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Numerical simulation of javelin best throwing angle based on biomechanical model

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ABSTRACT

This paper uses the motion aerodynamics principle to analyze the javelin flight process, integrates related factors with athletic performance in the study of the force condition and movement condition of the human body and the javelin, numerically simulates the different angles of fixed parameters by Mathematic software, obtains the theoretical optimum throwing angle 40°, that is when the shot angle is 40° and the angle of the javelin's long axis with the horizontal surface is 31° the throwing distance reaches the greatest. The results are very consistent with the actual situation; this article can make reasonable suggestions for the promotion of this project's athletic performance, provides a theoretical basis for the javelin sports technique, and confirms the reasonableness of existing theory and technique.

KEYWORDS

Biomechanics;
Aerodynamics;
Throw angle;
Mathematic numerical simulation.

INTRODUCTION

In the javelin movement, moving trajectory and moving results of javelin are primarily reflections of a set of human movement. Using the biomechanical principles can reasonably prove the maturity of the technique and correct errors of technique. When the javelin releases from the hand it suffers the gravity and air resistance. Due to its shape and mass, it determines that the air resistance of the javelin during movement in the air cannot be ignored, so when we study the moving trajectory of javelin after disposing the aerodynamics principle is a good theoretical tool. Only by combining the kinetic characteristics and moving trajectory of the javelin after disposing can we determine the best shot angle and speed combination of javelin. Therefore, using sport biomechanics and aerodynamics principle to conduct objective analysis of the javelin throwing movement has an actively promoting effect on the development of sports technology.

Javelin throwing process includes: run-up, final force and javelin releasing flight three phases, where the run-up phase takes the longest time, and this stage provides the best posture for throwing and at this foundation stage the role of initial kinetic energy is related to achievements; final stage is also used to provide the initial kinetic energy for the javelin flight, but its effect is far better than the run-up phase, this stage also provides the throwing angle of javelin flying, which is critical stage related to athletic performance; During flight javelin receives air resistance and gravity, although the results do not have a subjective relation, but it provides result reference for the research of validity and rationality of first two phases.

In this paper, through biomechanics theory and the aerodynamics theory, it conducts a detailed analysis for the three stages of javelin throwing movement, confirms the reasonableness of the existing technique of this movement combing with the analysis results, and provides rationalization proposals for the scientific training.

SPORTS MECHANICAL ANALYSIS OF LAST FORCE TECHNIQUE (TAKE THE RIGHT HAND THROWING FOR EXAMPLE)

The final stage of javelin throwing technology starts from the right foot, through series of actions delivering by the legs, hips, torso, shoulder, elbow, and hand, and finally throw out the javelin. The duration time of the final stage is about 0.12s-0.15s, which is very short from the time interval. But force sequence and speed change of all aspects of the body are consistent with the biomechanics whipping principles. In the braking process it has shown a very large instantaneous impulse, makes the javelin have greater instantaneous momentum, thus it can have a high initial kinetic energy.

In the throwing arm whipping process, when the hand, forearm and upper arm are in the same line, the three links do not exist the relative rotation, but have the same angular velocity relative to the shoulder axis, as shown in Figure 1.

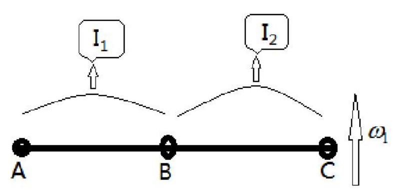

Figure 1 : The simple schematic when the arm is in straight line

In Figure 1 Point A represents the shoulder joint, point B represents the elbow joint, point C represents the wrist joint, I_1, I_2 respectively mean the moment of inertia of upper arm and forearm, ω_1 means the angular velocity of the arm rotates straightly around the shoulder joint. But in the throwing process, forearm and upper arm has the relative rotation. We suppose the forearm rotates around the elbow point B, where point B is equivalent to the braking point, as shown in Figure 2.

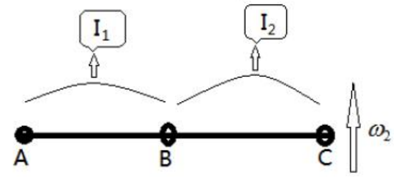

Figure 2 : Schematic of the forearm rotates relatively around the elbow joint

The rotation moment of momentum of the forearm relatively around Point B is as formula (1):

$$\mathbf{M = I_2\beta} \qquad (1)$$

In Formula (1) *M* represents the torque generated in the forearm muscle contraction, β represents the angular acceleration of the forearm around point B.

According to the definition of angular acceleration the angular momentum theorem can be obtained as formula (2) below:

$$\boldsymbol{\beta = \frac{\omega_2 - \omega_1}{\Delta t} \Rightarrow M\Delta t = I_2(\omega_2 - \omega_1)} \qquad (2)$$

In Formula (2) Δt shows the action time of forearm muscles torque *M*; by the formula (2) the expression of angular velocity ω_2 can be obtained as formula (3):

$$\boldsymbol{\omega_2 = \omega_1 + \frac{M\Delta t}{I_2}} \qquad (3)$$

The formula (3) shows that the angular velocity of the forearm is increasing on the basis of ω_1 in the process whipping of throwing arm, and the increased value is $\frac{\mathbf{M\Delta t}}{\mathbf{I_2}}$.

When the rotation angle of forearm around point B is very small, according to the relationship of angular and linear velocity, we have the expressions in formula (4):

$$\left.\begin{aligned} \mathbf{v_1} &= \boldsymbol{\omega_1}\mathbf{r_1} \\ \mathbf{v_2} &= \boldsymbol{\omega_2}\mathbf{r_2} \\ \mathbf{v} &= \mathbf{v_1 + v_2} \end{aligned}\right\} \Rightarrow \mathbf{v} = \boldsymbol{\omega_1}\mathbf{r} + \boldsymbol{\omega_2}\mathbf{r_2} \qquad (4)$$

In Formula (4) v represents the linear velocity of the point C in wrist relatively to the shoulder joint, v_1 represents the linear velocity of the point B in elbow joint relatively to the shoulder joint, v_2 represents the linear velocity of the point C in wrist relatively to the elbow joint, and r_1, r_2 respectively represents the length of the upper arm and forearm.

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Substitute the formula (2) and (3) into the formula (4) formula (5) can be obtained:

$$\mathbf{v} = \boldsymbol{\omega}_1(\mathbf{r}_1 + \mathbf{r}_2) + \frac{\mathbf{r}_2 \mathbf{M} \Delta \mathbf{t}}{\mathbf{I}_2} \qquad \textbf{(5)}$$

According to formula (5), when forearm whips, the line speed of the wrist increases by $\frac{\mathbf{r}_2\mathbf{M}\Delta\mathbf{t}}{\mathbf{I}_2}$ comparing with no whipping.

In the final force stage, the body's center of gravity speed is constantly declining; human kinetic energy is also reducing. The direction of the braking by the left leg landing and the inertia by the throwing arm on the javelin in the acceleration process is opposite to the acceleration direction of the javelin. So the body's speed is declining, if in the last throwing process of throwing arm, throwing objects, the stronger the force of inertia of the throwing matter is, the much thorough that momentum transfer of the body on the javelin is.

AERODYNAMIC ANALYSIS

After disposing in addition to its own gravitational force Javelin also suffers air resistance. Studying the movement condition of javelin releasing can reflect the relationship between movement characteristics and athletic performance when releasing the Javelin, and it is the entry point to study the movement's throwing technique problem of non-forces influencing factors, so it is necessary to study the movement of the javelin after disposing.

For any one kind of javelin it has its fixed shape and quality. We can use the polynomial fitting way to dispose each measurement point, and get the physical characteristics parameters of the javelin. This paper takes the javelin for adult males as the research object, uses the previous 4 order polynomial function as a model base below. The javelin physics parameters in TABLE 1 can be obtained.

TABLE 1 : Javelin physics parameter table for adult male

Parameter name	Physical magnitude
Total mass of Javelin	811.5g
Distance from the gun breech to the centroid	1585mm
Distance from centroid to gun head	1055mm
Surface area of Javelin	2.098×105mm2
The maximum projected area of javelin	6.352×104mm2
The rotational moment of inertia around its own shaft (the axis perpendicular to the javelin direction)	0.4563×109g*mm2
The rotational moment of inertia around its own shaft (the axis along the javelin direction)	0.1379×106g*mm2
The rotational moment of inertia around its own shaft (another axis perpendicular to the javelin direction)	0.4563×109g*mm2

The initial kinetic parameters when releasing javelin include: the shot height of javelin centroid is h_0, the shot velocity of centroid is v_0, the angle of javelin centroid shot velocity with the horizontal surface is θ_0, the angle of javelin with the horizontal plane is α_0, the pitch angular velocity when releasing the javelin is ω_0, the angle of the projection of the javelin long axis in the *xoy* surface and the projection of the javelin centroid velocity in the *xoy* surface is γ_0 generally known as the yaw angle, the releasing moment of the javelin is in the spatial coordinate system as shown in Figure 3:

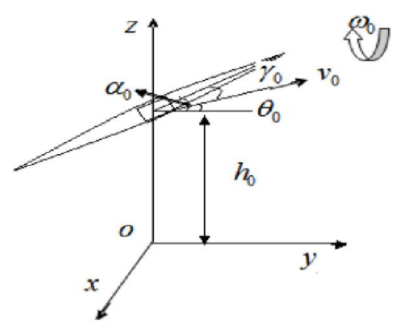

Figure 3 : The initial state of javelin releasing instant in the coordinate system

Javelin suffers gravity vertically downward and resistance generated by air during movement in the air. Air resistance is divided into frictional resistance, pressure drag and the induced drag. The friction resistance is relevant with the air viscosity coefficient, and the expression of the friction resistance is in formula (6):

$$\mathbf{F}_f = \iint_{S_f} \frac{1}{2} \boldsymbol{\rho} \mathbf{C}_f \mathbf{v}_\tau^2 \mathbf{dS} \qquad \textbf{(6)}$$

In Formula (6), F_f means the friction of air on the javelin, ρ means the air density, C_f means the viscosity coefficient of air, S_f means the surface area of the javelin, and v_τ indicates the relative parallel velocity of javelin centroid to the gas.

The expression of the pressure drag is as the formula (7):

$$\mathbf{F_p} = \iint_{S_p} \frac{1}{2}\rho \mathbf{C_p v_{//}^2 dS} \tag{7}$$

In Formula (7) $v_\perp$ means the relative vertical velocity of javelin centroid to the gas, and S_p means the projected area of the javelin.

Javelin also receives induced drag during the flight. The air resistance acts on the javelin, decompose the resistance in a direction relatively parallel to air flow and relatively perpendicular to air flow. Since in the javelin flight the air joint force that it receives does not necessarily act on the javelin centroid, it will produce torsional moment on the javelin. The javelin movement can be seen as the plane motion in *yoz*; according to the synergistic effect of the rotation law of rigid body and the projectile movement of the objects, the resultant moment equations in the *y* axial direction and *z* axial direction can be obtained, as shown in formula (8):

$$\begin{cases} \mathbf{F_{py}} = -\mathbf{sin}(\gamma) \times \int_{-l_1}^{l_0} \frac{1}{2}\rho \mathbf{C_p v^2 sin^2}\gamma\, \mathbf{sin}\,\alpha \mathbf{f}(\xi)\mathbf{d}\xi \\ \mathbf{F_{fy}} = -\int_{-l_1}^{l_0} \frac{\pi}{2}\rho \mathbf{C_f v^2 cos^2}\gamma\, \mathbf{cos}\,\alpha \mathbf{f}(\xi)\mathbf{d}\xi \\ \mathbf{F_{pz}} = -\mathbf{sin}(\gamma) \times \int_{-l_1}^{l_0} \frac{1}{2}\rho \mathbf{C_p v^2 sin^2}\gamma\, \mathbf{cos}\,\alpha \mathbf{f}(\xi)\mathbf{d}\xi \\ \mathbf{F_{fz}} = -\int_{-l_1}^{l_0} \frac{\pi}{2}\rho \mathbf{C_f v^2 cos^2}\gamma\, \mathbf{sin}\,\alpha \mathbf{f}(\xi)\mathbf{d}\xi \\ \mathbf{M} = \mathbf{sin}(\gamma) \times \int_{-l_1}^{l_0} \frac{1}{2}\rho \mathbf{C_p v^2 sin^2}\gamma \mathbf{f}(\xi)\mathbf{d}\xi \end{cases} \tag{8}$$

The formula (8) shows that the air resistance will generate rotation torque on the javelin, and the gravity goes the Javelin center of gravity, so the gravity will not generate rotating torque and the movement of the two forces can be superimposed. The numerical simulation results indicate that when the pitch angular velocity is zero, for the average athlete the range of best shot angle is between [38°, 44°], if the pitch angular velocity is not zero, we should appropriately increase the shot angle. When the initial attack angle is 0, the throwing distance of javelin is the farthest; the smaller the air viscosity coefficient is, the better throwing distance is.

INITIAL PARAMETERS AND THROWING DISTANCE NUMERICAL SIMULATION WHEN JAVELIN RELEASES AWAY FROM THE HAND

Based on the above force condition of javelin after disposing, conduct numerical simulation for formula (6) (7) (8), we can obtain the throwing distance of the javelin with different initial parameters. TABLE 2 shows the centroid speed of the javelin when shot, the angle of the velocity and the horizontal direction, the angle of javelin long axis and the horizontal surface and the initial yaw angle. In order to explore the problem of shot angle, this paper selects the shot speed 26m/s that athletes generally can reach in major match, the yaw angle is 0°, the air viscosity coefficient is 0.003, pressure drag coefficient is 1.2, the air density is 1.18 * 10-5g/mm3, it uses Mathematic software to conduct numerical simulation for javelin throwing distance, the simulation results are in TABLE 2.

TABLE 2 : The combination comparison table of computer simulation results

Shot angle θ_0	The angle α_0 of Javelin long axis and the horizontal plane	Throwing distance (m)
30°	15°	62.6
30°	18°	63.4
30°	21°	64.4
30°	24°	65.3
30°	27°	65.8
30°	30°	66.0
30°	33°	65.9
30°	36°	65.9
30°	39°	65.8
30°	42°	65.6
30°	45°	65.0

The change trend of throwing distance with α_0 when θ_0 is 30° is shown in Figure 4:

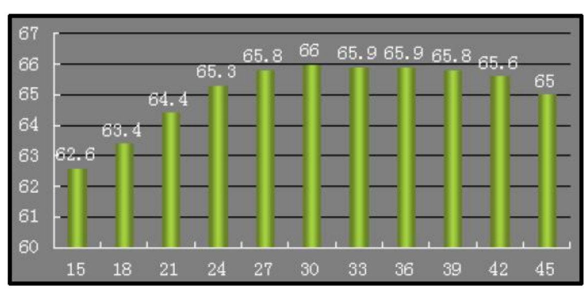

Figure 4 : The comparison chart of throwing distance and α_0 when θ_0 = 30°

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Because there are too much data, it is shown in the form of bar graph also the final result, respectively θ_0 = 32°, 34°, 36°, 38°, 40°, 42°; the corresponding α_0 is shown in Figure 5 - Figure 10.

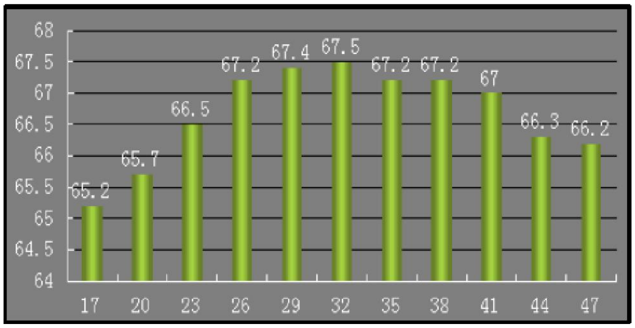

Figure 5 : The comparison chart of throwing distance and α_0 when θ_0 = 32º

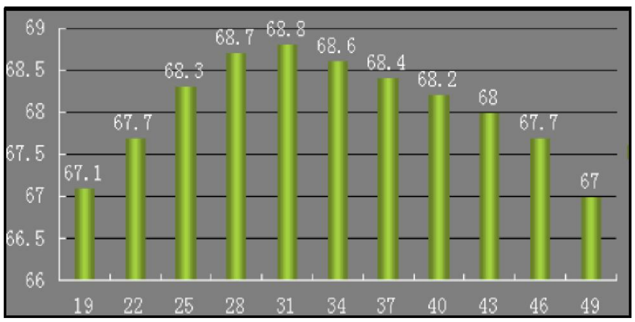

Figure 6 : The comparison chart of throwing distance and α_0 when θ_0 = 34°

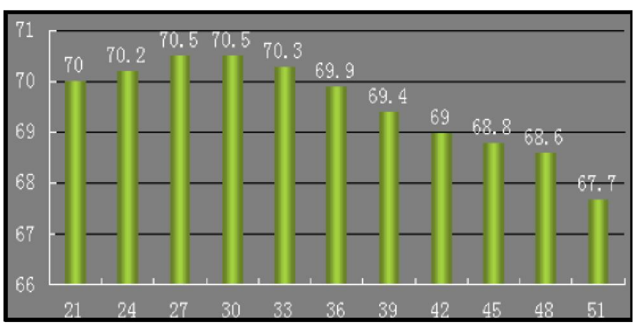

Figure 7 : The comparison chart of throwing distance and α_0 when θ_0 = 36°

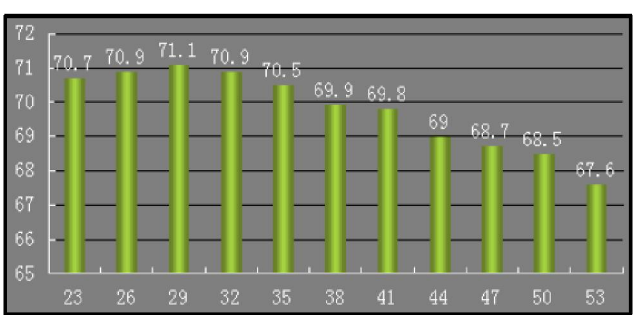

Figure 8 : The comparison chart of throwing distance and α_0 when θ_0 = 38°

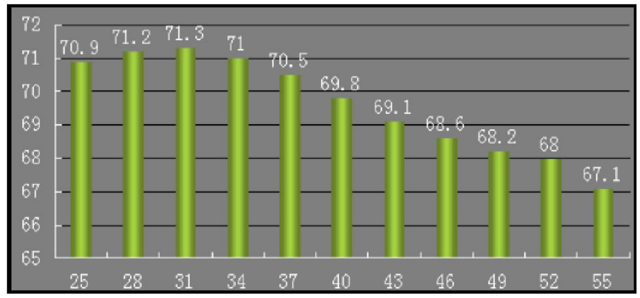

Figure 9 : The comparison chart of throwing distance and α_0 when θ_0 = 40°

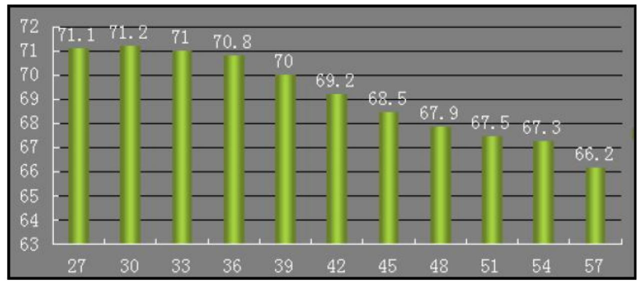

Figure 10 : The comparison chart of throwing distance and α_0 when θ_0 = 42°

Figure 4 - Figure 10 shows the following results:

1) When θ_0 = 30° and α_0 = 30° the maximum throwing distance is 66.0m;
2) When θ_0 = 32° and α_0 = 32° the maximum throwing distance is 67.5m;
3) When θ_0 = 34° and α_0 = 31° the maximum throwing distance is 68.8m;
4) When θ_0 = 36° and α_0 = 27° or 30° the maximum throwing distance is 70.5m;
5) When θ_0 = 38° and α_0 = 29° the maximum throwing distance is 71.1m;
6) When θ_0 = 40° and α_0 = 31° the maximum throwing distance is 71.3m;
7) When θ_0 = 42° and α_0 = 30° the maximum throwing distance is 71.2m;

According to the simulation results, when θ_0 = 40° and α_0 = 31° we have the maximum throwing distance, and then with the assumed parameters, this combination is the best throwing angle.

CONCLUSIONS

This paper uses sports biomechanics and aerodynamics to well explain javelin movement, and propose the best throwing angle and precautions of throwing; obtains optimal throwing angle combination by numerical simulation. Aerodynamics is the theoretical basis to study the javelin movement after releasing it, which well explains the air resistance of the javelin; in the satisfied condition air resistance has a rotational torque role on the javelin, so that during the flight it can generate rotation; The numerical simulation results show that when the shot angle $\theta_0 = 40°$ and the angle $\alpha_0 = 31°$ of the javelin with the ground the throwing distance is the greatest, and this combination is the best throwing angle.

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