FLUID MECHANICS ANALYSIS IN VOLLEYBALL SERVICES

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INTRODUCTION: The service is considered the first attack action in volleyball games. Most types of services can be recognized through the athlete's posture before he hits the ball. Frequently this information is not enough to prepare an adequate reception. Erratic behavior seems to appear along the trajectory hindering the reception. This work focuses on the characterization of the service ball's trajectories.
The interaction between the ball and the air is treated by fluid mechanics. Other authors have analyzed volleyball throwing. For example KAO et al. (1994) quantified a mathematical model for the trajectory of a spiked volleyball using wind tunnel aerodynamic tests.
Here we studied the behavior of real service balls through the three-dimensional reconstruction of their trajectories.
OBJECTIVES: The aim of this research is: 1) to study service balls trajectories; 2) to relate characteristics of the balls' movement to the so called "drag crisis" phenomenon; 3) to quantify the drag force and the drag coefficient.
METHODOLOGY: Four types of volleyball services were performed by a high-level player of the Brazilian national league. The chosen ones were: the underhand service, the floater service, the floater service with jumping and the overhand service with jumping. In all cases the athlete was told to throw the ball with low or without spin effects.
Two fixed video cameras registered the trajectories of the balls in an indoor court, obtaining two sequences of stereoscopic images. Twenty-six throws were selected, digitalized and 3D reconstructed by the DLT method, applying the DVIDEO system of BARROS, R. et al. (1997). For each throwing we obtained the coordinates that correspond it to the 3D position of the ball, in its flight phase, at every 1/30 second. The precision of the measurements and 3D reconstructions was shown to be better than ± 3 cm.
For the analysis we adopted a Cartesian reference system with "x" horizontal, in the direction of the throwing, "y" vertical upward and "z" orthogonal to the vertical plane (x, y). In this way we obtained a type of description of the trajectories that doesn't depend on the direction of the executed service.
The coordinates (x and y) of each trajectory were fitted by a polynomial of 4th degree of time, allowing the calculation of the velocities and accelerations of the balls.

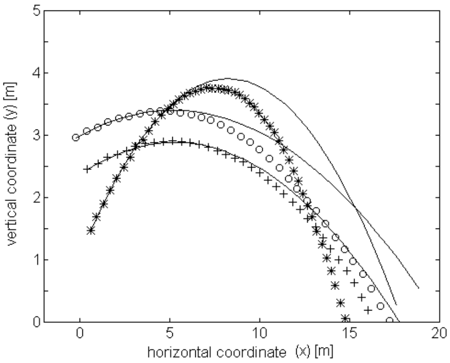

Figure 1- Real trajectories(*,+,°) compared with "in vacuum" idealized ones projected in the vertical plane.

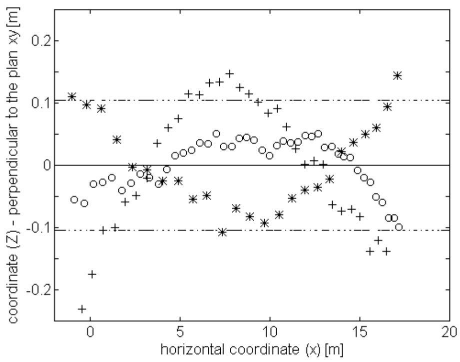

Figure 2 - Real trajectories (*,+,°) compared with "in vacuum" idealized ones projected in the horizontal plane.

Initially we used the position data of the ball to compare all the real trajectories with idealized ones which would be obtained for an object thrown with the same initial conditions in vacuum, i.e., without air resistance. For each service we calculated the initial launching position and velocity vector in the vertical plane, using the first five points of the real trajectory of the ball. These initial conditions allowed the calculation of the trajectory under the action of the gravitational force alone. Real and idealized trajectories y(x) of three services are represented, as examples, in Figure 1. The comparison of these curves evidences the effect of the resistance of the air to the movement of the ball in the vertical plan.

Subtler effects like "floatation" of the ball which are present in many real trajectories cannot be seen in the vertical plane projections because they are dimmed by the intense actions of the gravity and drag forces. However, such weak effects appear clearly in the horizontal plane projection of the movement. In this plane the expected idealized trajectory is a straight line given by Z = 0 relative to our system of coordinates. Thus any lateral deviation of the straight line can be attributed to measurement errors or interference of the air. Such effects are illustrated in Figure 2. We observe that the amplitudes of the lateral instabilities are as large as a ball radius.

Fluid dynamics shows how to quantify the interaction between the ball and the air. Under the effect of the relative velocity between the object and the fluid the viscous friction promotes a drag force F_D which is opposed to the movement. The intensity of the force acting on a smooth sphere of diameter D (cross-section $A = \pi D^2/4$), moving in a fluid of density ρ, with a velocity V, is:

$$F_D = ½\, C_D\, \rho\, A\, V^2 \qquad \text{(I)}$$

C_D is the drag coefficient whose value depends on the type of flow, on the geometry of the object and on the object-fluid relative velocity. For a given shape, the type of the flow can be characterized by an adimensional parameter called the Reynolds Number (R_e) that considers the size of the object (D), the density (ρ) and the viscosity (μ) of the fluid, as well as the object-fluid relative velocity (V). R_e is given by:

$$R_e = \rho\, D\, V / \mu \qquad \text{(II)}$$

In the literature the drag coefficient C_D is presented graphically as a function of the Reynolds Number $C_D(R_e)$ (LANDAU & LIFSHITZ (1993)). For low values of R_e, the flow is laminar. For high values of R_e a turbulent flow appears in the posterior part of the ball. Depending on the value of R_e, two turbulence types can appear whose transition is abrupt and characterized by a drastic fall in the value of C_D (factor four or more). This phenomenon is called "drag crisis" and happens in a region defined by $1 \cdot 10^5 < Re < 3 \cdot 10^5$. As we show below, the velocity of the balls, in high level services, corresponds to Reynolds Numbers of this size.
In the case of the present experiment, knowing the velocities and the accelerations of the balls, we can estimate the drag forces, the drag coefficient values (C_D) and the Reynolds Number (Re) for each service using equations (I) and (II). With the ball mass (m) and the acceleration of gravity (g) we get a two-dimensional model for C_D as function of the accelerations (a_x, a_y) and of the velocities (v_x, v_y) (DEPRÁ et al. (1997)):

$$C_D{}^2 = \frac{4m^2}{\rho^2 A^2} \frac{a_x{}^2 + \left(a_y + g\right)^2}{\left(v_x{}^2 + v_y{}^2\right)^2}$$

The calculation of C_D and of R_e were made in respect to the median position of each trajectory of the 26 executed services. The following values of the constants were used: diameter D = 0.21 [m]; mass m = 0.26 [kg]; density of the air ρ = 1.115 [$Kg.m^{-3}$] and viscosity μ = 0.0000186 [$Kg.m^{-1}.s^{-1}$].
RESULTS AND DISCUSSION: The results of $C_D(R_e)$ for all 26 services are presented in Figure 3. The same figure shows the curve obtained from the literature for a moving smooth sphere (LANDAU & LIFSHITZ (1993)).
The graphic of the figure 3 shows that all services are located in the drag crisis region ($1 \cdot 10^5 < Re < 3 \cdot 10^5$). We observed that the four types of analyzed services formed clusters which are orderly in an increasing sequence of Reynolds Numbers (i.e., of velocities): underhand service, floater, floater with jumping and overhand service with jumping. The first three present a decreasing sequence of C_D values, accompanying the literature $C_D(R_e)$ curve. The fact that the points are somewhat to the left of the continuous curve can be interpreted as a ball surface roughness effect, while the continuous curve corresponds to a smooth sphere. The six points of the overhand service with jumping deviate from the curve proposed by the literature.
Knowledge of the drag coefficient allows us to calculate the drag force with equation (I). Figure 4 presents the drag force as a function of the Reynolds Number. We note that F_D increases even with decreasing C_D. Comparing the module of the two forces that act on the ball, we observed that the drag force reaches values 1.4 times larger than the weight force (mg = 2.55 N) in the case of overhand services with jumping. That is an indication of how much the drag force can influence the trajectories.

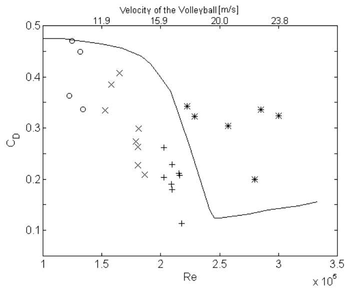

Figure 3 - Drag Coefficient C_D versus Reynolds Number R_e. Experimental points represented with the following convention: underhand service (o); floater service (x); floater service with jumping (+); overhand service with jumping (*). Continuous Line from LANDAU & LISHIFITZ (1993).

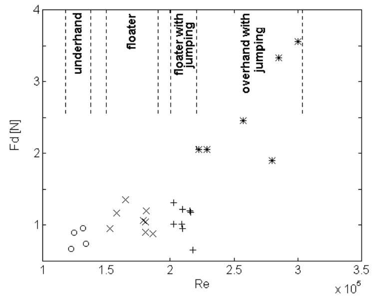

Figure 4 - Drag force Fd versus Reynolds Number R_e. Experimental points represented with the following convention: underhand service (o); floater service (x); floater service with jumping (+); overhand service with jumping (*).

CONCLUSION: This work allowed us to quantify kinetic and dynamic variables of the trajectories of twenty-six volleyball service balls thrown by an high level athlete. We observed that all services are placed in the region of the called "drag crisis" and present a great variation of the drag coefficient. We observed that the four analyzed services show orderly clusters in a growing sequence of Reynolds Numbers: underhand service, floater, floater with jumping and overhand service with jumping. The drag force is up to 1.4 times superior to the weight force of the ball. All these kind of quantification may also be used to compare the characteristics of different players.

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