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► **To cite this version:**

Martin Obligado, Mickaël Bourgoïn. The influence of turbulence in ball games. Christophe Clanet. Sports Physics, 2013. hal-02634277

HAL Id: hal-02634277

<https://hal.science/hal-02634277>

Submitted on 27 May 2020

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8 The influence of turbulence in ball games

by Martin Obligado¹, Mickael Bourgoïn¹
January 25, 2013

Abstract

This chapter presents recent experimental results on the possible influence of surrounding turbulence in the practice of ball sports. The focus is put on the question of the increased or decreased interest of such sports (in the sense of the richness of the possible dynamical features a player can impart to the ball) in turbulent conditions compared to the laminar case. To this end, we investigate the Lagrangian trajectory of spheres towed in laminar and turbulent flows. Although this situation is not identical to that of a kicked or pitched ball, we show that it shares at least some of the fluid-structure interaction features at the origin of the richness of ball games. The trajectories of the spheres are investigated in terms of statistical and dynamical properties of the position of the sphere. Our study shows that turbulence mainly tends to smear out the possible subtle effects that talented players may provide to the ball trajectory in laminar conditions.

1 Introduction

The aerodynamics of sport balls is a subject which has always captivated the attention of physicists. It is only by the end of the nineteenth century that the first relevant equation of motion for balls in sports has been derived after Rayleigh's work [1]. The dynamics of such a system is rather complex: several terms such as drag, lift, gravity and Magnus force need to be simultaneously taken into account. The balance of these forces depend on many factors, such as the characteristics of the ball (size, density, shape, surface texture, etc.) and the initial conditions given to it [2]. This is the origin of the variety and richness of sports played with balls and of the many effects talented players are capable to induce to the motion of the ball, as for instance lifted kicks, chaotic knuckleballs [3] or spinning ball spirals [4].

However, the influence of turbulence present in the environment surrounding the ball as it moves has never been carefully investigated yet in the context of sports. On one hand one can argue that the erratic behavior of turbulence may impose randomness to the dynamics of the ball, making its motion more more complex, richer and less predictable. On the other hand, if we consider homogeneous and isotropic turbulent conditions, some of the known generic laws of turbulence (as the gaussianity of velocity fluctuations, the Kolmogorov $-5/3$ energy spectra [5], the large scale brownian like turbulent diffusion properties, etc.) may be transferred to the ball

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dynamics. The fluctuations of its motion may then acquire some well characterized universal properties, which may in turn wipe out any subtle effect eventually imparted to the ball by the player. As a consequence, the dynamics of the particle may then be expected to be less complex and less rich, but simply obey to some generic statistical properties. In this chapter we address the question of how turbulence does influence the practice of sports. To this end, we present experimental results to compare the dynamics of a sphere with a partially imposed motion (mimicking the motion of a kicked ball) in a fluid under laminar and turbulent conditions.

On behalf of a realistic approach, the system consists of a sphere attached to a long cable in a wind-tunnel facility. This towed sphere configuration reproduces the situation of a ball traveling across the fluid, with an imposed mean relative velocity. The cable holding the particle helps mimicking subtle effects which would be eventually imparted to the ball by a player. In our system these effects result from the instability of the cable-sphere system triggered by the aerodynamic coupling [6] with the surrounding flow. As it will be shown below, although this does not reproduce all the possible effects for a ball game, it still give rise to a non trivial motion of the sphere under laminar conditions. We investigate how this non-trivial trajectory is affected by the presence of surrounding turbulence.

The chapter is organized as follows : the first section describes the experimental setup (wind-tunnel, turbulent and laminar conditions, particle classes, and Lagrangian tracking technique) ; the second section focuses on the results and the comparison between laminar and turbulent phenomena. In the last section we propose a brief discussion of the observed behaviors, trying to answer to the question on the larger or lesser complexity of ball motion in the presence of turbulence.

Particle#	Diameter (mm)	Density (kg/m ³)
1	2.08	36.1
2	3.05	24.2
3	6.29	13.4
4	4.3	23.1

Table 1 : Particle classes studied in this work for the turbulent flux.

2 Experimental Setup

The experiment is run in a large wind tunnel (figure 1), with a measurement section of $0.75 \text{ m} \times 0.75 \text{ m}$. The tunnel has a very low intrinsic turbulence level of the order of a few per thousands (estimated as the ratio between the standard deviation of velocity fluctuations to the average streamwise wind velocity). A turbulence generating grid can be inserted at the entrance of the test section. In this case, an almost ideal

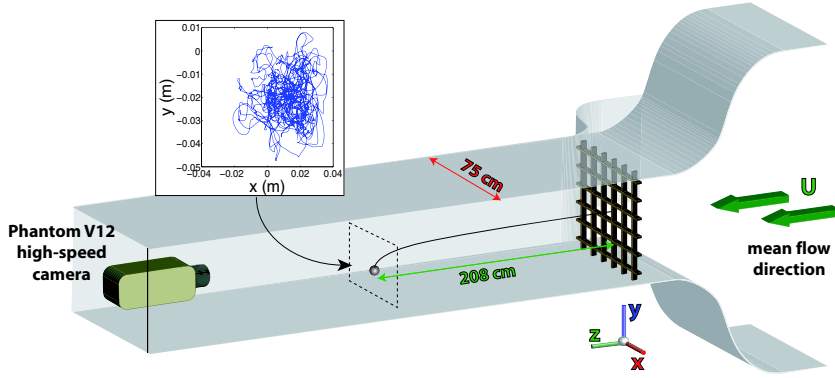


Figure 1 : Experimental setup.

isotropic turbulence is produced far downstream the grid with a fluctuation level increased up to 3%. Table 2 give the main parameters of the turbulence generated in the tunnel for three typical test velocities.

The cable used to tow the sphere has been chosen as thin and light as possible to minimize its inertia compared to that of the particle. It has a maximum lineal density of $20 \mu\text{g}/\text{cm}$ and is composed of three filaments of Polyamide-Nylon with a diameter of $25 \mu\text{m}$ each. The cable is 2.08 m long. It is fixed at one end at the center of the tunnel at the entrance of the test section. A sphere is attached at the free end of the cable. As a consequence, particle's streamwise motion is blocked, but it is free to move in the transverse directions x and y .

U_z [m/s]	7.3	10	12.4
R_λ	125.7	146.0	163.7
ϵ [m^2s^{-3}]	0.3148	0.7718	1.5376
L [m]	0.056	0.056	0.056
T_e [s]	0.1800	0.1335	0.1061
η [m]	3.22×10^{-4}	2.57×10^{-4}	2.16×10^{-4}
τ_η [s]	0.0069	0.0044	0.0031

Table 2: Turbulence parameters for the velocities used. R_λ is the Reynolds number (based on Taylor micro scale [7]), ϵ the energy dissipation rate par unit of mass, L is the energy injection scale (typical scale of the largest turbulent eddies), T_e is the integral time scale (eddy turn over time of the largest eddies), η is the viscous dissipation scale (typical size of the smallest turbulent eddies), τ_η the associated time scale.

Four classes of spherical particles, with different sizes and densities were investigated. All of them were made of expanded polystyrene. Table 1 summarizes their main characteristics. The particle Reynolds number Re_P is defined as $Re_P = Ud/\nu$,

with d the particle diameter, U and ν the streamwise velocity and ν the kinematic viscosity of the fluid. Re_p varies from 1000 to 6000 depending on particle diameter and flow velocity. Although this number is small compared to typical values in sports (where Re_p can exceed 10^5) the choice of the class of particles investigated was guided by the requirement of particle size to be smaller than the integral scale of the generated turbulence, as it is the case in sports. This condition is important as one of the main properties of turbulence is its multi-scale nature: turbulent energy is injected at some large scale (the integral scale L shown in table 2) and then cascades down the smallest scales up to the viscous dissipation scale η [7]. Turbulent eddies exist over the entire range of scales between L and η (known as the inertial range of turbulence), for which specific statistical properties prevail due to local spatial and temporal correlations between eddies. At small scales (below η), the flow is dominated by viscous effects and becomes smooth, while at larger scales (above L) eddies are fully uncorrelated and follow a brownian like dynamics. In real field indoor or outdoor turbulent conditions, the injection scale may be of the order of one or several meters, while the dissipation scale may be typically millimetric. In such conditions, any sport ball will have a size fully lying in the inertial range of turbulence. We have chosen spheres whose diameter satisfy this important condition.

We started the investigation with the largest particle (#3), for which a systematic comparison of particle trajectory under laminar and turbulent conditions was performed. As discussed below this motivated to extend the investigation in the turbulent case to the other classes of particles.

Particles transverse trajectories are recorded with a high speed camera, Phantom V12 from Vision Research Inc. (New Jersey, U.S.A.), at a maximum frame rate of 3000 fps. The camera is located inside the tunnel, at least 1 m downstream the particle in order not to perturb its motion. With standard particle tracking techniques [8], we reconstruct the trajectory of the particle (see inset in figure 1). At least 40 recordings, 20 seconds long, are acquired for each particle and each investigated velocity, ensuring enough data for a proper statistical analysis of particles dynamics.

3 Results

Figure 2a shows examples of trajectories recorded for particle #3 in the case of laminar flow, for two towing velocities. At low velocities the trajectory remains relatively localized and well aligned with the mean velocity. At higher velocities the shape of the trajectory becomes non-trivial. In particular, it exhibits a forbidden region in the alignment of the mean velocity, which is statistically almost never explored by the particle. Such toroidal trajectories are systematically observed at sufficiently high velocities in the case of laminar flow. The actual mechanism causing the transition to this toroidal regime is not yet well understood from the fluid-structure interaction perspective and will be further investigated in future researches. However, for the

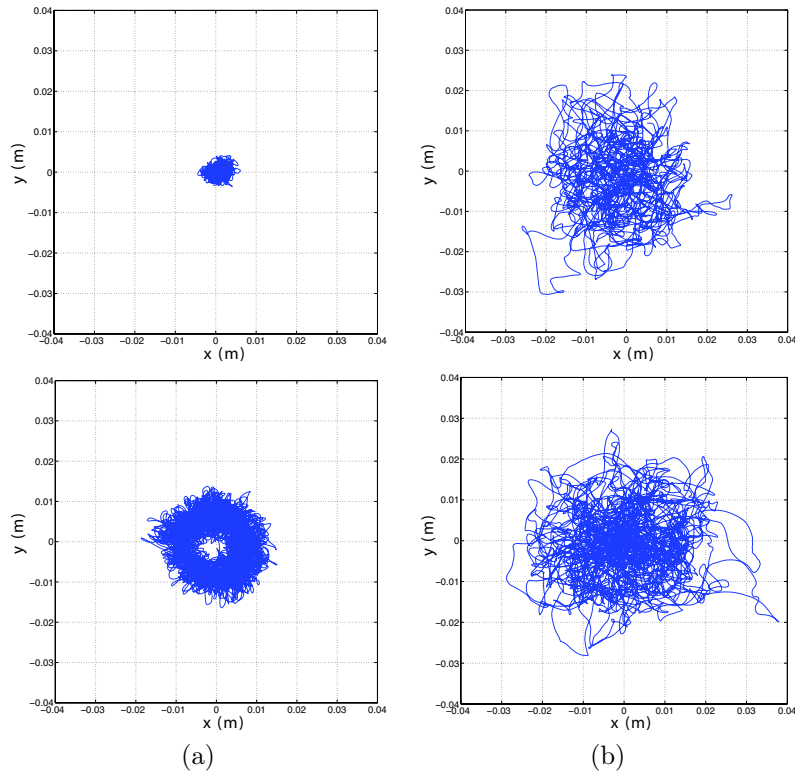


Figure 2: Trajectory in the real space for the third particle in the laminar flux for in laminar (a) and turbulent conditions (b). For each case is also represented a low (up) velocity (with $Re_P = 3.210^3$ for both cases) and a high velocity (down, with $Re_P = 5.210^3$ for the first and $Re_P = 6.210^3$ for the second case).

purpose of the present study, we use this peculiar behavior to mimic the trajectory of a ball in sports, with an *easy to catch* case at low velocities and a less predictable kick at higher velocities. This shares similarities for instance with the well known knuckleball [3], that talented pitchers and soccer players are capable to produce and which is feared by batters and goalkeepers.

Figure 2b shows the trajectories for the same sphere, at the same velocities, when 3% of turbulence intensity is introduced by the grid at the entrance of the test section. It can be qualitatively seen that trajectories fluctuations are now larger but all the subtle effects present in laminar conditions seem to have disappeared. In particular no transition toward a toroidal trajectory is visible anymore. The absence of any subtle effect in presence of turbulence with this specific sphere motivated the investigation of the trajectory of other classes particles, with different densities and size, as previously presented in table 1.

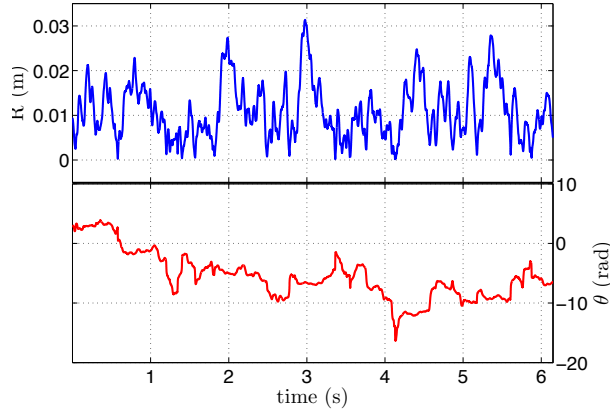


Figure 3: Time evolution of the particle polar coordinates. The example shown here corresponds to the laminar case at $Re_p = 4.1510^3$.

A more quantitative inspection of the statistical properties of particles trajectories is given by the analysis and comparison of the radial probability density function of the position of the sphere in the different situations. To achieve this, we first transform the cartesian coordinates (x, y) of the particle position to polar coordinate (r, θ) . A typical time evolution of the radial (r) and angular (θ) coordinate is shown in figure 3 (not that angular coordinate has been unwrapped). PDFs of the angle θ (not shown here) do not show any specific pattern, what simply reflects the isotropy of the particle motion, with no preferential angular position neither in the laminar, nor in the turbulent case. On the contrary PDFs of the radial coordinate exhibit a more interesting scenario. Figure 4a&b show the PDFs of r for the laminar and turbulent cases respectively. Measurements for all the particles and velocities explored are superimposed: for the laminar case, this corresponds to particle #3 at several velocities, while for the turbulent case, several particle classes at several velocities are considered (note that PDFs has been normalized by the average trajectory radius for each case). The transition toward a toroidal like position probability is clearly seen for the laminar case (figure 4a). At low velocities the radial distribution is essential gaussian, with a maximum of probability at the center of the trajectory ($r_{max} = 0$). For the highest velocities, the maximum of radial probability moves toward a non-zero value, while the probability at $r = 0$ is reduced is significantly. This statistical richness completely disappears in the turbulent case, where all the PDFs collapses onto a single Gaussian distribution.

PDFs shown in figure 4a&b have been normalized by the average radius, so they are only informative regarding the qualitative shape of the radial distribution, but not regarding its quantitative extent. To this respect, figure 5 shows the average radial position of the sphere as a function of the particulate Reynolds number Re_p . It can be seen, that for the laminar case, the radial position is very sensitive to variations of Re_p

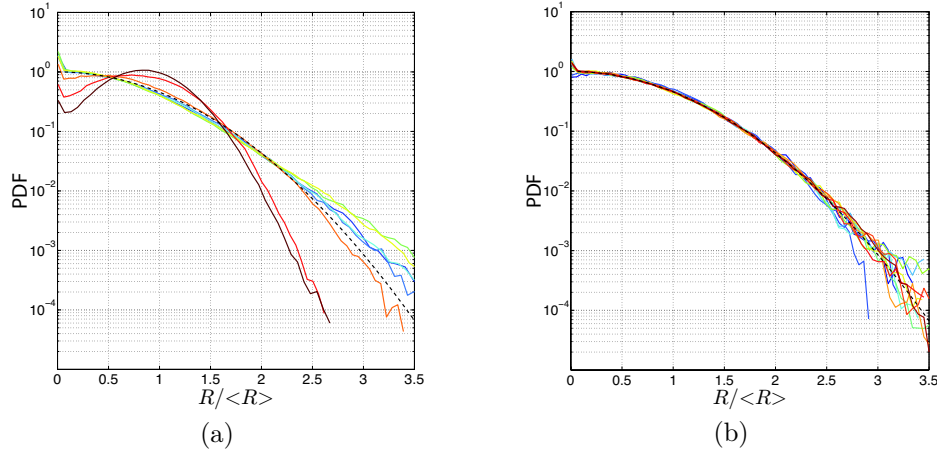


Figure 4: Probability density function for the radial component of the position for the laminar (a) and turbulent case (b).

(corresponding here to variations of velocity). On the contrary, for the turbulent case, the mean radius of the particle trajectory is essentially independent of Re_p (within the explored range), regardless of how it is varied (changing the particle size or its velocity).

Finally, dynamical aspects of the motion of the sphere can be analyzed from the Lagrangian power spectral density (PSD) of the particle trajectory (defined as the Fourier transform of the correlation function of the time evolution of the particle spatial coordinates). Figure 6a,b,c&d show the Lagrangian PSD for the radial and angular position both in laminar and turbulent cases. Spectra for all available configurations (depending on particle class and velocity) have been superimposed. It can be observed that in the laminar case qualitative and quantitative trends are observed depending on experimental details. For instance the appearance of spectral peaks can be seen for the highest sphere velocities (we have shown in a previous work that such peaks may be related to an aero-elastic instability, similar to *flutter* [6]). This dynamical richness is lost in the turbulent case, where the spectra have all the same shape regardless of the considered configuration. In the turbulent case, spectra are mostly dominated by a flat PSD at low frequencies (characteristic of the uncorrelated large-scale fluctuations) followed by a rapid cut-off for frequencies above 10 Hz. We also note that the level of large-scale fluctuations (at low frequencies) does not significantly change with experimental conditions. This explains why the average radial position in turbulent conditions was mainly independent on experimental details. On the contrary, the level of low-frequency plateau of uncorrelated fluctuations, clearly increases with increasing velocity in the laminar case. This corresponds to the increase of uncorrelated radial fluctuations (and hence of the average radius of the sphere trajectory) with increasing Re_p previously reported.

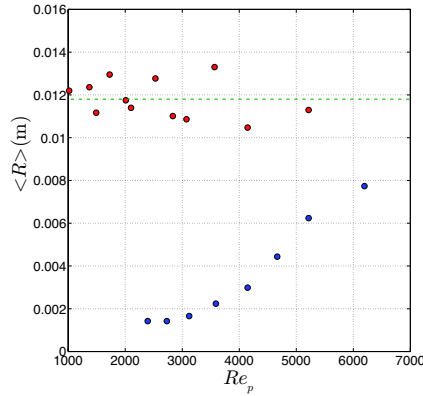


Figure 5: (a): Mean value for the radial component of the position for the laminar case (blue) and the turbulent case (red), where the green line represents the average of these points ($R = 1.18$ cm).

4 Discussion and Conclusions

We have investigated the constrained dynamics of towed spheres in laminar and turbulent flows. We use this configuration as a model to investigate the dynamics of a thrown ball, with an imposed relative velocity with respect to the surrounding fluid environment. Besides, this configuration is also of direct interest for new emerging mechanical sports, such as for instance “RC-bowling” [9], where the player has to strike pins using a ball towed by a radio-controlled aircraft.

Our study shows that in laminar conditions this “towed ball” configuration reproduces subtle and non-trivial dynamics of the sphere, mimicking effects of balls in sports. In particular, non-trivial statistics of the radial position of the particle, similar to knuckleball effects in sports is well reproduced. We have shown that the radial position of the particle is very sensitive to experimental conditions (as for instance changes of the sphere velocity) which mimic here different initial conditions eventually imposed in the field by a player pitching or kicking a ball. We have shown that the dynamics of the particle also exhibits non-trivial trends with experimental conditions. These observations support the fact that in laminar conditions, the coupling between the particle and the surrounding flow is very sensitive to experimental details (and hence to initial conditions in the field of sports). For instance although the transition toward a toroidal trajectory is not fully understood at the moment, it is very likely to be related to small asymmetries in the system (either intrinsic to geometrical imperfections, or inherent to aerodynamic effects, as the appearance of an asymmetric wake, as observed under certain conditions for settling spheres for instance [10]). Similarly, the appearance of a dominant peak in the power spectral

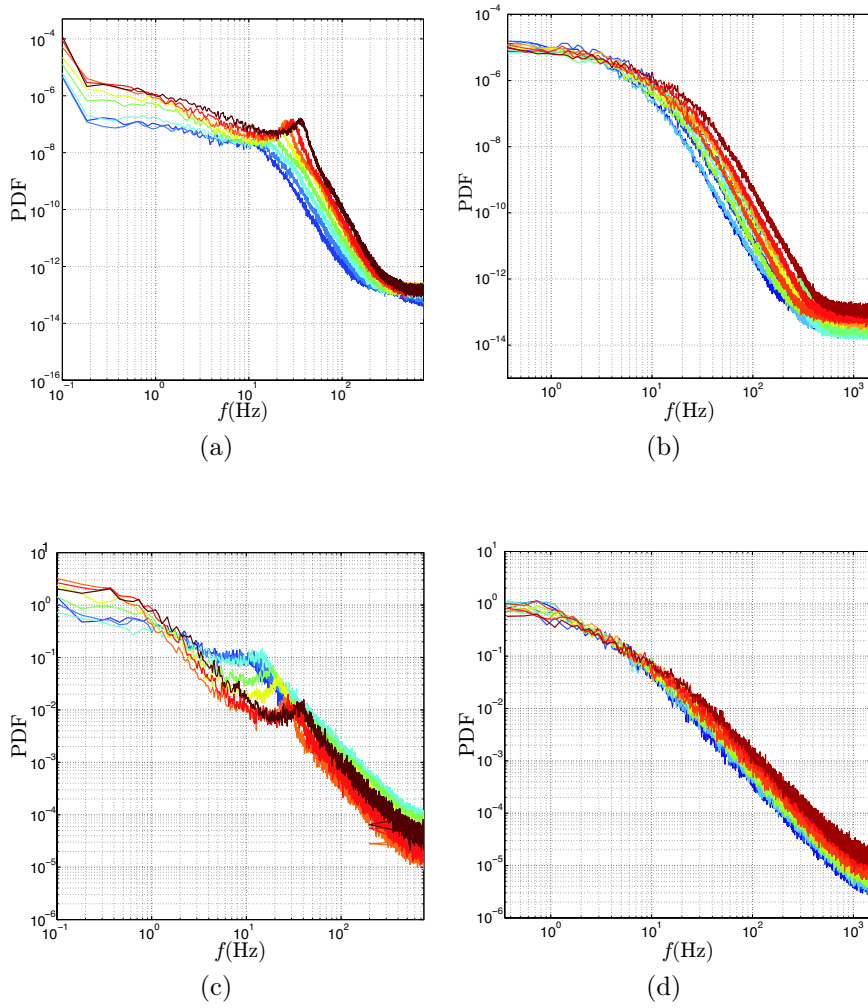


Figure 6: Power Spectral Density of the radial evolution of the sphere position for the laminar (a) and turbulent case (b). Power Spectral Density of the angular evolution of the sphere position for the laminar (c) and turbulent case (d).

density of particle trajectories is believed to be related to subtle aero-elastic instabilities of the system *sphere+cable* [6]. Although effects actually involved for balls in real sports are different in details, they rely on similar fluid-structure interactions. It is the richness of such mechanisms that produces the broad variety of possible kicks and pitches and that makes the beauty of ball sports ; and it is the capacity to control them (by imparting appropriate initial conditions to the ball) that makes the talent of a player.

Our results in turbulent conditions show that even a low level of fluctuation rate of the surrounding environment (our grid generates a flow with 3% of velocity fluctuations) suffices to smear out all the subtleness of the coupling between the moving sphere and the surrounding fluid. The variety of effects and of dynamical signatures visible in laminar conditions has completely disappeared in the turbulent case. Although fluctuations of the sphere are quantitatively larger in the turbulent case, from a qualitative point of view they are essentially featureless, in the sense that their statistical properties remain generic and independent of experimental details.

An interpretation of this observation can only be speculated at the moment. A complete relevant theoretical frame to accurately model the coupling between turbulence and finite size objects as the particles investigated here (or balls in sport fields) has indeed still to emerge [11]. However, existing experimental studies on freely advected particles in turbulent flows have shown that statistical properties of the carrier flow (as velocity and acceleration statistics) tend to be robustly transferred to the Lagrangian dynamics of the advected particles [12, 11, 13].

To conclude, let us note that although more work is still needed for a clear understanding of the precise role of turbulence in ball sports, our results show that this influence is eventually important and not always in agreement with our common sense. At present, it seems that the main effect we can expect from turbulence in ball games is to transform the qualitative richness of the whole ensemble of possible trajectories, which may be differently explored according to the talent, the creativity and the will of the payer, into a purely random process with well determined statistical laws, independent of the talent, the creativity and the will of the player. Therefore, it somehow turns a game of skill into gambling, but these are games to be played in different fields.

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