($r = -0.244$, $p = 0.027$), respectively. The longer the backswing time, the closer the coming ball to the body, and the more difficult for players to return the ball, which makes the stroke effect reduced. There was a significantly negative correlation between the time duration of the forward phase and the ball speed ($r = -0.390$, $p < 0.01$), spin speed ($r = -0.369$, $p < 0.01$), and placement ($r = -0.270$, $p = 0.014$), respectively. There was also a significantly

negative correlation between the time duration of the backward phase and the ball speed ($r = -0.272$, $p = 0.013$).

The linear velocity of right wrist joint was positively correlated with ball speed ($r = 0.298$, $p < 0.01$) and spin speed ($r = 0.238$, $p = 0.031$), and had no significant correlation with the placement of the stroke ($r = -0.022$, $p = 0.847$). As the final power transfer point of the upper body when striking the ball, the linear speed of the right wrist joint has a positive impact on the ball speed and spin speed of the stroke. The linear speed of the right elbow joint was positively correlated with the spin speed of the stroke ($r = 0.227$, $p = 0.040$), and had no significant correlation with the ball speed ($r = 0.212$, $p = 0.056$) and placement of the stroke ($r = -0.096$, $p = 0.392$). The linear speed of the right shoulder joint and right hip joint had no significant correlations with the ball speed, spin speed, and placement of the stroke (all $p > 0.05$), respectively. The linear speed of the right knee joint had a significantly negative correlation with the spin speed of the stroke ($r = -0.255$, $p = 0.021$), and had no significant correlation with the ball speed ($r = -0.124$, $p = 0.268$) and placement of the stroke ($r = 0.082$, $p = 0.462$). The linear velocity of right ankle joint had no significant correlation with the placement ($r = -0.019$, $p = 0.869$), but had a significantly negative correlation with the ball speed ($r = -0.369$, $p < 0.01$) and spin speed ($r = -0.430$, $p < 0.01$), respectively.

The angular velocity of right elbow joint had a significantly positive correlation with the ball speed of the stroke ($r = 0.219$, $p = 0.013$) and spin speed ($r = 0.172$, $p = 0.048$), and had no significant correlation with the placement ($r = -0.018$, $p = 0.870$). The angular velocity of the right wrist joint and right shoulder joint had no significant correlation with the ball speed, spin speed, and placement of the stroke (all $p > 0.05$), respectively. The angular velocity of the right hip joint had no significant correlation with the placement of the stroke ($r = 0.175$, $p = 0.115$), however, it had a significantly positive correlation with the ball speed ($r = 0.427$, $p < 0.01$) and spin speed ($r = 0.277$, $p = 0.012$), respectively. The angular velocity of the right knee joint had a significantly negative correlation with the placement of the stroke ($r = -0.246$, $p = 0.026$), and had no significant correlation with the ball speed ($r = -0.197$, $p = 0.077$) and spin speed ($r = -0.150$, $p = 0.177$), respectively. The angular velocity of the right ankle joint had a significantly positive correlation with the ball speed of the stroke ($r = 0.443$, $p < 0.01$), and had no significant correlation with the spin speed ($r = 0.217$, $p = 0.050$) and placement ($r = 0.102$, $p = 0.360$), respectively.

Discussion

The technique of backspin forehand stroke was taken as an example in this study. The data of stroke structural characteristics and stroke effect during the backspin forehand stroke were collected, and the correlations between the stroke structural characteristics and stroke effect were explored. The results showed that the stroke effect was affected by the different contributions of the upper and lower limb three joints movement.

As the end of the power transfer segment of the upper body, the faster the wrist joint moves, the faster the racket swings, which leads to faster ball speed when swinging the racket to hit the ball. Thus, the linear

speed of the wrist joint movement has an obviously positive influence on the ball speed of backspin forehand stroke [32].

During the forward phase of the stroke, the angle of the elbow joint changes from large to small, thus driving the movement of the wrist joint. Therefore, the larger the angular velocity of the elbow joint, the faster the wrist joint moves, which means a larger linear speed of the wrist joint and a faster stroke of the ball. The linear speed of the wrist joint movement has a positive correlation with the ball speed, so the angular velocity of the elbow joint was positively correlated with the ball speed of the stroke.

The hip joint is the central part connecting the upper and lower limbs. The rotation of the hip joint can increase the strength of turning the waist, thus increase the striking power and improve the rotation speed and ball speed [16, 17, 33]. Therefore, the angular velocity of the hip joint had a significantly positive effect on the ball speed and spin speed of the stroke.

The movements of the knee joint and ankle joint are the two main lower limb joints that regulate the center of gravity of the human body. In order to achieve a better stroke effect, players should keep their body center of gravity as stable as possible. The unstable body center of gravity will lead to an uncomfortable striking point and thus a decline in striking effect.

The translation of the ankle joint is mainly to adjust the body's center of gravity in the horizontal direction. The faster the linear speed of ankle joint, the more unstable of the body center of gravity, which leads to poor stroke effect. Thus, the linear speed of ankle joint was negatively correlated with the ball speed and spin speed of the stroke. The rotation of knee joint is mainly to change the body's center of gravity in the vertical direction. The larger the angular velocity of knee joint, the greater fluctuation of the body center of gravity, which leads to poor control of the hitting point and ball placement. Thus, the angular velocity of the knee joint is negatively correlated with the stroke effect.

A perfect table tennis stroke requires players not only to strike the ball quickly, but also to distribute the time of each phase of the stroke reasonably. The more reasonable the distribution of each phase's time duration of the stroke, the better the stroke effect. If the time duration of the backswing is too long, the spin speed and ball speed will be reduced. The longer the backswing time, the closer the coming ball to the body, and the closer the hitting point to the body, which leads to a shorter distance for players to swing the racket to hit the ball, and results in limited striking power and reduced stroke effect [16].

The forward phase is the most important stage during the whole stroke. The longer the forward phase's duration is, the slower the wrist joint moves, which leads to a slower swing of the racket. The slower swing of the racket results in a decrease of the spin speed and ball speed, and unstable control of the placement of the stroke, thus affecting the stroke effect. For the recovery phase, the longer the recovery time, the less time to prepare for striking the next ball, which also results in a decrease of stroke effect.

Conclusions

This study investigated the relationships between the stroke structural characteristics and stroke effect of young table tennis players. The results demonstrated that the time allocation of the three phases of the stroke, especially the backswing phase and forward phase, had an important impact on the stroke effect, especially on the ball speed and spin speed. During the process of striking the ball, the movements of different joints had varying degrees of influence on the stroke effect. The elbow joint, wrist joint, knee joint, ankle joint, and hip joint had a significant influence on the stroke effect. The rotation of the elbow joint drives the translation of the wrist joint, so the angular velocity of the elbow joint is significantly correlated with the speed of swing racket and also the ball speed of the stroke. As the central part of connecting the upper and lower limbs, the rotation of the hip joint contributes to racket acceleration and upper body rotation to performing shots. Thus, the angular velocity of the hip joint has a positive impact on stroke effect. The movements of the knee joint and ankle joint are to adjust the fluctuation of the body center of gravity, thus, the motion of the knee joint and ankle joint is essential for the selection of the best hitting point.

According to the above analysis, the ball speed of the stroke was mainly affected by the following structural characteristics: the time allocation of the three phases of the stroke, the translation of the wrist joint and ankle joint, the rotation of elbow joint, hip joint, and ankle joint, etc. The spin speed of the stroke was mainly affected by the following structural characteristics: the time allocation of the three phases of the stroke, the translation of the wrist joint, knee joint, and ankle joint, the rotation of the hip joint, etc. The placement of the stroke was mainly affected by the time duration of the forward phase of the stroke and the rotation of the knee joint.

Implication

During the daily training of young table tennis players, more attention should be paid to the following aspects in order to improve the stroke effect of backspin forehand drive. Firstly, strengthen the training of hip joint rotation and the control of the transformation of the body's center of gravity in order to improve the coordination of the upper and lower limbs in the process of hitting the ball. Moreover, the body center of gravity should not fluctuate too much during the stroke in order to improve the stability of the stroke. Secondly, strengthen the training of the flexion movement of the elbow joint in the forward phase of striking so as to improve the movement speed of the wrist joint. Thirdly, improve the rationality of time allocation in the three phases of the stroke, and try to shorten the forward time duration under the premise of full friction between the racket and the ball in order to improve the ball speed and rotation velocity of the stroke.

Limitations

In this study, only six body joints (on the playing side), such as the shoulder joint, elbow joint, wrist joint, hip joint, knee joint, and ankle joint, were selected to describe the structural characteristics of the stroke. In the future study, more human body joints can be selected to illustrate the structural characteristics of hitting, thus the influence of the structural characteristics of young table tennis players' striking action on

the stroke effect of young table tennis players can be comprehensively analyzed. Besides, there may be some differences in the stroke structural characteristics of young table tennis players between males and females. In this study, the participants were not classified by gender. The differences of stroke structural characteristics between males and females and their influence on stroke effect can be explored in the future study. Moreover, only kinematics-related indicators were selected for the description of the structural characteristics of striking. The dynamics-related indexes can be selected for a more in-depth and comprehensive analysis of the structural characteristics of striking in the follow-up research. Finally, this study takes the technique of backspin forehand stroke as an example. Therefore, the findings of this study cannot be generalized to other techniques of stroke.

Abbreviations

Not applicable.

Declarations

Ethics approval and consent to participate

Ethical approval for this study was obtained from the ethics committee at Shanghai University of Sport. All participants signed the written consent forms before they joined the study and written consent forms were also obtained from a parent or guardian for participants under 16 years old. All participants were provided a full explanation regarding the purpose and potential benefits/risks of the study, confidentiality, and their right to withdraw from the study.

- **Consent for publication**

Not applicable.

- **Availability of data and materials**

The datasets generated during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

- **Competing interests**

The authors declare that they have no competing interests.

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- **Authors' contributions**

All authors (YX, YJX, MML, and YXZ) contributed to the conception of the study, drafting and critical revision of the manuscript, and provided final approval of the manuscript.

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Tables

Table 1. Outcome measures of a stroke

Primary index	Secondary index
stroke structural characteristics	position of body joints
	angle of body joints
	linear velocity of body joints movement
	angular velocity of body joints
stroke effect	ball speed
	spin speed
	placement

Table 2. Position changes of the upper and lower limb three joints movement in the three phases of backspin stroke with forehand (mm)

Body joints		backswing-phase (M±SD, N=42)	forward-phase (M±SD, N=42)	backward-phase (M±SD, N=42)
Upper limb three joints	Right shoulder joint	311.07±75.82	339.11±67.29	173.22±64.27
	Right elbow joint	470.87±110.43	738.88±86.10	540.57±134.41
	Right wrist joint	674.12±128.47	910.42±121.30	571.59±118.93
Lower limb three joints	Right hip joint	209.06±74.65	203.80±80.19	175.00±107.95
	Right knee joint	155.59±124.40	207.78±104.30	195.98±110.13
	Right ankle joint	120.89±115.77	149.23±152.00	175.68±116.33

Table 3. Angle changes of the upper and lower limb three joints movement (in degrees) in the three phases of backspin stroke with forehand

Body joints		backswing-phase (M±SD, N=42)	forward-phase (M±SD, N=42)	backward-phase (M±SD, N=42)
Upper limb three joints	Right shoulder joint	16.29±11.01	23.74±15.90	21.79±14.61
	Right elbow joint	39.64±27.34	33.73±20.41	29.50±25.06
	Right wrist joint	32.24±23.86	34.70±35.39	35.08±44.25
Lower limb three joints	Right hip joint	81.42±16.07	126.08±20.21	50.60±19.58
	Right knee joint	28.72±14.12	25.22±17.35	15.53±12.48
	Right ankle joint	27.91±9.20	45.51±15.75	28.70±11.70

Table 4. Changes of linear velocity of the upper and lower limb three joints movement in the three phases of backspin stroke with forehand (m/s)

Body joints		backswing-phase (M±SD, N=42)	forward-phase (M±SD, N=42)	backward-phase (M±SD, N=42)
Upper limb three joints	Right shoulder joint	0.43±0.29	0.90±0.52	0.26±0.17
	Right elbow joint	0.66±0.34	1.94±0.61	0.83±0.36
	Right wrist joint	0.96±0.46	2.40±0.85	0.89±0.40
Lower limb three joints	Right hip joint	0.29±0.11	0.52±0.18	0.27±0.17
	Right knee joint	0.20±0.14	0.53±0.24	0.30±0.18
	Right ankle joint	0.16±0.15	0.37±0.33	0.26±0.20

Table 5. Changes of angular velocity of the upper and lower limb three joints movement in the three phases of backspin stroke with forehand (degree/s)

Body joints		backswing-phase (M±SD, N=42)	forward-phase (M±SD, N=42)	backward-phase (M±SD, N=42)
Upper limb three joints	Right shoulder joint	22.68±17.90	63.07±47.17	34.90±28.09
	Right elbow joint	58.61±52.03	89.11±59.83	46.56±42.27
	Right wrist joint	45.10±36.31	92.48±101.20	53.40±66.31
Lower limb three joints	Right hip joint	115.41±42.00	327.63±65.17	76.98±33.11
	Right knee joint	37.85±17.15	65.52±46.60	24.49±21.29
	Right ankle joint	39.15±16.74	120.05±47.78	44.75±22.23

Table 6. The duration of the three phases of backspin stroke with forehand (unit: frame)

Three phases	Duration (M±SD, N=42)
backswing-phase	92.98±28.10
forward-phase	47.18±8.55
backward-phase	82.39±22.84

Note. The sampling frequency of the high-speed infrared motion capture system was 120 frames per second.

Table 7. Stroke effect of backspin stroke with forehand (N=42)

Stroke effect	M±SD
Ball speed	10.34±2.09 (m/s)
Spin speed	106.78±17.29 (r/s)
Placement	2.93±1.33 (points)

Table 8. Correlation analysis between the stroke structural characteristics and stroke effect

Variables		Ball speed	Spin speed	Placement
Duration	backswing-phase	-0.403**	-0.244*	-0.117
	forward-phase	-0.390**	-0.369**	-0.270*
	backward-phase	-0.272*	-0.116	-0.013
Linear velocity	Right wrist joint	0.298**	0.238*	-0.022
	Right elbow joint	0.212	0.227*	-0.096
	Right shoulder joint	0.134	0.118	-0.087
	Right hip joint	-0.140	-0.116	-0.212
	Right knee joint	-0.124	-0.255*	0.082
	Right ankle joint	-0.369**	-0.430**	-0.019
Angular velocity	Right wrist joint	0.130	0.102	-0.018
	Right elbow joint	0.219*	0.172*	0.125
	Right shoulder joint	0.076	-0.003	-0.002
	Right hip joint	0.427**	0.277*	0.175
	Right knee joint	-0.197	-0.150	-0.246*
	Right ankle joint	0.443**	0.217	0.102

Note. ** $p < .01$; * $p < .05$.

Figures

Figure 1

Experimental equipment layout

Figure 2

Marker placement on the player's body

Figure 3

Calibration of spatial coordinate system

Figure 4

Regional map of bottom corners

Figure 5

Experimental protocol

Figure 6

T-pose position