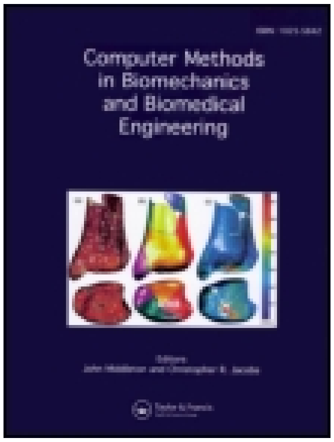

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Analysis of wind velocity and release angle effects on discus throw using computational fluid dynamics

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The aim of this paper is to study the aerodynamics of discus throw. A comparison of numerical and experimental performance of discus throw with and without rotation was carried out using the analysis of lift and drag coefficients. Initial velocity corresponding to variation angle of around 35.5° was simulated. Boundary condition, on the top and bottom boundary edges of computational domain, was imposed in order to eliminate external influences on the discus; a wind resistance was calculated for the velocity values of 25 and 27 m/s. The results indicate that the flight distance (D) was strongly affected by the drag coefficient, the initial velocity, the release angle and the direction of wind velocity. It was observed that these variables change as a function of discus rotation. In this study, results indicate a good agreement of D between experimental values and numerical results.

Keywords: discus throw; computational fluid dynamics; aerodynamics; numerical analysis; turbulent model

1. Introduction

Discus throw is a popular event in track and field athletics competition, in which an athlete throws a heavy disc – called a discus – in an attempt to mark a farther distance than his/her competitors. From the perspective of biomechanics, discus throw phenomenon can be divided into two phases: the release phase (taking into consideration speed, height and angle as main parameters) and the flight phase (which includes angle of attack, wind speed and wind direction as main parameters). Release parameters are essentially kinematic factors and flight parameters are aerodynamic factors, both directly bearing on the range of discus throw (Ganslen 1964; Berger et al. 1995; Hubbard and Cheng 2007).

During the release phase, when the initial speed (the magnitude of the release velocity) and height are optimal, there is an increase in range (Maronski 1991). The release speed is basically proportional to the square of the initial speed (Hubbard and Cheng 2007), thus the most important factor affecting the range (Bartlett 1992). The release height is the distance between discus centre of mass (CM) and the ground at the moment of release. Increase in the height of release keeps the discus in air for a longer time, resulting in increase of the range (Soong 1976). An increase of 1 m in release height would increase the range to about 2 m (Frohlich 1981), but elite discus throwers maintain variations of few degrees in competitions (Knicker 1997). The release angle is the angle between discus CM and the ground (angle of the trajectory). Also, for a relative release height higher than zero, the release angle must be lower than 45°. And studies on elite athletes demonstrate that the optimum angle is close to 35° (Bartlett 1992). Several biomechanical researchers in the past had used simple statistical methods to understand and predict the discus range (Hay and Yu 1995). Nevertheless, the linear statistical regression indicates that only release speed made a significant contribution in predicting the range of the discus throw (Teraudus 1978; Gregor et al. 1985; McCoy et al. 1985; Yu et al. 2002; Dinu et al. 2004). The reasons for this significant contribution for release speed from statistics point of view depend upon small variations in release height and nonlinear relationship between angle and range (Bartlett 1999). The study of three release parameters, excluding interaction between them, limits the full prediction of the discus range with good precision. There is also a significant interplay between kinematic components and flight parameters in representing a complex discus throw phenomena.

The flight phase is an airborne phase, involving factors like gravitational and aerodynamic forces, which are beyond the direct control of athlete after the point of release. The contribution of aerodynamic effects on discus flight and range is very important, but previous studies did not consider in detail the contribution of aerodynamic effects during discus flight, instead concentrated mainly on optimum release conditions. Assuming that rotational speed of discus gives enough angular stability, the most important variables that influence aerodynamic forces

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during discus flight are (a) the angle of attack, consisting of the angle between discus central plane and relative wind flow direction (Hay 1978), (b) the wind speed that blows forward or against the discus throw and (c) the relative velocity (V_{rel}), which depends upon discus speed (V_d) and wind velocity (V_w; Frohlich 1981).

The numeric simulations have become a key tool influencing industrial design and a fundamental method in the study of general biomechanics and sports. A similar approach is equally applicable in general biomechanics and sport biomechanics applications through the incorporation of design variables, which may be easily varied in the experimental model (Sueyoshi and Maruyama 1992).

In this study, three objectives are established: the first is to carry out comparative studies using lift and drag coefficients obtained through computational fluid dynamics (CFD) simulation and experiment; the second objective is to solve the aerodynamic equations known by equation of motion of the discus throw and the third objective is to study the introduction of rotation movement of the discus on its performance.

2. Methods

2.1 Definitions of basic variables

During the flight phase, discus is affected by the gravity and aerodynamic drag and lift forces (see Figure 1). If there is wind with non-zero velocity V_w, then the aerodynamic drag will not act along a direction opposing the velocity V_d of the discus, but rather it will act along the direction of the relative velocity V_{rel} as seen in Equation (1), where

$$\vec{V}_{rel} = \vec{V}_d - \vec{V}_w. \quad (1)$$

The magnitude of the drag and lift forces are usually studied as a function of the dimensionless drag and lift coefficients c_d and c_L as follows:

$$F_{drag} = \frac{1}{2} c_d \rho A \vec{V}_{rel}^2; \quad F_{lift} = \frac{1}{2} c_L \rho A \vec{V}_{rel}^2, \quad (2)$$

where ρ is the density of the air and A is the maximum cross-sectional area of the discus. From Equation (1), the acceleration due to aerodynamics forces is as follows:

$$M\vec{a} = \frac{1}{2} \rho A \vec{V}_{rel}^2 (c_d^2 + c_L^2)^{1/2}, \quad (3)$$

where c_d and c_L depend strongly on the angle of attack, which is the angle between the plane of the discus and the direction of $\vec{V}_{rel}$, ρ and discus rotational velocity ω. For simplicity, it has been assumed that c_d and c_L are independent of ρ and ω, and that the rotation vector (ω) is perpendicular to the plane of the discus. The characteristics of discus under study are present in Table 1.

Table 1. Characteristics of the discus.

Event	Diameter (mm)	Thickness (mm)	Mass (kg)	Current world record (m)
Men's discus	221	46	2.00	74.08
Women's discus	182	39	1.47	76.80

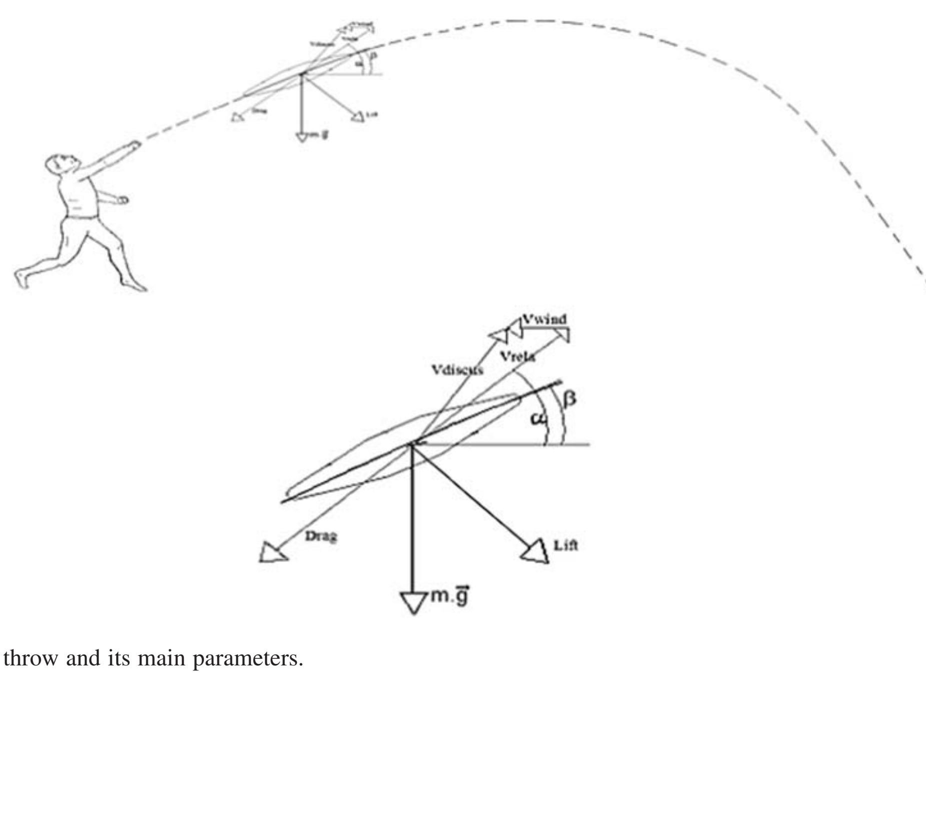

Figure 1. Discus throw and its main parameters.

2.2 Aerodynamics parameters

In this section, the dimensionless coefficients c_d and c_L are calculated using a commercial CFD software ANSYS-FLUENT$^{\mathrm{TM}}$. The air flow around the discus during its flight is turbulent. It is usually stated that a system of equations representing turbulent models, as $k-\varepsilon$ turbulent model, even when including a low Reynolds number, cannot predict the details of an unsteadied flow such as the flow around the structures. The incompressible Reynolds averaged Navier–Stokes equations with the standard $k-\varepsilon$ turbulent model was considered. The governing system of equations based on $k-\varepsilon$ turbulent model was shown in Equations (4)–(7). The solution of these differential equations was solved using the algebraic multigrid (AMG) method. This approach has been validated, in the case of the fluid flow around the hand/forearm (Rouboa et al. 2006). The continuity equation, momentum conservation equations, turbulent kinetic energy and rate of dissipation of turbulent kinetic energy equations, for an incompressible fluid in Cartesian coordinates, were written in conservative form as

$$\nabla U = 0, \tag{4}$$

$$\frac{\partial U}{\partial t} \pm U.\nabla U + \nabla p \pm \nabla\left(v + c_\mu \frac{k^2}{\varepsilon}\right)\left(\nabla U + \nabla U^t\right) = 0, \tag{5}$$

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho V_x k}{\partial x} + \frac{\partial \rho V_y k}{\partial y} = \frac{\partial\left(\frac{\mu_t \partial k}{\sigma_k \partial x}\right)}{\partial x} + \frac{\partial\left(\frac{\mu_t \partial k}{\sigma_k \partial y}\right)}{\partial y} + \mu_t \phi - \rho\varepsilon, \tag{6}$$

$$\frac{\partial p\varepsilon}{\partial t} + \frac{\partial \rho V_x \varepsilon}{\partial x} + \frac{\partial \rho V_y \varepsilon}{\partial y} = \frac{\partial\left(\frac{\mu_t \partial \varepsilon}{\sigma_\varepsilon \partial x}\right)}{\partial x} + \frac{\partial\left(\frac{\mu_t \partial \varepsilon}{\sigma_\varepsilon \partial y}\right)}{\partial y} + \mu_t \frac{\varepsilon}{k}\phi - C_2 \frac{\rho\varepsilon^2}{k}, \tag{7}$$

where k is the turbulent kinetic energy and ε is the turbulent kinetic energy dissipation rate, V_x and V_y are the x- and y-component of the discus average velocity U, μ_t is turbulent viscosity, ρ represents the air density, T is the air temperature and subscripts x and y denote the horizontal and vertical coordinates, respectively. The variables μ_t, ρ and T are assumed to be constant. Table 2 presents the $k-\varepsilon$ turbulent model constants incorporated in the system of Equations (4)–(7).

2.3 Solution method

The numerical scheme used is based on the finite volume method. The solutions to the governing system of equations are given in each quadrilateral gird cell of the discretised domain. The horizontal and vertical average velocity components, average pressure, turbulence kinetic energy (k) and turbulence kinetic energy dissipation rate are the degrees of freedom in each gird cell.

Table 2. Modified $k-\varepsilon$ model constants.

Constants	Standard $k-\varepsilon$
C_2	1.92
C_μ	0.09
σ_ε	1.30
σ_k	1.00

The convergence criteria chosen for an AMG solver were 10^{-5} for the two velocity components V_x and V_y, and 10^{-3} for pressure, turbulence kinetic energy k and turbulence energy dissipation rate ε. The numerical simulation was carried out in a two-dimensional (2D) computational domain (Figure 2).

2.4 Equation of motion

The equations of motion are particularly simple if wind velocity (V_w), discus velocity (V_d) and the normal to the plane of the discus are all positioned within a vertical plane, i.e. if the discus is thrown either with or against the wind, and assuming that the discus does not lean to the right or the left. In the current 2D case, Equation (3) can be modified when they are projected in x- and y-axis as follows:

$$\begin{cases} \ddot{x} = -\frac{\rho A V_{\mathrm{rel}}^2}{2.M}(c_d \cos\alpha + c_L \sin\alpha) \\ \ddot{y} = -g + \frac{\rho A V_{\mathrm{rel}}^2}{2.M}(c_L \cos\alpha + c_d \sin\alpha) \end{cases}, \tag{8}$$

where α is the angle between the horizontal plane and the relative velocity (V_rel). In addition, if the lift and drag forces are applied to the torques of the discus, the angle β between the plane of the discus and the horizontal plane remains constant throughout the flight. In this case, the path of the discus is determined completely by a system of Equation (8) if the initial conditions are known since the initial release. The initial conditions include the initial release velocity $V_{\mathrm{d}0}$, the wind velocity V_w, the release angle, the discus inclination angle α (see Figure 1) and the release height y_0.

The equations can be solved if the initial conditions are known, in particular, at time t after the discus has been released with the initial velocity

$$\vec{V}_{\mathrm{rel}}^2 = \dot{x}^2 + \dot{y}^2 = \left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}t}\right)^2. \tag{9}$$

And, Equation (4) can be written as follows:

$$\begin{cases} \frac{\mathrm{d}^2x}{\mathrm{d}t^2} + \frac{\rho A}{2.M}(c_\mathrm{d}\cos\alpha + c_\mathrm{L}\sin\alpha)\left[\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}t}\right)^2\right] = 0 \\ \frac{\mathrm{d}^2y}{\mathrm{d}t^2} - \frac{\rho A}{2.M}(c_\mathrm{L}\cos\alpha + c_\mathrm{d}\sin\alpha)\left[\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}t}\right)^2\right] + g = 0 \end{cases}, \tag{10}$$

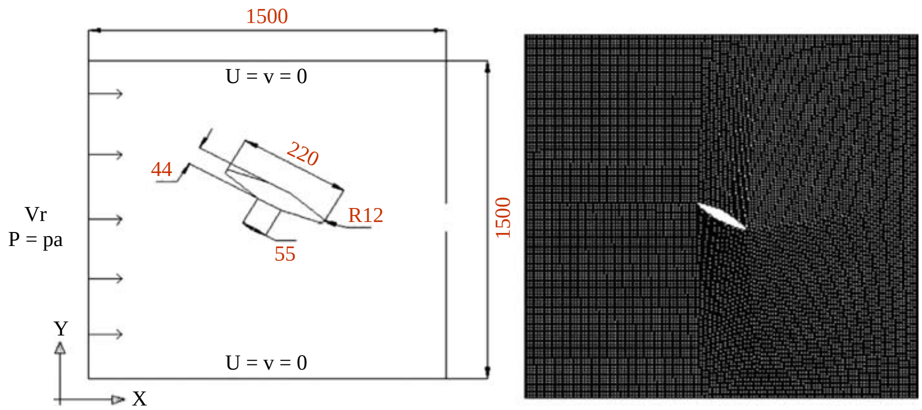

Figure 2. Physical and meshed model.

where $A = 0.038\,\mathrm{m}^2$, $M = 2\,\mathrm{kg}$, $\rho = 1.29\,\mathrm{kg/m}^3$ and $g = 9.81\,\mathrm{m/s}^2$.

In order to solve system of Equations (9) and (10), it is assumed that the dimensionless coefficients will be determined by the CFD simulation and the initial conditions. It is assumed that initially discus is located at 0 m of height and the height at the occurrence of release from the hand is 1.8 m. The initial conditions are defined as

$$\begin{cases} \text{at } t = 0\,\mathrm{s}, \quad \text{we have} \quad x = 0\,\mathrm{m}, \; y = 1.8\,\mathrm{m}, \\ \frac{\mathrm{d}x}{\mathrm{d}t} = V_{\mathrm{d0}} \cos\alpha \quad \text{and} \quad \frac{\mathrm{d}y}{\mathrm{d}t} = V_{d0} \sin\alpha, \end{cases} \tag{11}$$

where V_{d0} represents the initial velocity.

The discus throw was studied for initial throw velocities of 25 and 27 m/s, varying the angle of attack α from 0° to 90°. In Table 3, the angle of attack as the function of lift and drag coefficients, and differential coefficients of a system of Equation (6) are presented.

2.5 *Numerical scheme*

The computational domain along with corresponding geometrical parameters is presented in Figure 2. On the top and bottom exterior boundary edges of the domain, normal velocity is null ($V = 0$) implying symmetry boundary condition. At the inlet, relative velocity of 25 and 27 m/s are applied along with atmospheric pressure *P*. The outlet is applied with pressure boundary condition. The CFD simulations were performed with stationary discus in the air flow, simulating movement of discus in air with zero normal velocity of the discus and the tangential velocity contributing towards the increase in lift force on the discus. The computational domain is meshed by quadrilateral grid consisting of 22,500 cells. Refined mesh is generated in proximity to discus for better precision.

Table 3. Modified $k - \varepsilon$ model constants for $V = 25$ m/s.

Angle α	C_{d}	C_{L}	$A_X = B_X$	$A_Y = B_Y$
0	0.0152	0.0714	0.000186	−0.000186
10	0.2940	0.0642	0.03680	−0.003410
20	0.5410	0.2000	0.00706	−0.005390
30	0.7880	0.3370	0.01040	−0.006290
32.4	0.7780	0.5460	0.01160	−0.004460
45	0.6580	0.7470	0.01210	0.000771
50	0.6110	0.8280	0.01250	0.002960
60	0.4960	0.9740	0.01330	0.007290
70	0.3820	1.1200	0.01440	0.011200
90	0.0202	1.2200	0.01490	0.014900

2.6 *Introduction of rotation movement*

The rotational motion of the discus stabilises its orientation during flight and minimises the effect of drag forces. In order to simplify the problem, it is assumed that the initial orientation of the discus is preserved throughout its flight path. In order to increase the performance of the discus throw, the thrower usually attempt to orient the discus so as to maximise the effect of lift forces and minimise the effect of drag forces. Most of biomechanical researchers attribute that the optimum strategy in still air is to release the discus at an inclination angle of about 5°–10° less than the release angle.

If one carefully observes the orientation of discus during flight, one notices that for a right-handed thrower the left side of the discus tilts (rolls) gradually downward about 10° during the concluding part of its flight. This deviation is explained in Figure 1, where it can be observed that the aerodynamic lift forces F_{a} are apparently larger on the forward half of the discus, creating a torque vector pointing to the right. As the angular momentum vector points mostly downward, and the torque equals the rate of change of angular momentum, the torque to the right causes the left side of the discus to tilt downwards.

Similarly, as the discus rotation causes the relative air velocity to be slightly higher on the left side of the discus,

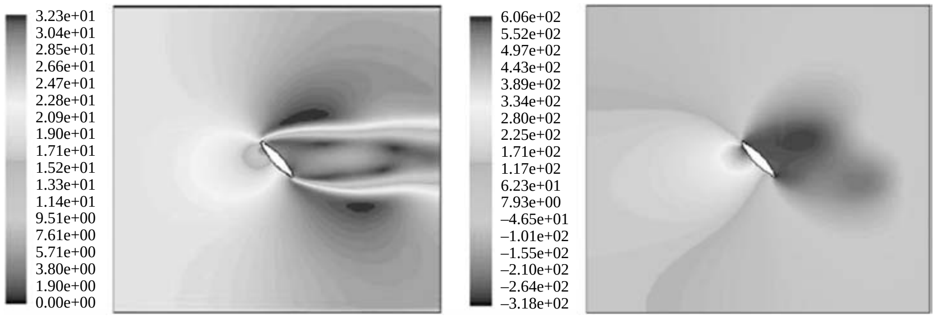

Figure 3. Velocity (left side) and relative pressure (right side) distributions around the discus during its flight for release velocity of 25 m/s and release angle of 38°.

the aerodynamic forces are effectively applied slightly to the left of the CM (Figure 1). These forces create a torque vector pointing in the direction of flight, causing the front edge of the discus to tilt (pitch) vertically upward about 1.5″. during the course of its flight. Presumably, aerodynamic forces during flight also slow the rate of rotation of the discus about its own axis; however, this effect has not been measured and assumed to be negligible.

3. Results

3.1 Dimensionless coefficient validation

Velocity inlet on the left side of the computational box is verified and is equal to 25 m/s (Figure 3). For this case, the release angle is 38°, the maximum velocities are situated on the immediate upper and lower zones of the discus throw (Figure 3). Velocity values fluctuate between 0 m/s on the back region of the discus and 32 m/s on the upper and lower regions. These velocity values are proportional to the lift forces on the studied discus.

The highest pressure is located at the frontal face of the structure (Figure 3) where the maximum relative pressure can reach about 20% of the local hydrostatic pressure. It reduces to less than 2% of the local hydrostatic pressure towards the frontal face and the rear part of the discus.

Figure 4 shows a comparison of the present numerical results of mean drag and lift coefficients with the similar experimental study available in the literature (Bartlett 1992). The comparative analysis was carried out between numerical results through CFD and experimental results obtained in the previous literature (Frohlich 1981). The mean lift and drag coefficients obtained are in a good agreement with the experimental values for the release angles between 0° and 55°. And for the release angle between 30° and 40°, the CFD results are in better agreement with the experimental data. The numerical results overestimate the drag coefficients to about 20% and lift coefficients of around 8% with the experimental values for the release angle higher than 55°.

3.2 Distances of discus throw without rotational movement

The modified equations using lift and drag coefficients were solved numerically through the commercial software Mathematica® to calculate the range values as a function of time ($x(t)$ and $y(t)$; Irtegov and Titorenko 2001). These calculations were made for the release velocities of 25 and 27 m/s. The calculation indicated the overestimated performance of discus throw.

The range along the x- and the y-direction of the discus throw is increased as a function of the release angle. This calculation was made for 10 m/s of wind velocity in the opposite direction of the throw. For the release velocity of

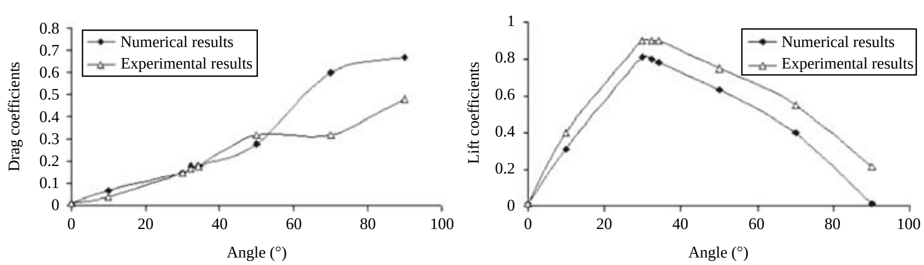

Figure 4. Comparison between experimental and calculated drag and lift coefficients for 25 m/s as relative velocity and for each release angle.

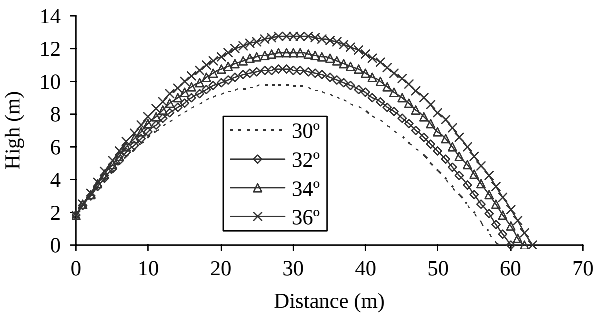

Figure 5. Distance and height as a function of release angle for velocity equal to 25 m/s.

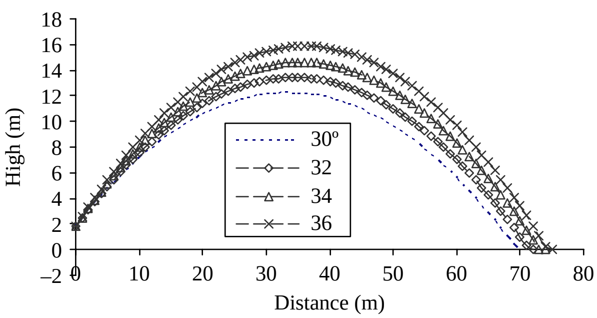

Figure 6. Distance and height as a function of release angle for velocity equal to 27 m/s.

25 m/s, the discus range is around 56, 61, 63 and 65 m for respective release angles of 30°, 32°, 34° and 36° (Figure 5). The corresponding height was increased from 8.5 to 12.7 m. It was observed that the discus range increased with increase in release angle. The peak value of discus range is 65 m with the release velocity of 25 m/s at 36° of release angle.

Figure 6 shows the trajectory and the height as the function of distance of the discus throw. For the release velocity of 27 m/s, the range of the discus throw is 74 m for 36° of release angle. The results for each release angle and 27 m/s of release velocity are closer to the above results. Indeed, the distances calculated for release angle of 30°, 32°, 34° and 36° are corresponding to 70, 72, 73 and 75 m, respectively. The height value varies between 12 m corresponding to the release angle of 30° and 16 m corresponding to the release angle of 36°.

3.3 *Effect of rotational movement*

The main objective of introducing discus throw with rotation movement is to study the stabilising effect on the discus during the flight. This rotation motion in effect influences the air resistance. As seen in Figure 1, the rotation effect minimises the influence of the drag forces and allows the discus to achieve a larger flight distance, in turn improving the range. Figure 7 shows the comparison between the range of the discus throw with and without rotation effect. The study was carried out for discus with a rotation of 4 rps. For the release velocity of 25 m/s, the gain with rotation effect is equal to 2 m, whereas for 27 m/s it is 5 m. It was interesting to note that the rotation motion on the discus does not decrease the vertical distance of the throwing discus.

4. Discussion

The aim of this paper is to study the effect of aerodynamics of a spinning discus during the flight. The numerical and experimental comparative study of discus throw with and without rotation was carried out using the analysis of lift and drag coefficients. The results indicate that the flight distance (D) was strongly affected by the drag coefficient, initial velocity, release angle and the direction of wind velocity. It is observed that these variables change as the function of discus rotation and are in good agreement between experimental data and numerical results.

Figure 4 presents the results of comparative study, with lift and drag coefficients obtained from CFD simulation and experimental data available in the literature (Frohlich 1981). The mean lift and drag coefficients are in harmony with the experimental results for the release angles

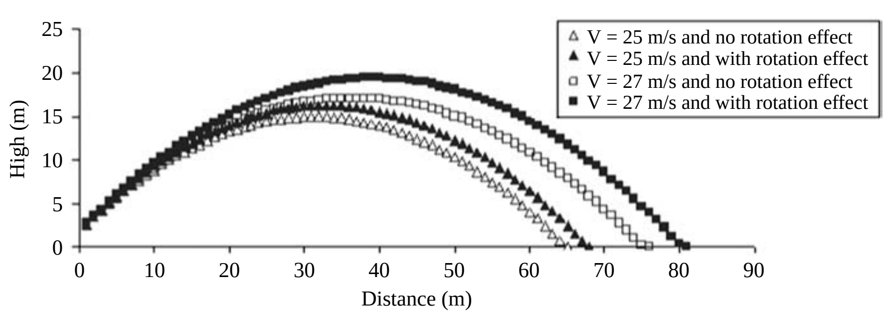

Figure 7. Trajectory of the discus throw with and without rotation effect for 34° as release angle, and 25 and 27 m/s as relative throw velocities.

between 0° and 55°. For release angles between 30° and 40°, the CFD simulation results are in a good agreement with the experimental data. For the release angle higher than 55°, the numerical results overestimate the lift coefficients by approximately 8% and drag coefficients by approximately 20%. This is attributed to limitation caused by the simulation of real-life, three-dimensional (3D) phenomena in simple 2D situation.

The aerodynamic equations of the discus throw were solved with inclusion of optimisation method as studied in the past (Remizov 1984; Maronski 1991; Dapena 1994). The outcome of differential equations lead to an analysis of discus throw distance as a function of aerodynamic and kinematic parameters within an error of approximately 5%. Based on the results, we conclude that to improve discus performance, the two most important factors that a discus thrower should address are the release velocity and the release angle. These results have a direct application to athletes during training sessions, where weight lifting is used primarily to increase strength and agility drills are used to improve body speed. Additionally, the results also underline the importance of the morphology of elite discus throwers, mainly the contribution of arm span in relation to their performance.

The most fascinating effect observed about discus aerodynamics is that discus throwers can throw significantly farther if the wind blows against the direction of the throw than if there is no wind or if the wind blows in the direction of the throw (Frohlich 1981). Our results do support a notion that is popular among elite athletes: that the best throws should be made against fairly stiff winds, rather than against regular winds or against no wind at all. The discus throwers aiming for record performances are correct in their preference for throwing in the face of stiff wind.

The introduction of rotational motion resulted in better agreement with experimental results published in the literature. In fact, we have concluded that for the same throwing conditions, the rotation of the discus results in larger throwing distances. Most of biomechanical researchers agree that the optimum strategy in still air is to release the discus so that its inclination angle is about 5°–10° less than the release angle. Since the discus rotation causes the relative air velocity to be slightly higher on the left side of the discus, the aerodynamic forces are applied slightly to the left of the CM. These forces create a torque vector pointing forward, causing the front edge of the discus to tilt (pitch) upward about 1.5 s during the course of its flight. Presumably, aerodynamic forces during the flight also slow the rate of rotation of the discus about its own axis. However, this effect has not been measured and is presumed to be minimal. Probably, it is possible to throw a discus against the wind in such a way that the aerodynamic torques cause it to pitch forward during the flight, thereby allowing the discus to maintain a near-optimum release angle throughout a greater portion of the entire trajectory. Moreover, the effect of rotation motion on the discus did not decrease the vertical distance of the throwing discus and there was marked gain in range of the discus throw.

In summary, this study shows that the discus range is strongly affected by the drag coefficient, the initial velocity, the release angle and the direction of the wind velocity. These variables change as a function of the discus rotation. The numerical results are in a good agreement with the experimental data for release angles between 0° and 55° and for release velocities considered in this study.

The important observation was the fact that for greater release velocities, the observed values for throwing distances showed large deviation from experimental values. This is attributed to limitation of current numerical simulation, which might be improved by the use of better turbulent models and also inclusion enhanced mesh with inclusion of boundary layer. At high velocities there is change in aerodynamics around discus, which has to be studied with more enhanced precision. However, the main limitation inherent in this study is the choice of 2D physical model to simulate a 3D flow phenomena. And this limitation is attributed to an overestimation of numerical results for the release angle higher than 55°. 3D effects could not be taken into account in this preliminary study but will be principally used in future studies.

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