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Research article / *Article de recherche*

Left- versus right-handed badminton slice shots: opposite spinning of the chiral shuttlecock and Magnus effect

Slices de gaucher versus droitier au badminton : rotation inverse du volant chiral et effet Magnus

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Abstract. The chiral nature of a badminton shuttlecock is responsible for its counter-clockwise spinning as it naturally propagates through the air. This induces a dissymmetry between left- and right-handed players and the resulting trajectories of the shuttlecock, which were captured in real condition on the badminton court in slow motion at 3700 fps. The videos clearly evidence this dissymmetry as slice shots performed by right-handers induce a natural counter-clockwise spinning, while the ones performed by left-handers induce a clockwise to counter-clockwise spinning, making trajectories of shuttlecocks different. The slow motion videos also caught a brief Magnus effect, often neglected in badminton, lifting up the shuttlecock for both left-handers and left-handers and affecting the effectiveness of the slice shot.

Résumé. La nature chirale du volant de badminton est responsable de sa rotation antihoraire lorsqu'il se propage naturellement dans l'air. Cela induit une dissymétrie entre joueurs gauchers et droitiers et les trajectoires du volant qui en résultent, capturées en conditions réelles sur le terrain de badminton en slow motion à 3700 ips. Les vidéos mettent clairement en évidence cette dissymétrie puisque les slices effectués par les droitiers induisent une rotation antihoraire naturelle, tandis que ceux effectués par les gauchers induisent une rotation d'horaire à antihoraire, rendant les trajectoires de volants différentes. Les vidéos ont également mis en évidence un bref effet Magnus, souvent négligé au badminton, soulevant le volant pour les gauchers comme les droitiers et affectant l'efficacité du slice.

Keywords. Physics of badminton, Magnus effect, Symmetry, Chirality, Badminton trajectory, Time-resolved.

Mots-clés. Physique du badminton, Effet Magnus, Symétrie, Chiralité, Trajectoires au badminton, Temps résolu.

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1. Introduction

The Badminton World Federation reported that badminton is one of the most popular sports, played by over 339 million people worldwide [1]. About 23% of them are left-handed players [2]. While in most sports, there is no geometrical difference between left-handed and right-handed players, this is not true for badminton. This dissymmetry comes from the chiral nature of feather shuttlecocks, composed of an array of diverging stems, the ends of which are at the convergent end of the skirt, joined together in an end ring. Figure 1 shows the nomenclature of feather shuttlecocks. Its global symmetry corresponds to the C_{16} point group, which contains 2-, 4-, 8- and 16-fold rotation symmetry axes [3]. The feathers of a goose's left wing are typically used to make shuttlecocks because they are more symmetrical, have a more consistent shape and are more flexible than those from the right wing [4]. Shuttlecocks do not exhibit mirror symmetry and are chiral bodies, due to the way the feathers are placed into the cork, which is responsible for the natural counter-clockwise spinning of these projectiles as they propagate through the air. The symmetry of the badminton court is different as it corresponds to the mm2 point group. Figure 2 shows mirror symmetry at the net and 2-fold symmetry at the center of the court. When two right-handed players (or two left-handed players) face each other (Figure 2a,b), there is a global 2-fold symmetry on the court, which is also contained in the symmetry of the shuttlecock, which spins equivalently counter-clockwise on both sides of the court. The situation is therefore symmetry-equivalent for both right-handed (or both left-handed) players facing each other. When a left-handed player faces a right-handed player (Figure 2c,d) the 2-fold symmetry is lost and a mirror symmetry appears at the net. To maintain this mirror symmetry, the shuttlecock should spin in opposite directions on both sides of the court. However, there is no mirror symmetry for the shuttlecock, due to its chiral nature, and the clockwise spinning and the natural counter-clockwise spinning are not equivalent. The situation is therefore different by symmetry for the left-handed and right-handed players, due to the fact that the racket manipulated by both players can induce opposite shuttlecock spinning.

Most of the studies of shuttlecock trajectories found in the literature concern experimental measurements, including wind tunnel experimental data of fast cameras, and/or theoretical descriptions of net shots, serve shots, smashes and high clear shots [5–12]. These studies aimed at gaining knowledge of the equations of motion of a shuttlecock's flying trajectory. Usually the trajectory is described in a plane, defined by the initial position and the horizontal and vertical components of velocities. The reproducibility and quality of such studies are essential for quantitative analysis of the flying properties of the different shuttlecocks. Since the rotation axis of the shuttlecock is usually collinear with its velocity, it is often considered that the Magnus effect [13] never occurs in badminton [14], contrary to other ball sports such as baseball, volleyball and soccer to name a few [15]. Measurements of the lateral force on the shuttlecock suggested that the spinning of the shuttlecock does induce a Magnus effect, which may be the origin of the shuttlecock "drifting" noticed by players for feather shuttlecock during high clear [6, 16]. In many studies, trajectories are not induced by players because the initial trajectory of the projectile after real impact with the racket is sometimes hard to control or to reproduce precisely. It is also player dependent, which precludes quantitative analysis.

In this study, we present a qualitative comparison of the shuttlecock trajectories after slice shots performed by right-handed and left-handed players. Badminton slicing technique is known for causing the shuttlecock to spin and altering the angle of return. Here we focused our attention on cross-court slice drop shots (Figure 3). Right-handers played the slice in the right-hand corner of the court, while left-handers played the slice in the left-hand corner of the court. A high-speed Phantom Miro 3a10 camera was used on the badminton court, in order to capture high frame rate (3700 fps) videos of the trajectories of the shuttlecock in real condition. At this frame rate,

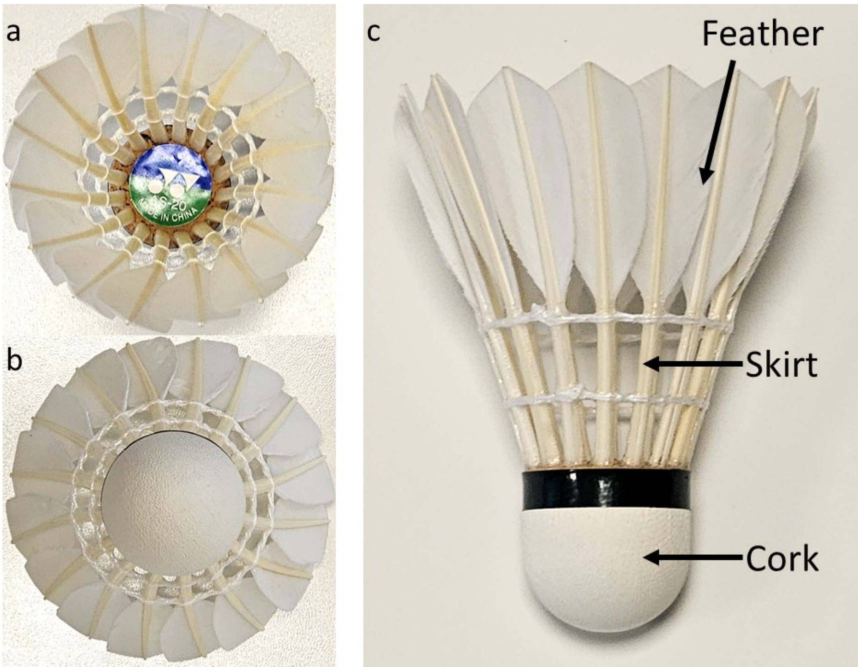

Figure 1. Structure and symmetry of a feathered shuttlecock. The top and bottom views along the rotation axis (a,b) show the 16-fold symmetry. This is due to the way the 16 bent feathers are placed into the cork (c). The shuttlecock also exhibits a 2-fold symmetry.

the resolution of the videos was maximized to 1024 × 768 pixels and the exposure time for each frame was set to 268 μs. We used Yonex AS 20 shuttlecocks for the slice shots. The videos are shown in supplementary material. Due to the fact that videos were collected on the court (3D), it was not possible to extract precise measurements of distances (and therefore speed) from the videos. We estimated roughly speed by scaling lengths with shuttlecock (9 cm) or racket sizes (68 cm). Given the expected readership, the choice is made to use popular units for speed (km/h) and rotational speed (rps) to make this article readable by non-physicists. In the following we discuss: shuttlecock flipping after a smash; right-handed versus left-handed slices; magnus effect after slice shots; shuttlecock trajectories.

2. Shuttlecock flipping after a smash

It is well known that, due to their peculiar chiral structure, badminton shuttlecocks spin as they fly in a high-drag. This specificity compared to sports balls has been the subject of an intensive research from the point of view of aerodynamics [5–12], with unexcepted applications such as improvements in landing accuracy of re-entry vehicles [17]. The value of the ballistic coefficient of badminton shuttlecocks is small, which translates their ability to overcome air resistance in flight [5]. The shuttlecock is a light and extended particle, which flies with a pure drag trajectory, so that initial velocities of shuttlecocks of ≃240 km/h are reduced in only ≃0.6 s [18, 19], to near the terminal velocity of ≃25 km/h [16, 20]. Women's record for fastest badminton shot is currently set to 438 km/h and belongs to P. Tan, while the men's record at 565 km/h belongs to S. Rankireddy. Both are right-handed players. Kitta *et al.* [5] compared trajectories of spinning and non-spinning feather shuttlecock and concluded that spinning shuttlecock exhibit a marginally larger drag.

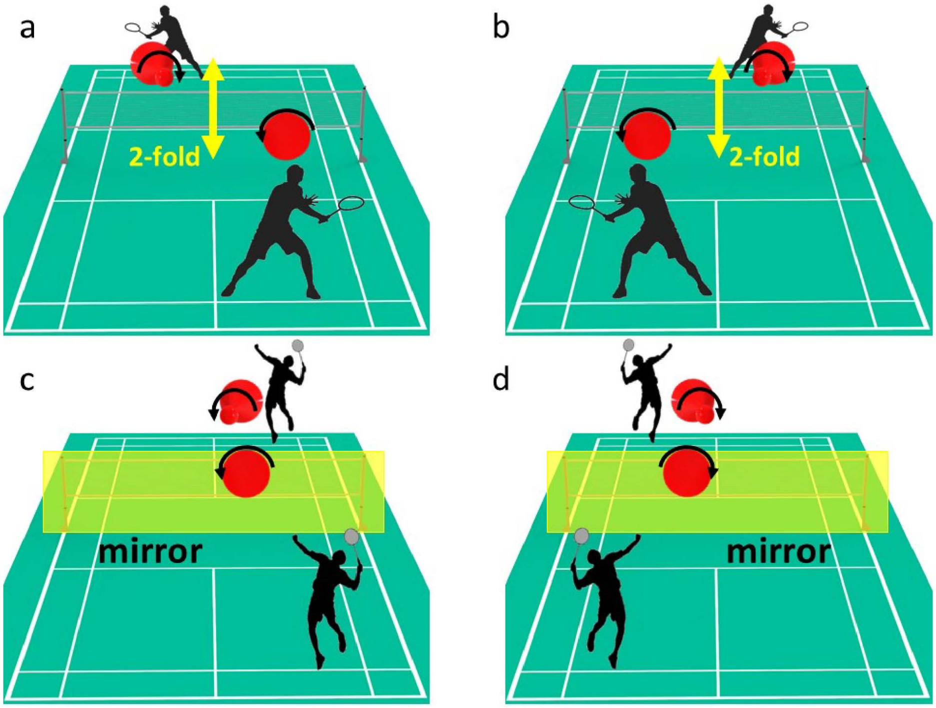

Figure 2. Sketch of a badminton court, exhibiting 2-fold symmetry around the court center and mirror symmetry centered on the net. A situation where right-handed (a), or left-handed (b), players face each other corresponds to 2-fold symmetry, and counter-clockwise spinning of the shuttlecock on both sides of the courts. For mirror symmetry to exist, left-handed and right-handed players would have to face each other (c,d) and the shuttlecock to rotate equivalently clockwise and counter-clockwise, which is not the case due to its chiral nature.

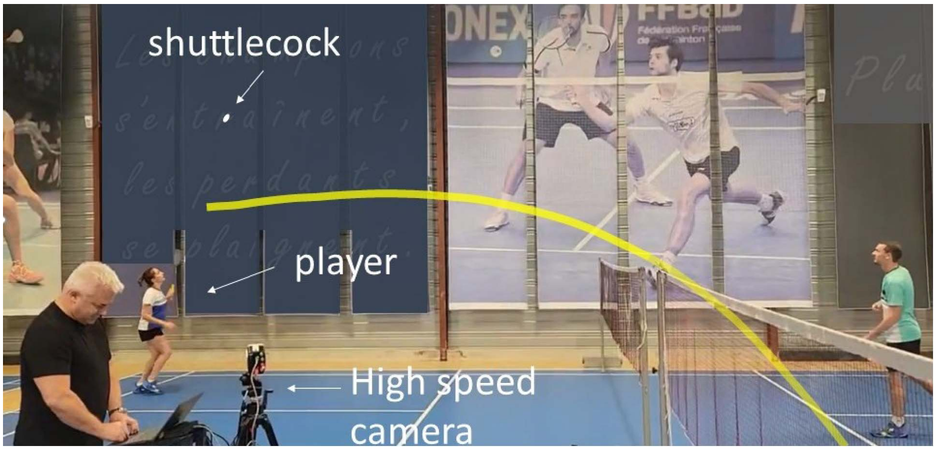

Figure 3. A high-speed camera captured videos of the trajectories of the shuttlecock at 3700 fps on the badminton court, as players performed different cross-court slice shots.

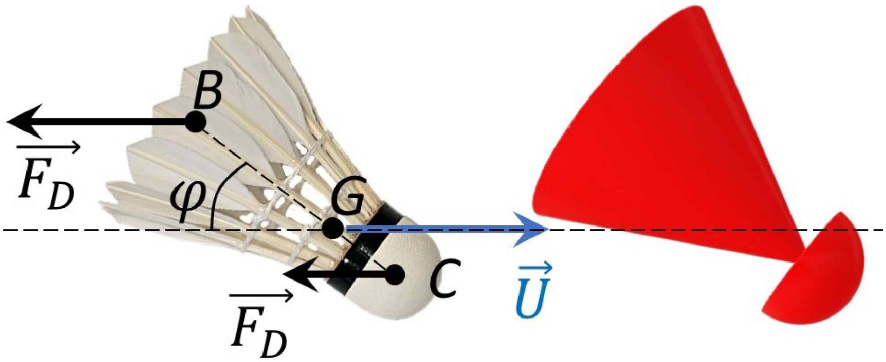

Figure 4. Left: the drag forces F_D applied on the feather and the cork generate a torque, stabilizing the shuttlecock axis along its velocity (see Ref. [8]). Right: schematic representation used in Figure 6.

Cohen and colleagues considered the effect of the aerodynamic pressure forces on the shuttlecock, with a global drag force applied at the pressure center point at the level of the feather [8], which depends on the surrounding pressure profile. When the pressure is uniform on the feather, the aerodynamic center is the centroid of the object. However, the center of gravity, closer to the cork, differs from the center of pressure [21]. Cohen and colleagues introduced a model explaining the shuttlecock flipping after impact with the racket, changing the direction of the shuttlecock propagation. They have shown that the stabilizing aerodynamic torque sets the shuttlecock nose ahead after impact. They modeled the shuttlecock with two spheres (Figure 4): one representing the light skirt with a large cross-section (positioned in B) and one representing the heavy small cork with smaller cross-section (placed in C) [8]. They explained that when the projectile flies with an angle φ with respect to the velocity $\vec{U}$, after an impact with a racket, a torque balance around the center of gravity G, due to different drag forces on the skirt and cork, makes the shuttlecock axis collinear to velocity $\vec{U}$. For an initial shuttlecock velocity of $\simeq$10 m·s^{-1} (36 km/h), they found a flipping time of $\simeq$20 ms, while the stabilization of the symmetry axis of shuttlecock along the direction of its velocity occurs typically within 150 ms and over $\simeq$1 m [8, 22]. Video 1a [23] shows such flipping processes for different shots. For example, when the initial velocity after racket impact is $\simeq$50 m·s^{-1} (290 km/h), the flipping time is of the order of 5 ms, while the stabilization of the symmetry axis of shuttlecock occurs within $\simeq$35 ms and over $\simeq$1 m (one racket length is about 68 cm).

Video 1b [24] shows the important deformation of the shuttlecock after impacts with the racket. When the shuttlecock incident velocity is perpendicular to the racket, we can observe a deformation that is akin to a blooming flower as observed in other studies [25], or a swimming jellyfish. Indeed, part of the kinetic energy is transferred to internal degrees of freedom of the shuttlecock, which act as energy bumper. As shown in the chronophotographies in Figure 5a, the shuttlecock is then exhibiting a damped breathing after impact with a pseudo-period of the order of $\simeq$2.16 ms. The overall feather diameter expands from 6.7 cm to $\simeq$8.6 cm within $\simeq$1.1 ms during the first oscillation and this breathing is damped within 4 oscillations. The third shot in Video 1b shows that when the racket does not strike the shuttlecock perpendicular to its axis, the deformation is more oval. However, this is difficult to analyze because of the camera's angle of view. For much weaker impacts, where acceleration is lower, it is difficult to observe the deformation of the shuttlecock. This deformation mode is similar to the breathing mode of some molecules, revealed by femtosecond pump-probe techniques [26–28]. The shuttlecock breathing is due to the important deceleration during impact, which bends the feather. In Video 1b [24], the

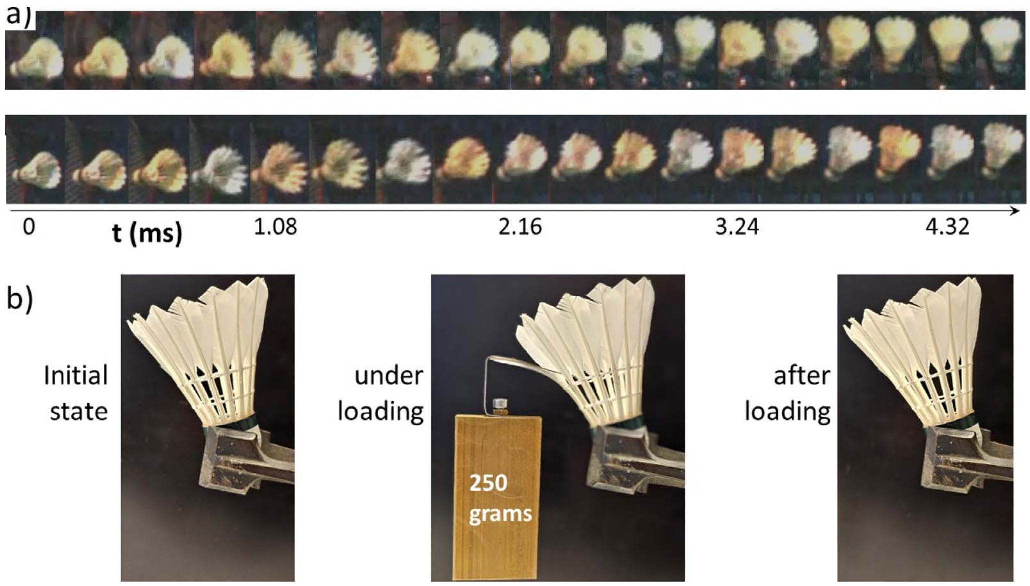

Figure 5. (a) Chronophotographies of the shuttlecock after impacts with the racket extracted from the Video 1b. For both shots the breathing period is ≃2.16 ms. (b) Reversible feather bending with a 250 g load.

incident velocities of the order of ≃11 $m \cdot s^{-1}$ (40 km/h) change to ≃44 $m \cdot s^{-1}$ (160 km/h) within ≃1.1 ms. This corresponds to an acceleration of the order of 50,000 $m \cdot s^{-2}$, i.e. 5000 g. During the impact lasting 1.1 ms, the 5 g of the shuttlecock are therefore equivalent to a weight of 25 kg. The weight of the flexible part of the feather, which is of the order of 0.05 g, transiently corresponds to 250 g. Figure 5b shows that the feather deformation induced by a 250 g load is similar to the one observed during impact and in the elastic deformation regime of the feather. This deformation is reversible after impact or loading in this elastic deformation regime.

3. Right-handed versus left-handed slices

Videos 2 [29–31] and 3 [32, 33] show different slices performed by elite right-handed and left-handed players. We extracted from the video analysis the temporal evolution of the shuttlecock rotation speed $\omega(t)$ around its symmetry axis. The cross-court slice shots were performed as shown in Figures 3, 6a and 6b, with left-handed players at the left corner of the court, sending the shuttlecock in diagonal at the opposite side just behind the net. We used the mirror symmetry situation with the right-handed players performing the slice shots from the right corner of the court towards the opposite side behind the net. Figure 6c shows the evolution of shuttlecock rotation speed $\omega(t)$ obtained from 3 slice shots performed by right-handed players (RH1, RH2 and RH3). The slice allows generating very high spinning, of the order of 100 revolutions per second ($\omega \simeq 100$ rps) just after contact with the racket. The counter-clockwise rotation is chosen as positive here, which corresponds to the natural rotation of the shuttlecock as it flies in the air. Figure 6c shows that the rotation speed rapidly decreases, with an apparent exponential decay. After ≃300 ms, on approaching the net, the rotation speed is of the order of 10–20 rps. The slice shot of left-handed players (LH1-3) generates similar fast spinning (≃100 rps) after contact with the racket, but the main difference is that the shuttlecock spins clockwise ($\omega < 0$)! As the rotation

Table 1. Fitting parameters from Equation (1) for the different slice shots for right-handed and left-handed players

	RH1	RH2	RH3	⟨RH⟩	LF1	LF2	LF3	⟨LF⟩
ω_i (rps)	103 (6)	112 (13)	120 (20)	112 (13)	−131 (3)	−121 (5)	−133 (7)	−128 (6)
τ (s^{-1})	33 (3)	32 (6)	32 (8)	32 (6)	55 (6)	80 (7)	49 (2)	61 (10)

The values in parentheses are the uncertainty.

accelerates (decelerates in absolute value), the shuttlecock goes out of spin after ≃100 ms, then starts to spin counter-clockwise due to air pressure on the chiral feather.

Around 300 ms after contact with the racket, the shuttlecock also reaches ≃15 rps, which is similar to the spinning observed for right-handed players. Since experimental data show an apparent fast exponential decay of rotation speed, followed by an almost linear decay, we used the following empirical model to fit the curves:

$$\omega(t) = \omega_i \exp\left(-\frac{t}{\tau}\right) + \omega_0 - at \tag{1}$$

$\omega_i + \omega_0$ corresponds to the initial rotation speed, just after contact with the racket and τ is the spinning deceleration time constant, which depends on shuttlecock, air density, etc. The fast-exponential decay corresponds to the equilibration of the shuttlecock rotation speed with its velocity. The almost linear decrease of rotation speed shown in Figure 6c ($\omega_0 - at$) corresponds to the natural decrease of rotation rate as shuttlecock is slowing down. We performed independent fits for the different slice shots (RH1-3 and LH1-3) with ω_0 = 23 rps and a = 34 rps·s^{-1} and the results are given in Table 1. The average initial rotation just after contact with the racket are similar for right-handed and left-handed players (≃120 rps). The spinning deceleration time constants are similar for the three right-handed player shots, with an average τ = 32 (6) ms ((6) refers to the uncertainty from the fit) and globally larger for left-handed players (τ = 61 (10) ms). These different spinning deceleration time constants are due to the aerodynamic of the spinning shuttlecock. Figure 6d shows that for a clockwise rotation of the shuttlecock the airflow runs parallel to the feathers, while for a counter-clockwise rotation the airflow collides with the edges of the feathers. Friction with the air is therefore greater for the counter-clockwise rotations induced by right-hander during slice shots, which results in faster angular deceleration compared to left-hander slice shots.

These very rapid changes in rotation speeds can be clearly seen in Video 4a [34] (slowed down 500 times). To highlight the difference between left-handed and right-handed slices, mirror symmetry is used in Video 4b [35], which shows that the shuttlecock slows down more on a left-handed slice than on a right-handed one.

As slice shots are performed, players and coaches noticed different sounds for left-handed and right-handed players. This is also due to the orientation of the feathers: the racket of the right-handed player rubs the shuttlecock almost parallel to the feathers, while it is almost perpendicular for the left-handed players. It may therefore be easier for left-handed players to spin the shuttlecock, but this process is too fast to be studied with the present videos set-up. The slice shot performed by both left- and right-handers generates high initial spinning rate (≃100 rps) of the shuttlecock, which makes this shot very different from a smash shot. Indeed, we can see in Video 1a [23] that the smash itself does not generate rapid rotation after the impact with the racket if the racket hits the shuttlecock perpendicular to the trajectory. Rotation is induced by the friction of the air on the feathers, and the shuttlecock typically reaches ≃60 rps within 50 ms (Video 1a [23]).

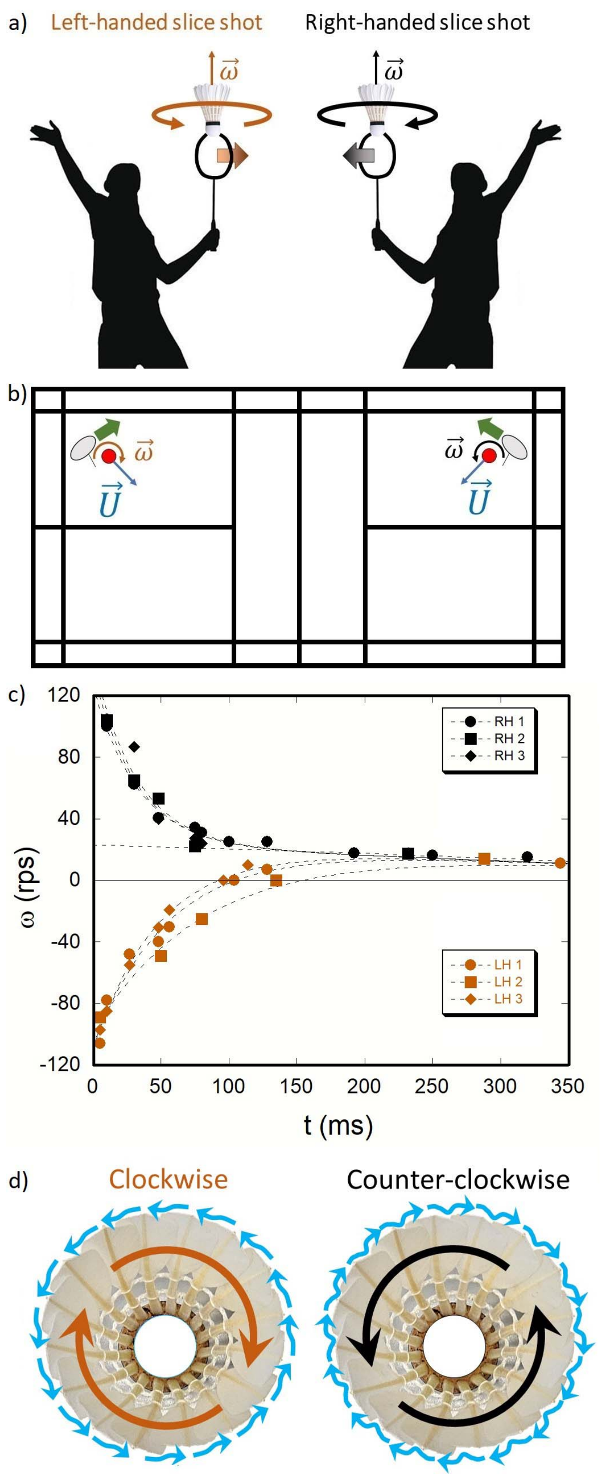

Figure 6. (a,b) Slice shot performed by right-handed and left-handed players, inducing opposite shuttlecock spinning after contact with the racket. (c) Rotation speed $\omega(t)$ after slice shots. (d) Schematic representation of airflow (blue) with the spinning of the shuttlecock.

The high rotational speed of the shuttlecock after slice shot is generating a large centrifugal force. Video 5a [36] shows the deformation induced by fast spinning perpendicular to velocity. The drag coefficient for a rotating standard shuttlecock can increase due to a large centrifugal force [37]. Obayashi *et al.* investigated the effect of a shuttlecock rotation on its skirt deflection [5]. They have shown that the skirt enlargement due to the centrifugal forces is compensated by the effect of the aerodynamic drag when the shuttlecock travels aligned along its rotation axis. We can see on different videos (2a, 2b, 2c, 2a, 3a, 4b) that there is no significant shape change when shuttlecock rotation axis is along velocity, while shuttlecock feathers clearly bend when the spinning axis is perpendicular to velocity, as aerodynamic drag does not compensate the deformation induced the centrifugal force. Figure 7 and Video 5b [38] show the deformation of the shuttlecock, mounted on a Dremel, with rotation speed. The deformation of the shuttlecock is characterized by the deflection d of the radius $R(\omega)$ measured at rotation speed ω, with respect to the radius at rest R_0 with $d = R(\omega) - R_0$. This deflection is due to the high centrifugal force, related to centrifugal acceleration a_c, acting on the feather. Considering $a_c = R\omega^2$, with $\omega = 785$ rad·s^{-1} (125 rps) and $R = 0.0335$ m, the centrifugal acceleration at the edge of the feather reaches 20,643 m·s^{-2}, which almost corresponds to 2000 g. Even if the mass of the feather is small, the very high g-force acting on its mass is able to bend it. If we approximate the mass density on the feather as homogeneous along its lengths, the deflection is then simply proportional to the g-force, itself scaling with ω^2. The fit in Figure 7, considering $d \propto \omega^2$ is in quite good agreement with experimental data, given the rough approximation considering the feather as homogeneous. The shuttlecock deformation observed on Video 5a [36] just after the slice is similar to the one observed around 125 rps in Figure 7, which confirms that its deformation is due to its high spinning rate after slice shot.

The clockwise to counter-clockwise shuttlecock rotation induced by the slice shots of left-handed players is therefore very different from the one of the right-handed players, as suspected from the symmetry considerations introduced above, and clearly shown by the super slow motion videos. For right-handed players, the fast counter-clock spinning may accelerate the shuttlecock, which experiences after a continuous decrease of spinning rate due to drag forces. On the contrary, for left-handers, the initial clockwise rotation should slow down the shuttlecock. In addition, for left-hander's slice shots the shuttlecock transiently flies without any spin, and therefore without rotation energy, before going into its natural counter-clockwise spinning on approaching the net. This clearly evidences an energy transfer from kinetic energy to rotational energy in the 100–300 ms range, which contributes to slowing down the shuttlecock. Indeed, during this time interval after the slice shot, the rotational energy increases for left-handers, while it monotonously decreases for right-handers. We will discuss how this process affects trajectories in more detail later, because the reader may have noticed a strange phenomenon on Videos 2 and 3 [29–33].

4. Magnus effect after slice shots

Videos 2 and 3 [29–33] show that, for some slice shots, after contact with the racket the shuttlecock is no more oriented along its initial speed $\vec{U}$, but almost perpendicular. For right-handers (Figure 8a), the shuttlecock points towards the player. Here again, the initial velocity towards the net is associated with drag forces (Figure 4) responsible for a torque stabilizing the shuttlecock with the cork pointing towards its velocity. Videos 2 [29–31] and 4b [35] and Figure 8a clearly show that in addition to flipping towards its stable orientation, the shuttlecock is lifting up during the early stage of the fly. This phenomenon is due to the Magnus effect [13]. When the shuttlecock rotates perpendicularly to its velocity as it flies, the surrounding air rotates. Therefore, the air speed on one side increases and decreases on the other side. Bernoulli's theorem indicates that

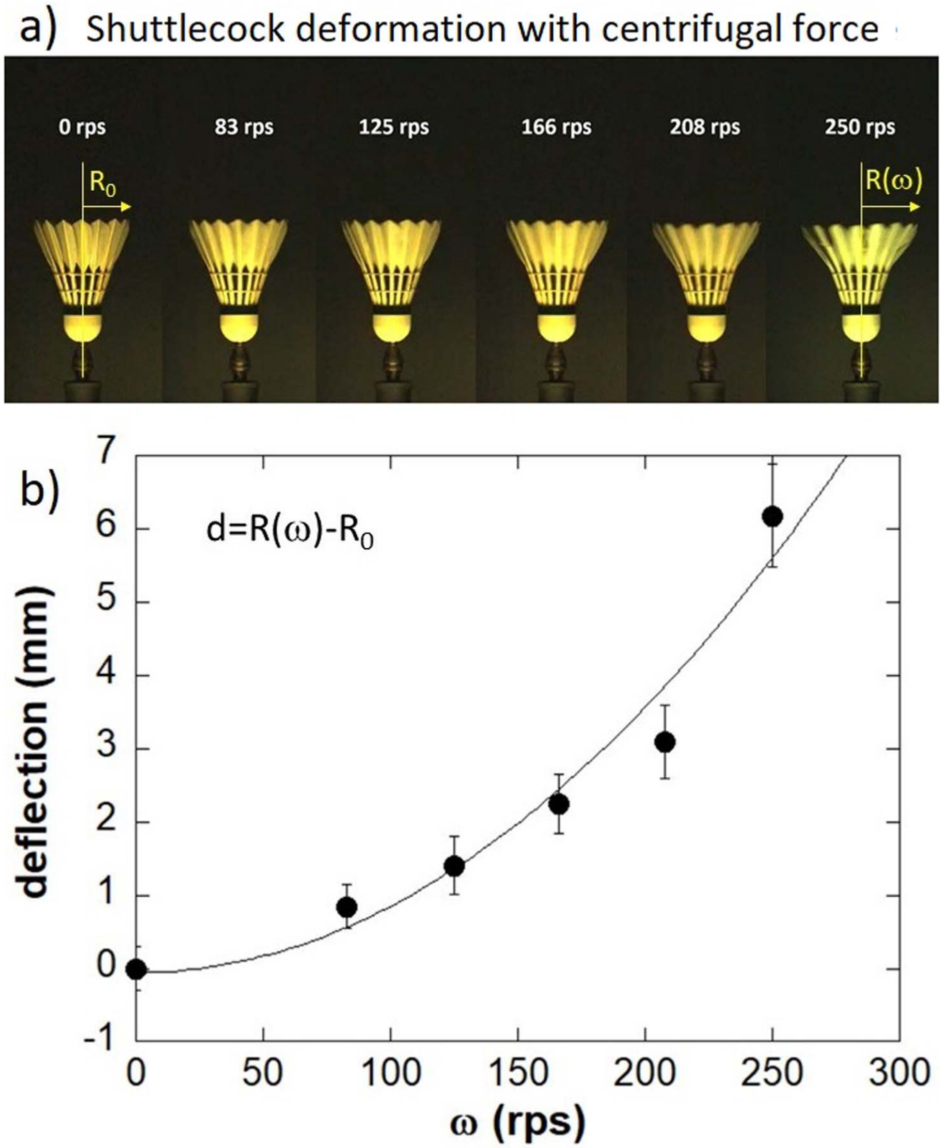

Figure 7. (a) Shuttlecock deformation with rotation speed observed in Video 5b [38]. (b) The radius deflection d (dots with error bars) increases with rotation speed ω. The continuous line shows the fit of the data with $d \propto \omega^2$.

an increase in fluid velocity leads to a decrease in pressure, which results in a transverse force, the Magnus force ($\vec{F_M}$), acting on the shuttlecock. The Magnus force is given by $\vec{F_M} \propto \rho V \vec{\omega} \wedge \vec{U}$, where ρ is the air density and V the volume of the shuttlecock. We mentioned above that Magnus effect is usually neglected in badminton, because the rotation axis is usually colinear with velocity. However, the Videos 2 and 4b clearly reveal that after slice shots the rotation axis can be almost perpendicular to the velocity during the first 30 ms, which maximizes the Magnus force at a moment when the rotation speed $\vec{\omega}$ is also very high (above 50 rps, Figure 6c). The angular right-hand rule is very useful to explain the Magnus effect from a right-handed player (Figure 8a): the right index points in the direction of the rotation ($\vec{\omega}$), the finger index points in the direction

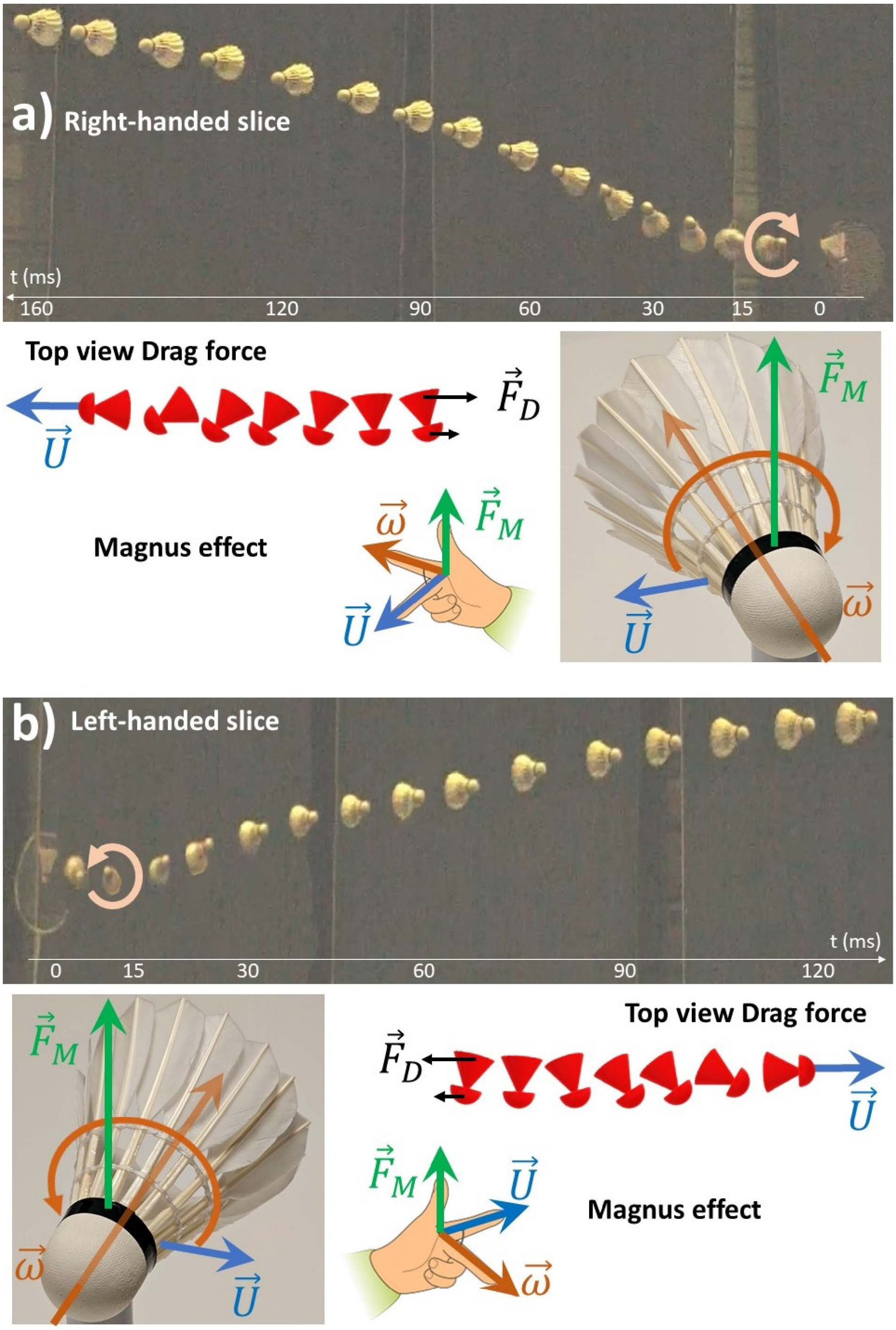

Figure 8. Magnus effect lifting up the projectile after slice shots performed by right-handed (a, extracted from Video 2c) or left-handed player (b, extracted from Video 3b). It occurs in the early stage of the trajectory, as the counter-clockwise (right-handers) or clockwise (left-handers) spinning axis $\vec{\omega}$ of the shuttlecock is perpendicular to its velocity $\vec{U}$. The Magnus effect stops when spinning axis gets collinear to velocity, due to the drag torque.

of the velocity ($\vec{U}$) and the thumb is then pointing towards the Magnus force ($\vec{F_M}$). The Magnus force is then lifting up the shuttlecock. This effect stops within ≃30 ms as the shuttlecock stabilizes its spinning axis $\vec{\omega}$ collinear to its velocity $\vec{U}$. It is therefore necessary to use super-slow-motion cameras to observe this transient Magnus effect and the fast initial spinning responsible for this phenomenon.

If we look at the trajectory of the shuttlecock after a left-handed player slice shot (Figure 8b), we can see that it also lifts up. Indeed, the left-handed player spins the shuttlecock in opposite directions, compared to the right-handed player, but the initial velocity also changes direction (Figure 6b). The cross product is then unchanged and the Magnus force also lifts up the shuttlecock. For the left-handed readers, in addition to the right-handed rule mentioned above, it is suggested to use for this specific case the angular left-hand rule (Figure 8b) to understand the direction of the Magnus effect: the left index points in the direction of the velocity ($\vec{U}$), the finger index in the direction of the rotation ($\vec{\omega}$) and the thumb is pointing towards the Magnus force ($\vec{F_M}$), which is also lifting up the shuttlecock. The timescales and trajectories of the shuttlecock lifting during the Magnus effect are similar for right-handed and left-handed players. This is due to the fact that during both types of slice shots the initial rotation speeds and velocities are similar for left- and right-handers. The magnitude of the Magnus effect observed in Videos 2 and 3 [29–33] is in the range of 20–70 cm, and we observe a weaker Magnus effect for the slice shots of left-handers. Again, this is due to the implementation of the feathers, which generates greater friction with the air when the shuttlecock turns counter-clockwise on right-handed slices (Figure 6d) than when the it turns clockwise on left-handed slices. When the player gives a large transverse component to the initial velocity of the shuttlecock (with the titled racket or shot), the shuttlecock flips and its rotation axis $\vec{\omega}$ gets perpendicular to its velocity $\vec{U}$, maximizing so the cross product behind the Magnus force, which lifts up the shuttlecock. As this transverse component is reduced, the Magnus effect lowers in amplitude. When the shuttlecock spinning axis is perpendicular to its velocity, the higher the initial spinning and velocities, the stronger the Magnus effect, which can therefore modify significantly the trajectories for both left-handed and right-handed players.

5. Shuttlecock trajectories

Video 6 [39] and Figure 9 show the global trajectories for typical slice shots performed by left-handed and right-handed players. For slice-shots crossing the court over similar distances, the time of flight is about 15–20% longer for left-handed player slice shots (0.91(4) s versus 1.08(4) s), as also highlighted in Video 4b [35]. This is due to the lowest average horizontal speed as the shuttlecock is slowed down by its clockwise initial spinning. As the shuttlecock reaches the net, the lowest horizontal speed translates in a more vertical trajectory for left-handers. Of course, many parameters—such as player's size, eight of the jumps, initial horizontal/vertical speed components, etc.—can affect the falling angle as the shuttlecock touches the ground. In Video 6 [39], where these parameters are similar, the falling angle is higher (≃65°) for the left-handed player compared to the right-handed player (≃50°). Consequently, if the shuttlecock passes just above the net for both types of players, it will fall closer to the net in the case of a slice shot performed by a left-handed player, compared to a right-handed player. The different ratios between horizontal and vertical speeds, once the shuttlecock has passed the net, are therefore due to the clockwise rotation of the shuttlecock after the left-handed slice shot, which rotates in the opposite direction to the natural rotation. Previous aerodynamic studies of spinning shuttlecock revealed a weak variation of the drag force with or without spinning, which may explain the slower trajectory for left-handed players. However, in the case of the clockwise spinning, opposite to natural rotation, the drag force and the aerodynamics may change significantly. In addition, as mentioned above,

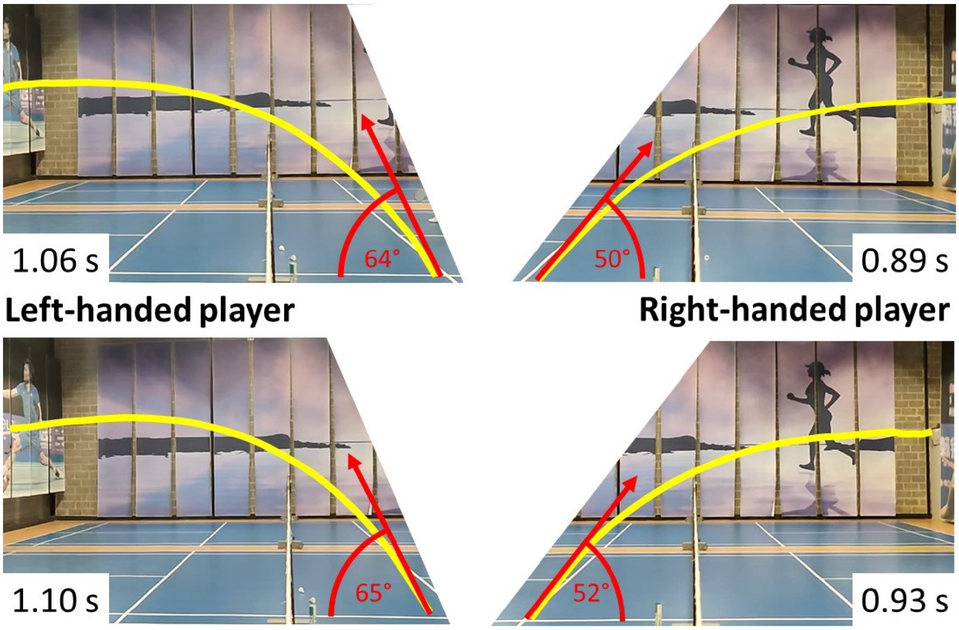

Figure 9. Typical trajectories for slice shots (yellow) performed by left-handed (left) and right-handed (right) players. The time of flight is longer for left-handed players and the slower trajectory translate in a higher falling angle (red) for left-handers (≃65°) than right-handers (≃51°).

the kinetic energy (and therefore the speed) is reduced for the left-hander's slice shot as part of this energy is transferred to rotational energy, as the shuttlecock spins clockwise, then stops spinning before spinning counter-clockwise on approaching the net. Both phenomena qualitatively contribute to different slowing down of the shuttlecock between left-hander's and right-hander's slice shot.

6. Conclusion

Super slow motion videos provide key information on ultrafast dynamics intrinsic to badminton physics, driven by extreme stresses applied to the shuttlecock after racket impact. For manufacturers, it is a real challenge to propose feather shuttlecocks able to support ultimate spinning rates (larger than 100 rps), ultrafast flipping or breathing deformation after impact with the racket. Indeed, there is often a moment in the game where players have to perform strategic powerful shots or fast slices. The videos revealed very different spinning dynamics, caught on the fly, after slice shots performed by left- and right-handers. A quantitative comparison is difficult because the slice shots for left- and right-handers are different in nature due to symmetry. On the one hand, right-handers rub the shuttlecock almost parallel to the feathers, while left-handers rub it almost perpendicular. On the other hand, the accelerated counter-clockwise spinning induced by right-handed players and the clockwise to counter-clockwise spinning induced by left-handed players intrinsically generate different trajectories of the shuttlecock, creating a steeper sliced shot for left-handed players. Although how much of an advantage this gives left-handers is not clear, it is an advantage. Hopefully, this is somewhat compensated by the possibility for the players to perform reverse-slice shots, which are then more advantageous for right-handers and which could be a subject for future studies. However, the joint constraints on the arm when the forearm is pronated for a right-handed player will modify the hitting plane and may also modify the shuttlecock's speed and behavior. It is important to underline that a slice shot is efficient when it skims the net. The present results highlight the importance of balancing the transfer of transverse speed to the shuttlecock, to limit the Magnus effect. In fact, too much Magnus effect raises the shuttlecock more than necessary and thus reduces the effectiveness of the slice shot. This concerns both right-handed and left-handed players. The players are thus left to make the right shot and as Robin Williams said, "What's right is what's left if you do everything else wrong."

Declaration of interests

The author does not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and has declared no affiliations other than his research institution.

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Supplementary material

The videos are also available on a YouTube channel: click the links:

Videos 1a and 1b: Shuttlecock flipping and breathing.
https://youtu.be/MxU08IsCOJs and https://youtu.be/uo_bSmp8LRI

Videos 2a, 2b and 2c: slice right-handed players
https://youtu.be/9Rwyw9OSROw, https://youtu.be/UgeZOBo--5M and https://youtu.be/uxcP8iKRBVc

Videos 3a and 3b: slice left-handed players
https://youtu.be/PivDQ0f4h5k and https://youtu.be/edMxKmq-E4M

Videos 4a and 4b: time evolution of rotation speed
https://youtu.be/9KG0-MBja6s and https://youtu.be/j-fQIZEmrMc

Video 5: centrifugal force on the shuttlecock
https://youtu.be/jNNvOnucV0Q1001 and https://youtu.be/ysxnumuBaSI

Video 6: shuttlecock trajectories https://youtu.be/5HjanVzecrE

References

[1] M. Phomsoupha, G. Laffaye, "The science of badminton: game characteristics, anthropometry, physiology, visual fitness and biomechanics", *Sports Med.* **45** (2015), p. 473-495.

[2] A. E. Flatt, "Is being left-handed a handicap? The short and useless answer is "yes and no."", *Proc. (Bayl. Univ. Med. Cent.)* **21** (2008), p. 304-307.

[3] IUCr, *International Tables for Crystallography, Volume A: Space Group Symmetry*, 5 revised edition ed., Kluwer Academic Publishers, Dordrecht, Boston, London, 2002.

[4] J. E. Morgan, *The Design and Development of a Shuttlecock Hitting Machine for Training Badminton Players at all Levels of the Game*, CRC Press, London, 1996.

[5] S. Kitta, H. Hasegawa, M. Murakami, S. Obayashi, "Aerodynamic properties of a shuttlecock with spin at high Reynolds number", *Procedia Eng.* **13** (2011), p. 271-277.

[6] C. M. Chan, J. S. Rossmann, "Badminton shuttlecock aerodynamics: synthesizing experiment and theory", *Sports Eng.* **15** (2012), p. 61-71.

[7] A. Verma, A. Desai, S. Mittal, "Aerodynamics of badminton shuttlecocks", *J. Fluids Struct.* **41** (2013), p. 89-98.

[8] C. Cohen, B. D. Texier, D. Quéré, C. Clanet, "The physics of badminton", *New J. Phys.* **17** (2015), article no. 063001.

[9] R. C. Mehta, "Aerodynamics of sport balls, badminton shuttlecock and javelin", *Sch. J. Eng. Tech.* **11** (2023), p. 4-16.

[10] L.-M. Chen, Y.-H. Pan, Y.-J. Chen, "A study of shuttlecock's trajectory in badminton", *J. Sports Sci. Med.* **8** (2009), no. 4, p. 657-662.

[11] B. D. Texier, C. Cohen, D. Quéré, C. Claneta, "Shuttlecock dynamics", *Procedia Eng.* **34** (2012), p. 176-181.

[12] J. E. Goff, "A review of recent research into aerodynamics of sport projectiles", *Sports Eng.* **16** (2013), p. 137-154.

[13] G. Magnus, "Ueber die Abweichung der Geschosse, und: Ueber eine auffallende Erscheinung bei rotirenden Körpern", *Ann. Phys. Berlin* **164** (1853), p. 1-29.

[14] M. A. González Hernández, "Aerodynamics performances in sports", in *34 International Conference of Biomechanics in Sport*, 2016, https://ojs.ub.uni-konstanz.de/cpa/article/view/692.

[15] B. D. Texier, C. Cohen, D. Quéré, C. Clanet, "Physics of knuckleballs", *New J. Phys.* **18** (2016), article no. 073027.

[16] A. J. Cooke, "Shuttlecock aerodynamics", *Sports Eng.* **2** (1999), p. 85-96.

[17] N. Johnson, E. J. Chae, "2D aerodynamic analysis of a badminton shuttle for re-entry vehicle applications", in *Active and Passive Smart Structures and Integrated Systems XIV*, vol. 11376, 2020, p. 15.

[18] C. Cohen, B. Darbois Texier, D. Quéré, C. Clanet, "Physics of badminton shuttlecocks. Part 1: aerodynamics", in *64th Annual Meeting of the APS Division of Fluid Dynamics*, vol. 56, 2011, Abstract ID: BAPS.2011.DFD.M10.8.

[19] M. Phomsoupha, G. Laffaye, "Shuttlecock velocity during a smash stroke in badminton evolves linearly with skill level", *Comput. Methods Biomech. Biomedical Eng.* **17** (2014), p. 140-141.

[20] M. Hubbard, A. Cooke, "Spin dynamics of the badminton shuttlecock", in *6th International Symposium on Computer Simulation in Biomechanics*, 1997, p. 42-43.

[21] A. Cooke, "Computer simulation of shuttlecock trajectories", *Sports Eng.* **5** (2002), p. 93-105.

[22] V. Kaushik, "Unique flight features of shuttlecock", *Int. Res. J. Eng. Technol.* **4** (2017), p. 521-525.

[23] E. Collet, "video 1a", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[24] E. Collet, "video 1b", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[25] C. S. H. Lin, C. K. Chua, J. H. Yeo, "Turnover stability of shuttlecocks – transient angular response and impact deformation of feather and synthetic shuttlecocks", *Procedia Eng.* **60** (2013), p. 106-111.

[26] H. T. Lemke, K. S. Kjær, R. Hartsock, T. Brandt van Driel, M. Chollet, J. M. Glownia, S. Song, D. Zhu, E. Pace, S. F. Matar, M. N. Nielsen, M. Benfatto, K. J. Gaffney, E. Collet, M. Cammarata, "Coherent structural trapping through wave packet dispersion during photoinduced spin state switching", *Nat. Commun.* **8** (2017), article no. 15342.

[27] S. Zerdane, L. Wilbraham, M. Cammarata, O. Iasco, E. Rivière, M. L. Boillot, I. Ciofini, E. Collet, "Comparison of structural dynamics and coherence of d–d and MLCT light-induced spin state trapping", *Chem. Sci.* **8** (2017), p. 4978-4986.

[28] M. Cammarata, R. Bertoni, M. Lorenc, H. Cailleau, S. Di Matteo, C. Mauriac, S. F. Matar, H. Lemke, M. Chollet, S. Ravy, C. Laulhe, J. F. Létard, E. Collet, "Sequential activation of molecular breathing and bending during spin-crossover photoswitching revealed by femtosecond optical and x-ray absorption spectroscopy", *Phys. Rev. Lett.* **113** (2014), article no. 227402.

[29] E. Collet, "video 2a", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[30] E. Collet, "video 2b", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[31] E. Collet, "video 2c", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[32] E. Collet, "video 3a", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[33] E. Collet, "video 3b", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[34] E. Collet, "video 4a", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[35] E. Collet, "video 4b", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[36] E. Collet, "video 5a", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[37] H. Hasegawa, S. Kitta, M. Murakami, S. Obayashi, "Flow analysis and aerodynamic characteristics of a badminton shuttlecock with spin at high Reynolds numbers", *Sports Eng.* **16** (2013), p. 91-98.

[38] E. Collet, "video 5b", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.

[39] E. Collet, "video 6", video, Zenodo (8 January 8, 2024), https://doi.org/10.5281/zenodo.10469558.