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A Study of Key Technical Factors of Volleyball Spike Based on the Biomechanical Analysis

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Abstract: In the technical actions for volleyball, spike is the most important technical means to win scores. Based on the previous studies, this study gives an analysis of spike skill, combined with the principles of biomechanics and kinematics. The results of the study show that the number of the optimum run-up steps is 3 and at the time the run-up velocity can reach 4 m sec^{-1}; the reasonable technical action for the arm swing spike is to bend the elbow before swinging the arm in order to reduce the moment of inertia; through the study, this study finds out the key to spike skill and aims at finding a more scientific and rational training method for the athletes to improve spike skill.

Key words: Volleyball spike, biomechanics, kinematics, theorem of momentum

INTRODUCTION

Volleyball is loved by the majority of the Olympic audience because of intense competition for scores, wonderful smash skill and perfect teamwork. In Olympic Games, volleyball athletes from different countries keep up their spirit, brave and battlewise and hope that they can fight for a glory for themselves and their countries. How to master skills through training to win over opponents are the key to win the game while spike skill is the key to volleyball skills. When confronting the opponent face to face, the athletes find out each other's weak points and make a fast, resolute, accurate and hard-drive spike. In volleyball game, spike skill is the most important part of completing the tactical offense and the defense and second pass in the game are preparing for the spike. Spike not only enables to win the scores but also boosts morale, attracts the audience and brings the game to a climax with its exciting action. Every world strong team must have its excellent spikers (Cui, 2013).

Spike skill is of complex structure. According to the summary and analysis of some scholars, we know that spike skill is divided into obverse hard-drive sipke, adjustment spike and fastball spike. Every spike mode has its own unique technique essentials and the three spike modes also have something in common. Some scholars have made a lot of research reports on the study of spike skill (Gu, 2013). Jia (2004) presented his programmed teaching method. From the perspective of biomechanics, Peng (1997), based on the study of spike skill and the analysis of technical parameters of the athletes, points out that take-off includes one-foot take-off and two-feet take-off, the velocity of one-foot take-off is faster than that of two-feet take-off and the two-feet take-off in "stride style" takes less time than that in "step touch style" at a higher height. Frontcourt spike is different from backcourt spike because backcourt spike shows a larger range of motion.

With the advancement of science and technology and the studies based on unremitting efforts of the predecessors, volleyball skill has been greatly improved. How to master skills through training to defeat the opponent is the goal every athlete and sports team to pursue by making unremitting efforts. Based on the previous studies, this study, from the perspective of biomechanics, studies the technical essentials of spike and aims at providing a more scientific and effective training method for the athletes to improve their technical level.

BIOMECHANICAL ELEMENTS OF VOLLEYBALL SPIKE

Volleyball spike mainly includes three aspects, run-up, take-off and air arm-swing stroke, as shown in Fig. 1.

In Fig. 1, represents the run-up stage, represent the take-off stage and represents arm-swing stroke stage.

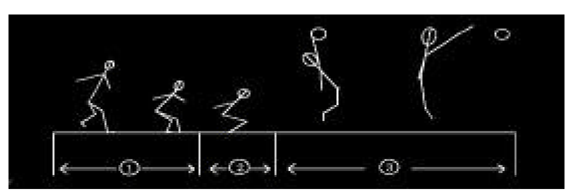

Fig. 1: Staged actions of volleyball spike

Run-up is designed to enable the athletes to quickly reach a suitable spot for attack and get a certain velocity so that the body can jump to a higher height. In the game, the athletes should be fully aware of their motion parameters, namely, the relation between the number of run-up steps or the size of steps and horizontal velocity at the moment of take-off and then achieve the required take-off height with the scientific take-off method (Zhang, 2013).

In the take-off process, the parts of the body muscles generate force at the same time and the forces generated by each part of the muscle vary in size and contributions in a very complicated situation. This study simplifies the force generation situation of human body muscle, divide the muscles of the human body in the take-off process into three parts: mainly the hip joint muscles, knee joint muscles and ankle joint muscles. The force size of the three parts is closely related to the bending angles off three joints. Through biomechanical analysis, this study finds out the most coordinated take-off mode to maximize muscle strength.

In the arm-swing stroke process, the human body is in flight stage and only subjected to the action of gravity which belongs to the vertically upward projectile motion. At the time of flight stroke, upper limb actions belong to whipping actions. According to the moment of momentum theorem and conservation law of moment of momentum, a technical analysis and guidance can be made for spike actions to provide more reasonable training modes.

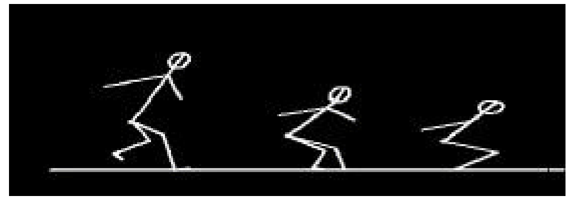

Fig. 2: Squat prior to take-off at the end of run- up

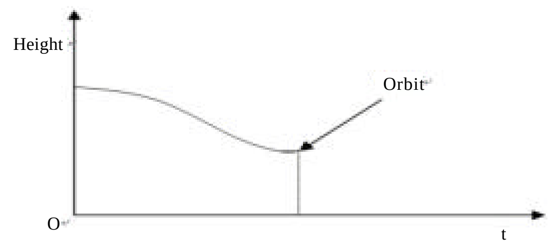

Fig. 3: Barycentre trajectory

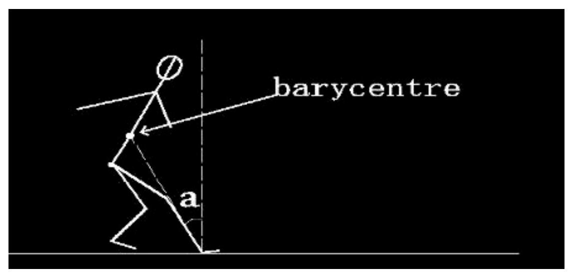

Fig. 4: Schematic figure for caster angle

BIOMECHANICAL ANALYSIS OF VOLLEYBALL SPIKE

Biomechanical analysis of run-up skill: Run-up skill of volleyball spike aims to make the athletes vertically take off to a higher height, but in the run-up process only the forward velocity can be generated and the upward force and velocity can not be generated. Therefore, how to make the forward velocity serve the vertically upward take-off is the key issue of run-up purpose and skill. We all know that there is a squat stage before the take-off stage, namely, the final stage of run-up as shown in Fig. 2.

In this process, the barycentre gradually lowers down and its movement trajectory is shown in Fig. 3.

According to Fig. 3, the barycentre is actually doing an oblique downward movement. At the moment of take-off after squat, in order to achieve the purpose of the vertical take-off, horizontal velocity of the barycentre should be zero. Therefore, it requires a counter-force in the horizontal direction in the process of squatting to decrease the velocity of the barycentre to zero. The counter-force in the horizontal direction can only be provided by the thigh. If a vertical squat is made, the thigh can not provide a counter-force in the horizontal direction, so the squat process requires a caster angle α (the definition of caster angle α: The included angle between the link line from the barycentre of human body to his arch and the vertical direction) as shown in Fig.4.

In Fig. 4, α represents the included angle between the link line from the barycentre of human body to his arch and the vertical direction).

In the course of squatting, the caster angle gradually reduces to zero and the maximum horizontal velocity of the barycentre gradually reduces to zero so as to achieve the purpose of the vertical take-off. According to the above analysis, we know that the higher the velocity of run-up is not really corresponding to the higher the height of vertical take-off, because it is also involved with the issue of the size of caster angle. For volleyball athletes, when the run-up velocity is 4 m sec^{-1} with proper caster angle, the athletes can jump to the highest height. When

Table 1: Relation between the number of run-up steps and the average run-up velocity

No. of run-up steps	1	2	3
Average run-up velocity	2.5 m sec^{-1}	3.5 m sec^{-1}	4 m sec^{-1}

the run-up velocity is more than 4 m sec^{-1}, the legs can not provide enough force to make horizontal velocity reduce to zero, so the athletes can not take off vertically and the take-off height is unstable. Therefore, the most reasonable vertical run-up velocity for take-off of the volleyball athletes is 4 m sec^{-1}.

To get a reasonable run-up velocity requires a reasonable number of run-up steps. Through the surveys on the biological parameters of volleyball athletes, we can know the relation between the run-up velocity and the number of run-up steps as shown in Table 1.

Therefore, if the volleyball athletes want to make a vertical take-off to the highest height, they should make a three-step run-up to achieve the run-up velocity up to 4 m sec^{-1} and generate a reasonable caster angle before take-off according to the run-up velocity. In the ordinary training process, the athletes should pay attention to coordinating the relation between the run-up velocity and the caster angle. Meanwhile, they should pay attention to the relation between the number of run-up steps and the run-up velocity to improve the run-up skill.

Biomechanical analysis of take-off force generation process: After take-off, the human body is only subjected to the action of gravity which belongs the vertically upward projectile motion, so the law of motion of the human body is in accordance with the following equation:

$$H = V_0 t + \frac{1}{2} at^2 \quad (1)$$

$$V_t = V_0 + at \quad (2)$$

Combined with the known characteristics of volleyball games, we know that in Eq. 2, 3, a = g (g is acceleration of gravity) and $V_t = 0$, V_0 is the initial velocity generated from the vertically upward projectile motion. Therefore, according to the Eq. 1 and 2 to deduce the equation:

$$H = \frac{V_0^2}{2g} \quad (3)$$

That is the relation expression between take-off height and the initial velocity at the moment of take-off. Equation 3 shows that only to improve the initial take-off velocity can achieve the higher height of take-off.

At the moment of take-off, the action time is very short, so conservation of momentum is achieved. The following equation can be derived from the conservation law of momentum:

$$\int_0^{t_0} F d_t = mv \quad (4)$$

According to Newton's third law, the action of forces is mutual and the force acting on the ground is equal to the force acting on the human body. Newton's third law and the Eq. 4 show that: The upward velocity V_0 generated by the human body is related to F the force of the ground acting on the human body and the action time t. The action time t in the take-off process is very short and it is instantaneous time beyond control. Therefore, in the training process, the athletes should pay attention to increasing the force F to maximize:

$$\int_0^{t_0} F d_t$$

so as to maximize V_0.

In the take-off process, the size of the force is involved with the force generation of different parts of the body muscles at the same time and the forces generated by each part of the muscle vary in size and contributions in a very complicated situation. This study simplifies the force generation situation of human body muscle, divide the muscles of the human body in the take-off process into three parts: mainly the hip joint muscles, knee joint muscles and ankle joint muscles. The force size of the three parts is closely related to the bending angles off three joints, hereinafter referred to as the hip angle, knee angle and ankle angle, namely $\angle A$, $\angle B$, $\angle C$ as shown in Fig. 5. Only when the three angles achieve the maximal force simultaneously and intercoordination, the muscles of the whole body can exert the maximal force.

The study shows that the relation between the size of the three angles and their force generation situation is shown in Fig. 6.

Figure 6 shows the condition that can make the muscles exert the maximal force is the hip angle is 90~100°, knee angle 110~120°, ankle angle 85~95°. Therefore, in the training process, the athletes should try to keep the three angles generally within the three ranges and increase coordination degree combined with their body conditions so as to achieve a higher height for take-off, a higher hitting point and more perfect spike skill.

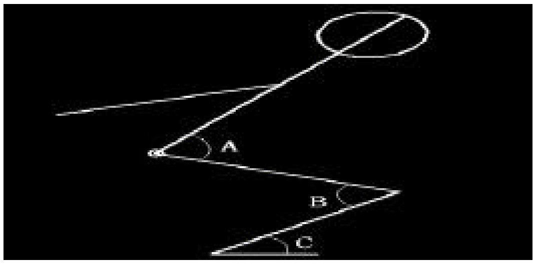

Fig. 5: Schematic figure of three joint angles

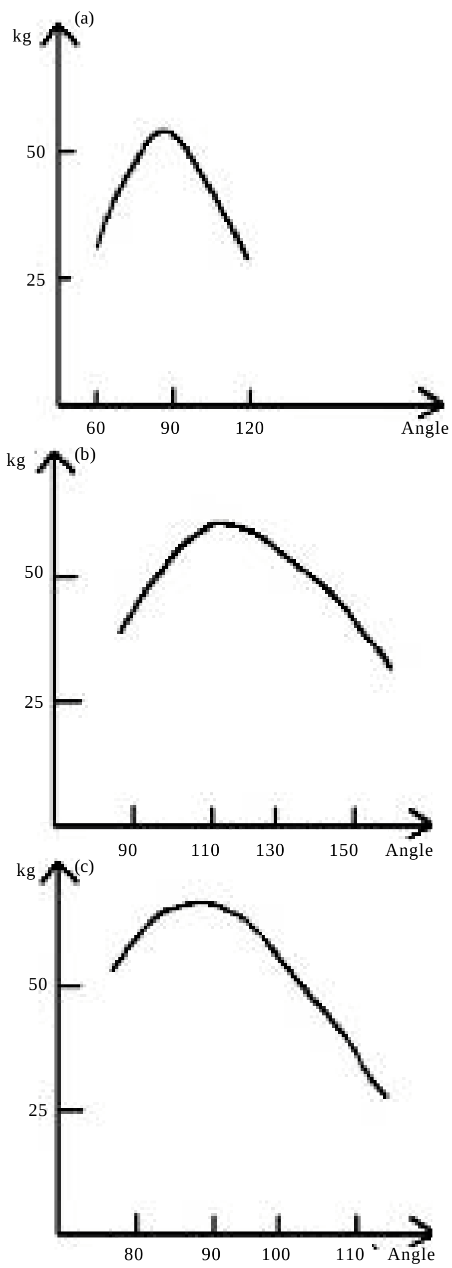

Fig. 6(a-c): From left to right the angles concerned in turn are hip angle, knee angle and ankle angle

Biomechanical analysis of arm-swing spike: In the process of arm-swing stroke, the upper limb belongs to whipping movement while the whole body is in flight stage. This study focuses on analyzing the spike skill during flight stage with the moment of momentum theorem and the conservation law of moment of momentum.

Moment of momentum theorem: If the moment of inertia of a rigid body on its axis is M, the constant torque is I, constant angular acceleration is α, angular velocity of t_0 moment is w_0 and angular velocity of t_1 moment is w_1, then:

$$M = I\alpha = I\frac{w_1 - w_0}{t_1 - t_0} \quad (5)$$

We can get from equation derivation:

$$M(t_1-t_0) = Iw_1-Iw_0 \quad (6)$$

In Eq. 6 $M(t_1-t_0)$ represents impulse moment, Iw represents moment of momentum.Then the moment of momentum theorem is-the variation of rigid body's moment of momentum equals the impulse moment acting on the rigid body.

In volleyball games, human body's moment of inertia is variational in the stroke process because the human body is different from the rigid body. I_0 represents the moment of inertia of the human body on centroid axis before spike and I_1 represents the moment of inertia of human body on centroid axis after spike. The spike time is Δt and then Eq. 4 can be transformed to:

$$M\Delta t = I_1w_1= I_0w_0 \quad (7)$$

We can make technical guidance to arm-swing stroke according to Eq. 7.

The application of moment of momentum theorem in spike skill:

- From the law of rotation, we can know that if the athletes want to obtain a faster angular velocity, they need to increase the muscle torque and there are two ways of increasing the muscle torque: one is to increase muscle arm, but it's impossible to increase the upper limb for human body, so this way is beyond the scope of consideration; the other way is to increase the muscle contraction force. The upper limb is in whipping motion during the flight stroke stage and the joints momentum accumulate from shoulder to hand gradually in order to make the hand achieve maximum velocity and force so as to acquire the maximum stroke force. It's worth noting that non-spiking arm must coordinate with the spiking arm, making forward swing action in order to reduce the moment of inertia of non-spiking arm on rotation axis so as to increase the strength of spiking arm. From the above analysis, we can know that the athletes should pay attention to coordination training of the upper body strength and shape so as to maximize the overall force effect.

- When the muscle torque is constant, if we want to increase the velocity of rotation angle, according to the equation $M(t_1-t_0) = Iw_1-Iw_0$, we know that we should reduce the moment of inertia of upper limb on rotation axis first. Therefore, the reasonable technical action for the arm swing stroke is to bend the elbow before swinging the arm in order to reduce the moment of inertia. The athletes swing the arms as they stretch the elbows, slowly lengthen the radius of rotation, straighten the upper arms at the moment of stroke to make the hand achieve the maximum velocity and make the spike more forceful

Conservation law of moment of momentum and its application in spike skill: When the torque of the resultant external force acting on rigid body is zero, the moment of momentum remains the same-that is the conservation law of moment of momentum. In arm-swing stroke process, the human body is in flight state and only subjected to the action of gravity while gravity extension cord cuts through the centroid, so there is no torque and the moment of momentum of the human body in flight stage remains the same, namely Iw = Constant vector, no matter how complex the human body's technique postures are, the conservation of both size and orientation of total moment of momentum is achieved.

For volleyball games, the moment of momentum in flight stage equals that at the moment of take-off. Therefore, at the moment of the arm-swing stroke, the upper limb is at the moment of increasing moment of momentum. In order to keep $\sum M\Delta t$ unchanged, according to Newton's third law, the athletes need to make waist, abdomen and lower limbs generate force at the same time and make opposite movement with the upper limbs. And the larger the moment of momentum generated under rotation axis, the larger the opposite moment of momentum generated by the upper limbs in order to achieve the effect of forceful stroke. Therefore, at the moment of am-swing stroke, the upper limb, waist and abdomen and lower limb should form an anti-radian, as shown in Fig. 7a.

At the moment of stroke, the upper limb and lower limb rotate around the rotation axis quickly and form a radian, (as shown in Fig. 7b) so that, the upper limb can achieve the effect of generating the maximum moment of momentum to give a more forceful stroke. According to the above analysis, we can know that the athletes should pay attention to the degree relation between anti-radian and radian and find the optimum degree of anti-radian and radian that suit them in order to give a forceful stroke.

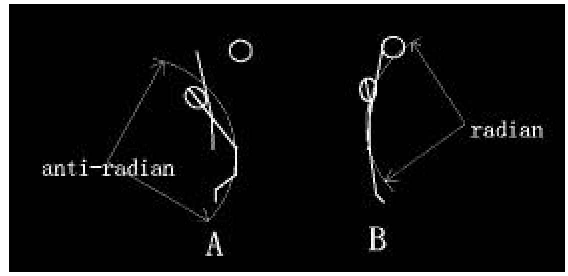

Fig. 7: Flight arm-swing stroke stage

CONCLUSION

Based on the analysis of the run-up process, this study shows the relation between the number of run-up steps and the run-up velocity and proves that the number of the optimum run-up steps is 3 and at the time the run-up velocity can reach 4 m sec^{-1}; the analysis of the take-off process shows that the take-off process is a process that the ground passes force to the human body and needs the whole body muscle to participate jointly and only the better coordination between each part of the muscles can maximize the force and help the human body achieve maximum take-off height; the study also studies the flight arm-swing stroke stage from the perspective of biomechanics, gives an analysis of the technical essentials in the flight arm-swing stroke stage combined with the moment of momentum theorem and the conservation law of moment of momentum and proves that the athletes should pay attention to coordination training of the upper body strength and shape so as to maximize the overall force effect; based on the biomechanics knowledge and the moment of momentum theorem, the study gives an analysis of upper limb movement in the process of arm–swing stroke and points out the reasonable technical action for the arm swing stroke is to bend the elbow before swinging the arm in order to reduce the moment of inertia. The athletes swing the arms as they stretch the elbows, slowly lengthen the radius of rotation, straighten the upper arms at the moment of stroke to make the hand achieve the maximum velocity and make the stroke more forceful; the study points out the technical essentials for the lower limb movement in the process of arm-swing stroke based on the conservation law of moment of momentum: it requires the waist, abdomen and lower limbs to generate force with the upper limbs at the same time to form a radian so that the upper limbs can generate greater force.

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