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GENERAL REVIEWS ABOUT THE PHYSICAL PROPERTIES OF BADMINTON SPORTS EQUIPMENT

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Annotation. This article will talk about the general analysis of the physical properties of the equipment of the sport of badminton. Also, observations and analyzes of many scientists were used in the coverage of the topic.

Keywords: badminton spot, physics analysis, flight, badminton trajectory, angle of inclination

Introduction

History

The first games important to the creation of badminton were practised in Asia 2500 yr BC. Soldiers played *ti- jian-zi*, which consisted of exchanging with their feet a shuttle generally made of a heavy leather ball planted with feathers (figure 1(a)). This game is now called *chien-tsu* and is practised with modern shuttles as shown in figure 1(b). Rackets were introduced for the first time in Japan with *hagoita* (figure 1(c)). During this period, shuttles were composed of the fruits of the Savonnier tree, which look like beans and were again furnished with feathers. Contemporary badminton is a racket sport originating from the Indian game *tomfool*, modified by British colonials, and played with a feathered shuttlecock and a racket made with strings, as attested by the painting of Jean-Siméon Chardin, reproduced in figure 1(d).

The modern game Badminton is played either by two opposing players (singles) or two opposing pairs (doubles). Each player (or team) stands on opposite halves of a rectangular court which is 13.4 meters long, 5.2 meters wide and divided by a 1.55 meter-high net (figure 2(a)). Players score points by striking a shuttlecock with their rackets (a typical racket is shown in figure 2(b)) so that it passes over the net and lands in the opponent's half-court. Each side may strike the shuttlecock only once before it passes over the net. A rally ends once the shuttlecock has hit the floor or a player commits a fault. The shuttlecock is a feathered (or, in uncompetitive games, plastic) projectile. It is made of 16 goose feathers planted into a cork (figure 2(c)). This object weighs $M = 5$ g, its length is $L = 10$ cm and its diameter is $D = 6$ cm. Shuttlecocks have a top speed of up to 137 m s^{-1}. Since the projectile flight is affected by the wind, competitive badminton is played indoors. Since 2008, all the finals of the Olympic Games and the World Championships have been contested by Lin Dan (China) and Lee Chong Wei (Malaysia). Looking at those finals, one observes that a typical game lasts about one hour (20 min by set), each rally lasts on average about 10 s with typically 10 exchanges.

Badminton strategy consists of performing the appropriate shuttlecock trajectory, which passes over the net, falls in the limit of the court and minimizes time for the opponent reaction.

The state of the art The trajectories of shuttlecocks have been extensively studied with experimental, theoretical and numerical approaches. Cooke recorded the trajectories of different shuttlecocks in the court and compared them to numerical simulations. The aerodynamics of several shuttlecocks was studied in a wind tunnel by Cooke and Firoz. They measured the air drag $F_D = \rho S C_D U^{2}$ 2 exerted by air on a shuttlecock (where ρ is the air density, $S = \pi (D\ \ 2)^2$ the shuttlecock cross-section and U its velocity) and showed that the drag coefficient C_D is approximatively constant for Reynolds numbers ($Re = DU\ \ \nu$, with ν the air kinematic viscosity) between 1.0×10^4 and 2.0×10^5. For commercial shuttlecocks, C_D varies between 0.6 and 0.7 depending on the design of the skirt. Wind tunnel measurements also reveal that there is no lift force on a shuttlecock when its axis of symmetry is aligned along the velocity direction. A synthesis of data collected in the court and wind tunnels has been done by Chan. Shuttlecock trajectories have been calculated by Chen, and Cohen *et al* proposed an analytical approximation for the range of projectiles submitted to weight and drag at high Reynolds number. Nevertheless, the peculiarities of shuttlecocks such as their conical shape and flipping properties have rarely been discussed. For instance, the observation of impacts with a racket (figure 3) reveals a dynamics specific to badminton: shuttlecocks fly with the nose ahead so that they can be hit on the cork by each player, which requires the shuttlecock to flip after each racket impact.

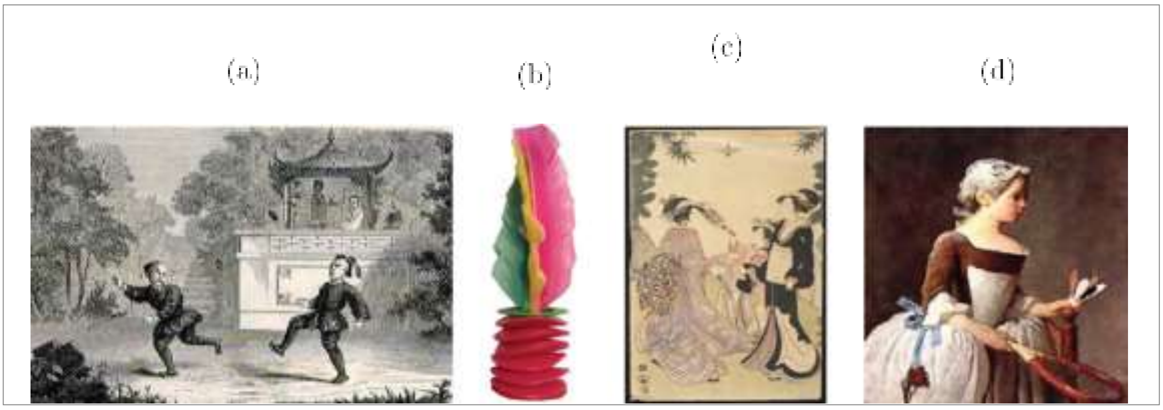
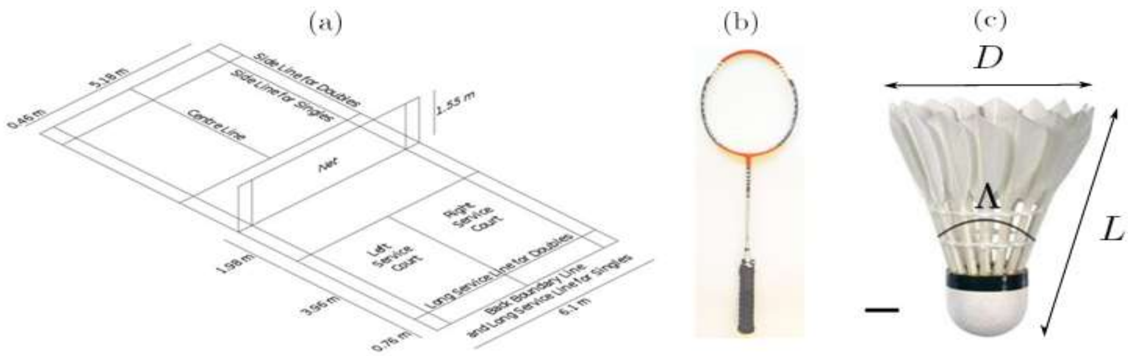


Figure 1. (a) Engraving of a ti-jian-zi game extracted from Le Tour du Monde: Nouveau Journal des Voyages written by Edouard Charton in 1860. (b) Shuttle used in chien-tsu. (c) Drawing of Three Beauties Playing Battledore and Shuttlecock by Utagawa Toyokuni in 1800. (d) La Fillette au Volant by Jean-Siméon



Chardin in 1741.

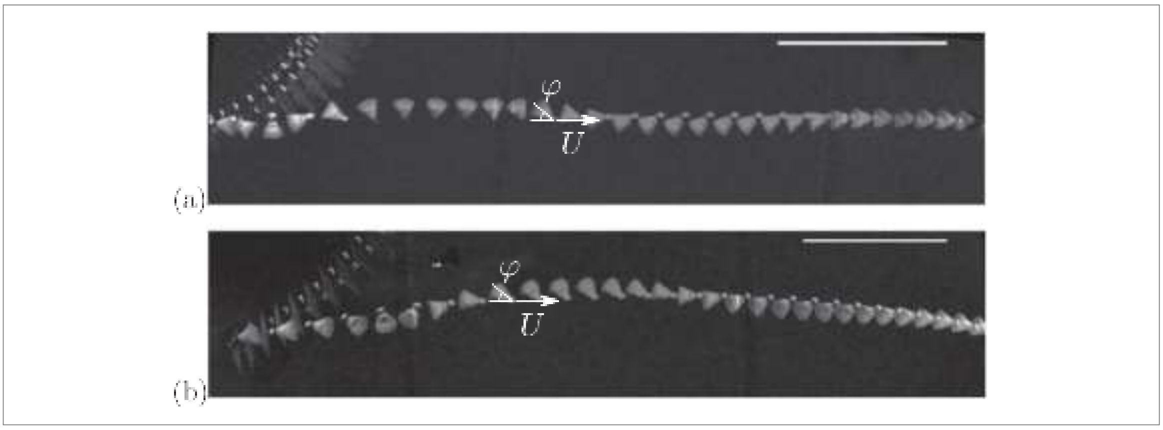
Figure 2. (a) Sketch of a badminton court. (b) A badminton racket. (c) An example of a feathered shuttlecock. The dark line indicates 1 cm. This image has been obtained by the author from the Wikipedia website and the owner of the copyright in the image is unclear.

The questions we address in this work are: what makes the shuttlecock flight unique, and how does it influence the badminton game? In the first section, we study the 'versatile' behavior of a shuttlecock. The characteristic times associated with the motion are measured, and we develop an aerodynamical model to predict them. The second part concerns trajectories at the scale of the court, that is, for clear strokes. In this section, we study how the flight of a shuttlecock depends on its characteristics (mass, composition and geometry) and on the fluid parameters (density, temperature and humidity). Finally, we discuss in the third section how the shuttlecock flight influences the badminton game in terms of techniques, strategies and rules.

Observations and analysis

Different sequences of the flip of a shuttlecock are recorded using a high speed video camera (figure 3). After contact with the racket (typical time of 1 ms), it takes typically 20 ms for the projectile to flip. Then, the shuttlecock axis undergoes damped oscillations until it aligns along the velocity direction **U**. The projectile never performs a complete turn. In figure 3(a), the flip lasts four time intervals, which corresponds to 15 ms. The oscillating time of the shuttlecock direction is estimated as 80 ms. After 130 ms, the shuttlecock axis of symmetry is aligned along the velocity direction. When the hit intensity decreases, the dynamics of the shuttlecock slows down. Figure 3(b) shows the same shuttlecock leaving the racket at a velocity two times smaller than the previous one. The flipping time increases to 35 ms, the oscillating time lasts about 120 ms and the stabilizing time is estimated as 180 ms.

Such movies allow us to measure the angle φ between the shuttlecock axis and the velocity direction, as defined in figure 3. A typical example of the time evolution of φ is plotted in figure 4. Such graphs highlight the three characteristic times introduced earlier. The first one is the flipping time τ_f needed for φ to vary from 180° to 0°. The second one, denoted as τ_o, is the pseudo-period of oscillations. The third one is the stabilizing time τ_s, which corresponds to the damping of the oscillations (red dashed lines in figure 4). The purpose of this section is to understand this complex



dynamics.

Figure 3. Chronophotographies of shuttlecocks after an impact with a racket, showing the time evolution of the angle φ between the shuttlecock orientation and its velocity **U**. White lines indicate 50 cm. (a) The time interval between each position is 5 ms, the shuttlecock initial velocity is $U_0 \approx$ 18.6 m s^{-1} and its initial angular velocity is $\dot{\varphi}_0$ = 206 rad s^{-1}. (b) Time interval between each position is 6.5 ms, the shuttlecock initial velocity is $U_0 \approx$ 10.4 m s^{-1} and its initial angular velocity is $\dot{\varphi}_0$ = 28 rad s^{-1}.

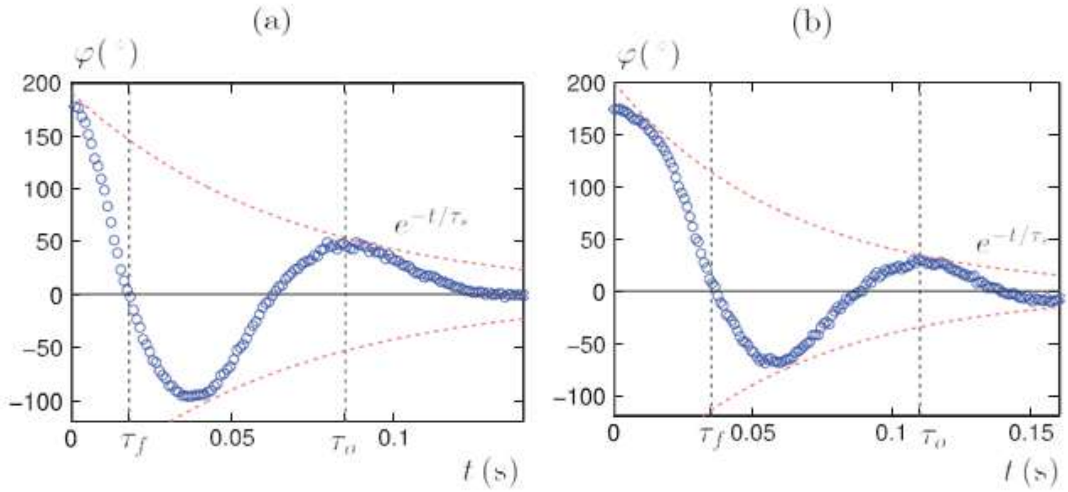


Figure 4. Time evolution of the angle φ between the shuttlecock axis of symmetry and its velocity **U**. Measurements correspond to experiments shown in figure 3. t = 0 is the time when the shuttlecock impacts the racket. Experimental data (blue dots) are bounded by an exponential envelope (red dashed lines). (a) The shuttlecock initial velocity is $U_0 \approx$ 18.6 m s^{-1} and its initial angular velocity is $\dot{\varphi}_0$ = 206 rad s^{-1}. (b) The shuttlecock initial velocity is $U_0 \approx$ 10.4 m s^{-1} and its initial angular velocity is $\dot{\varphi}_0$ = 28 rad s^{-1}.

In order to understand the shuttlecock behavior after impact, it is necessary to evaluate the forces applied to it, namely weight and aerodynamic pressure forces. These latter reduce to drag, the application point of which being the pressure center, where the aerodynamic torque vanishes. Its location depends on the pressure profile around the projectile. If this profile is constant around the projectile, the aerodynamic center is the centroid of the object. Since the mass as a function of axial distance is non-homogeneous in a shuttlecock, the center of gravity is closer to the cork and it differs from the center of pressure. Using numerical simulations, Cooke estimates that the distance l between the center of mass and center of pressure is about 3.0 cm. The sketch in figure 5(a) highlights the effect of the drag $\mathbf{F}_D$ on an inclined shuttlecock. The aerodynamic drag applies a torque in a way opposite to the projectile velocity **U** and stabilizes the cork (corresponding to φ = 0).

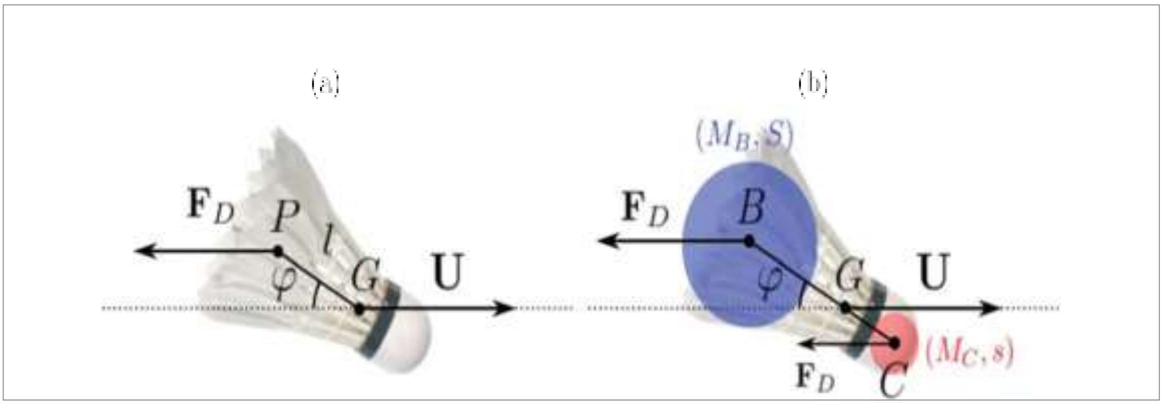


Figure 5. (a) Drag force $\mathbf{F}_D$ applied on a shuttlecock whose direction forms an angle φ with the velocity **U**. (b) Model system composed of a sphere of large section S and mass M_B, which stands for the skirt, and a sphere of small section s and large mass M_C, which represents the cork.

Result

We discussed in section 1 how shuttlecocks flip after being impacted by a racket. Among the strokes used in badminton, we aim to determine which ones are influenced by this versatile motion. The flipping dynamics of a shuttlecock is sensitive to the players only if the stabilizing time τ_s compares to the total flying time τ_0.

The graph reveals that there is only a small domain of the court ($x_0 \lesssim 0.25\ L_{field} = 3$ m) where players can receive a shuttlecock not yet aligned with its velocity direction. This situation only happens in the case of net drops. When a good player performs a net drop, his purpose is to delay the flip of the shuttlecock and let the skirt fly ahead. Then, the opponent cannot hit the cork of the shuttlecock and send it back properly. In practice, players perform tricks called 'spin in' and 'spin out', which consist of gently hitting the shuttlecock and simultaneously gripping the cork to maximize the initial spin $\dot{\varphi}_0$ positively or negatively. Relations (4) and (5) imply that a small initial velocity U_0, as employed in net drops, increases the shuttlecock oscillating and stabilizing times.

Badminton strategy consists in moving the opponent away from the court center using clear, drop or lift strokes before finishing the point with a rapid shot such as a smash or a net shot. This strategy impacts the strokes frequency as reported in table 1, which differentiates the killing shots from other ones. For clears, drops and lifts, the frequency of non-winning shots is much larger than the frequency of killing shots, which emphasizes that these shots are defensive or preparatory shots; this contrasts with drives, smashes and net shots which largely dominate the statistics of killing shots. Thus, ending a rally in badminton is mainly a question of flight duration.

Conclusion

The dynamics of a shuttlecock and its influence on the badminton game have been questioned. The versatile behavior of a shuttlecock after impact arises from its non-homogenous mass as a function of axial distance. The cork being denser than the skirt, a shuttlecock has distinct centers of mass and pressure, and thus undergoes a stabilizing aerodynamic torque setting its nose ahead. The geometry of commercial shuttlecocks is empirically chosen to minimize flipping and stabilizing times. In practice, badminton players try to delay stabilization with net drops, in order to prevent the opponent from hitting the projectile correctly.

For other strokes, the stabilizing time is much shorter than the total flying time. In this limit, a shuttlecock is aligned with its velocity. Because this light particle experiences a large drag, its trajectory is nearly triangular and it highly depends on the projectile properties. This explains why players carefully choose shuttlecocks as a function of skills and atmospheric conditions (see appendix B). Experienced players prefer shuttlecocks submitted to a slightly larger drag, such as feathered ones, in order to hit them violently without exiting the court. The difference in rotating speed between the two kinds of shuttlecock (plastic and feathered) also plays a role in this choice since a faster rotation of feather projectile limits its precession.

Beyond this study, many questions concerning the physics of badminton remain to be solved. For example, the impact dynamics of a shuttlecock with a racket is not considered in this paper. One may wonder if there is an optimal rigidity for the shaft and the strings to enhance the launching speed of a shuttlecock. Finally, the laws established for shuttlecock flights could be discussed with other projectiles having a non-homogeneous mass along their axis, such as air missiles or dandelion achenes.

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