SUSTAINABILITY & SPORTS SCIENCE JOURNAL

REVIEW ARTICLE

The scientific development of badminton shuttlecocks: Review paper

Terence Woo . *School of Engineering (Aerospace, Mechanical and Manufacturing Engineering). RMIT University. Melbourne, Australia.*
Firoz Alam. *School of Engineering (Aerospace, Mechanical and Manufacturing Engineering). RMIT University. Melbourne, Australia.*
Alex Kootsookos. *School of Engineering (Aerospace, Mechanical and Manufacturing Engineering). RMIT University. Melbourne, Australia.*

ABSTRACT

This paper reviews published works of the field of badminton research within the past 50 years, focusing primarily on the design and flight dynamics of shuttlecocks to identify any knowledge gap. With regards to shuttlecock research, various methodologies involving empirical and theoretical studies including: wind tunnel testing, simulation, shuttlecock design and prototyping, have been presented. To improve the readability, studies are discussed collectively based on the nature of the investigation according to whether empirical and/or combinations of theoretical approaches have been implemented. Upon reviewing the current body of literature, it is believed that there is a lack of emphasis in correlating the structural and aerodynamics aspects of the badminton shuttlecock. Further investigation into the structural mechanics of the bird feathers used for natural feather shuttlecocks may serve as an inspiration in the development of subsequent synthetic shuttlecock designs.
Keywords: Aerodynamics, Badminton, Computational fluid dynamics, Feather shuttlecock, Shuttlecock design, Synthetic shuttlecock.

Cite this article as:
Woo, T., Alam, F., & Kootsookos, A. (2024). The scientific development of badminton shuttlecocks: Review paper. *Sustainability and Sports Science Journal*, *2*(3), 149-165. https://doi.org/10.55860/ZQQE3823

Corresponding author. *School of Engineering (Aerospace, Mechanical and Manufacturing Engineering). RMIT University, PO Box 71, Bundoora, Victoria 3083, Australia.*
E-mail: terencewoo@outlook.com
Submitted for publication April 10, 2024.
Accepted for publication May 21, 2024.
Published June 26, 2024.
Sustainability and Sports Science Journal. ISSN 2990-2975.

Identifier: https://doi.org/10.55860/ZQQE3823

INTRODUCTION

The purpose of this review article is to consolidate the current body of literature in relation to the badminton shuttlecock design. This article is structured into four sections. *Section 1* introduces the fundamental features of different shuttlecock designs currently available in the market. *Section 2* discusses the trajectory of shuttlecock and how it is different from both the conventional concept of projectile motion and other mainstream ball sports. *Section 3* provides an overview on some of the academic research accumulated over the past 50 years: from exercise science to sports technology. *Section 4* summarises the current regarding badminton shuttlecock research and outlines potential future research opportunities.

CONTEMPORARY SHUTTLECOCK DESIGNS

A shuttlecock, also called a shuttle, bird or birdie, is the projectile used in badminton. It has an open-cone shape formed by natural bird feathers, or synthetic materials, inserted into the flat rear surface of a bullet-head base—which is made from either natural cork, composite cork or synthetic foam.

For a shuttlecock product to be approved by the Badminton World Federation (BWF) for official tournament use, several criteria need to be fulfilled (Table 1). It should be noted; however, it is not obligatory for manufacturers to comply with these criteria for their products to be sold. In the context of academia, however, using approved shuttlecocks provide scientists with additional confidence knowing that their samples can be measured against products that are manufactured based on set guidelines when necessary—such as during rapid prototyping.

Table 1. Shuttlecock manufacturing criteria to fulfil for gaining BWF approval (BWF 2018).

Feather Shuttle	Synthetic Shuttle
16 feathers fixed in a rounded cork base	Synthetic rubber with open-cone shape
Uniform feather stem/rachis length 62 – 70 mm (i.e. tip to top of attachment point on cork base)	Identical measurements & weight requirement as specified for feathered shuttles
Weight = 4.74 - 5.50 g	Acceptable variation in dimension up to ±10%*
Circular alignment of tips with diameter 58 – 68 mm	
Feathers are reinforced with threads, strings or any other weightless material deemed suitable	
The base shall be 25 - 28 mm in diameter & rounded on the bottom	

*Note. *Due to differences in specific gravity & other properties of synthetic materials.*

Synthetic shuttlecock products typically adopt a colour coding system where green, blue, and red represent low, medium or high speed respectively; for feather shuttlecocks several 5-number metric systems are used: 1-5, 48-52 or 75-79. A shuttlecock brand implementing a colour system as a speed and altitude indicator (Yonex, 2019). While the numbers seem to be arbitrary, the median number always represent products suitable for sea-level countries (e.g. most of Southeast Asia), lower numbers are recommended for highlands (e.g. Johannesburg) and high numbers for below sea level (e.g. Finland) (Badminton Oceania Confederation n.d.).

Feather shuttlecocks

The badminton shuttlecock is unique given its open design which allows air to flow through the projectile during flight. In addition, the shuttlecock—unlike other mainstream ball sports—has only a single axis of symmetry resembling an isosceles triangle. In principle, feather shuttlecocks can only be made aerodynamically consistent, but never aerodynamically constant, as the projectile requires the use of feathers from multiple birds (Taneepak 2005). This is because each bird may have lived under different environmental conditions like humidity, altitude and temperature (Willis 1996; Subramaniyan 2008).

Due to the projectile's blunt-headed appearance, the academic community refers the badminton shuttlecock as a bluff body—characterised by a wide flow separation at its rear end leading to the formation of vortices (Efstathios and Bouris 2012). Despite its open-gap design, it has been illustrated that jets of air flowing through the feather shuttlecock interacts with the outer flow to produce an unsteady and irregular wake pattern (Cooke 1999; Alam, Nutakom and Chowdhury, 2015).

Materials of natural shuttlecocks

A natural feather shuttlecock has a hollow conical shape, constructed using 16 waterfowl feathers—either from geese or ducks. The quills of the feathers are fixed into pre-drilled holes around the perimeter of the natural cork base such that the feathers fan out away from the cork (Figure 1).

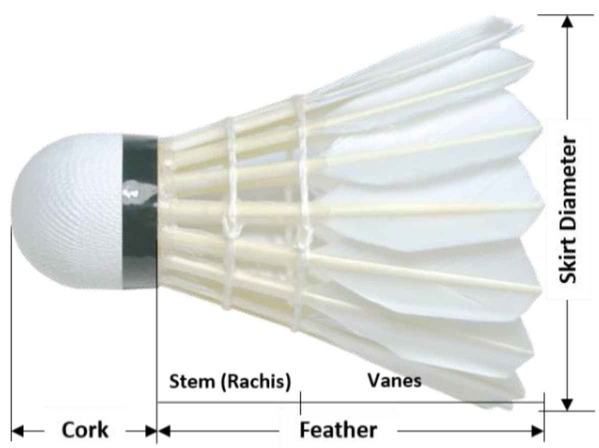

Figure 1. Lateral view of a feather shuttlecock. The main features include the cork tip, feather skirt and diameter of the skirt formed by the tips of the feathers.

The cork, sometimes referred to as the nose or head of the shuttlecock, is composed of a solid natural, or composite, cork covered by a polyester wrapping that provides a slight roughened leathery feel to the surface. This wrapping also serves to prevent the cork from flaking off during a rally due to repeated racquet strikes. A shuttle's "*skirt*" refers to the portion of the feathers extruding from the cork fanning-out in an angulated manner. The structure of the skirt is maintained by two strings intertwining the front and back of the feather stems. After being pulled taut, the strings are glazed over with industrial adhesive as additional reinforcement.

Manufacturing of natural shuttlecocks

The quality of flight of a feather shuttlecock is dictated by the feathers' shape, penetration (angulation, texture and curvature) and the colour of the feathers and storage period; climate (i.e. humidity) also affect the feather quality. Since feather selection is a key process during production, currently, it is extremely labour-intensive and contribute significantly to natural shuttlecock prices.

One will also notice subtle differences upon inspecting the feather of geese and ducks. For example, the grooved surface of a goose feather stem, or rachis, compared to the smooth surface that of ducks. It has been said that the rachis of goose feathers is structurally stronger than duck feathers as geese are said to have longer growth spurts (CNTV 2011).

Despite public opinions indicating that feathered shuttlecocks are only made from feathers of a bird's left wing (Basu 2016), it is not a specified criterion under the official statute set by the BWF (2018) and has previously been clarified by a leading badminton manufacturer in an official interview (Yonex 2012).

Controversially, the same interview also reports that the shuttlecocks should always *"…veer right to the same degree"* (p.13). Given that using feathers from both wings on a single shuttlecock would deter its spinning trait, thus, there may be some logic regarding shuttles using feathers of wings from the same side of different birds.

Synthetic shuttlecocks

Single-piece skirt

In contrast to the naturally feathered shuttlecock, the single skirt injection-moulded shuttle—also known as plastic or synthetic shuttle—is the feather alternative currently available (Figure 2). Although no definitive evidence is available, many believe the synthetic shuttlecocks manifested to address the natural feather shuttlecock's lack of durability. Other popular theories include an attempt to tackle global inflation which led to rises in natural shuttlecock prices (Ucantseeme 2015) and avian flu which is also associated with the fluctuation in shuttlecock prices (Carlol 2004; Daily Mail Reporter 2013).

Figure 2. Typical single-injection moulded synthetic shuttlecock.

The regulation of synthetic shuttlecock production is defined by the dimensions that of a feather shuttlecock (Table 1), but with a ±10% leniency to account for the different materials that manufacturers may utilise (BWF 2018). To date, most synthetic products have only achieved varying degrees of success and popularity, this is due to ineffective selection of synthetic materials (Lin, Chua and Yeo, 2013a), leading to substandard aerodynamics (Cooke, 1992).

One of the most discussed flaws of this shuttlecock type is the undesirable collapse of the skirt during flight which considerably alters its flight path. This shortcoming is due to the limitation of the single mould method unable to vary the nylon density at different parts of the skirt which exists in biological feathers (Figure 3).

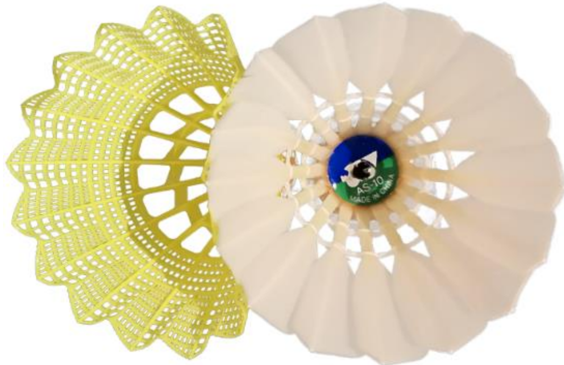

Figure 3. Demonstration of the structural resilience between feather and single injection-mould synthetic shuttlecock skirt.

Given the low production cost and improved durability, synthetic shuttlecocks are accepted by recreational badminton players who see badminton as a mean for social gathering and physical activity participation, as opposed to those playing competitively.

Two-piece skirt

The two-piece injection mould shuttlecock was developed to overcome the limitations of the single skirt shuttle. The design features a rigid lower portion (grey) and a lightweight (white) upper portion, where the two skirt components are joined together using adhesive, to imitate the stiffer rachis and vane portions of a natural feather (Figure 4). One noticeable difference in the design is the inclusion of a pin-like structure that extends from the insert section of the grey portion of the skirt which is then injected into the cork using a gelatinous adhesive substance. According to the manufacturer (Willis 2014a), the two-part skirt design achieves the peak-and-drop flight pattern that of the feather shuttlecock.

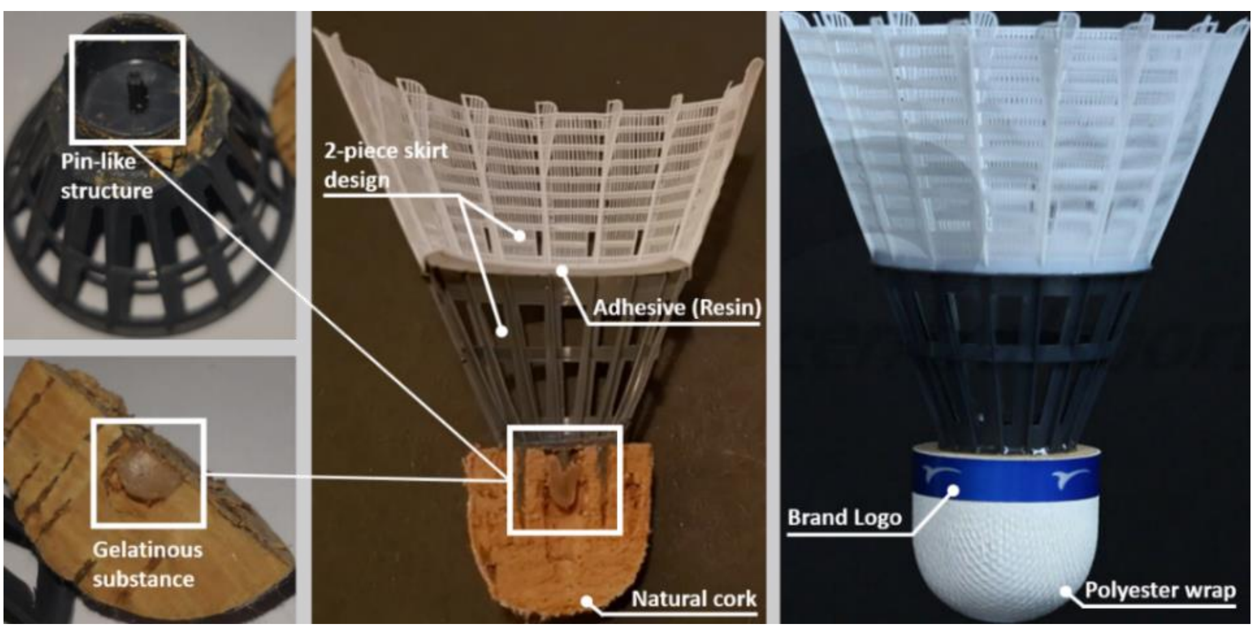

Figure 4. Dissection of the two-part skirt shuttlecock.

The shuttle constructed via this method has been reported to possess a three-fold increase in rigidity compared to the traditional synthetic shuttle—i.e. the skirt deforms less when subjected to a high-force racquet strike (Willis 2014b). It was subsequently reported that the two-part skirt design was able to more effectively model the aerodynamics of the feather shuttlecock at high speeds (Woo and Alam 2017).

Synthetic feather

The synthetic feather shuttlecock's general structure consists of a carbon fibre shaft; the typical stitching reinforcement seen on feather shuttles and a composite cork base (Figure 5).

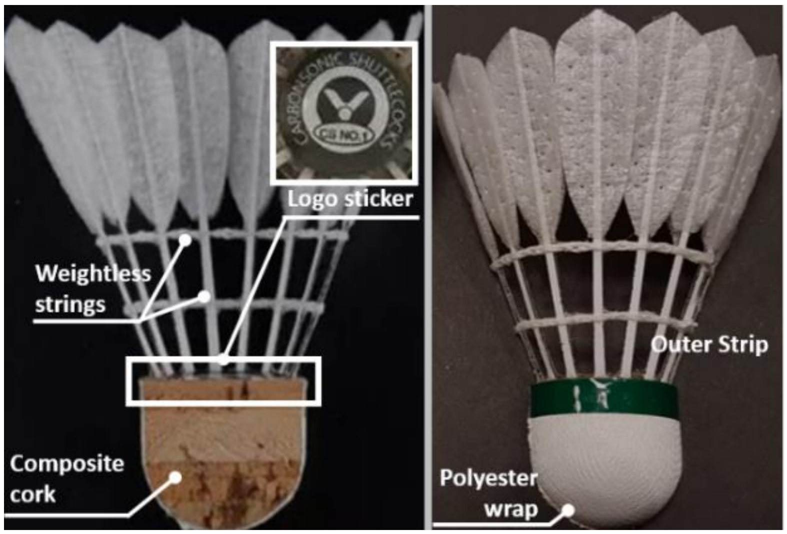

Figure 5. Dissection of a synthetic feather shuttlecock.

The construction imitates the outlook of a feather shuttlecock. The vane of feathers is being replaced using transparent dimpled polystyrene-like "*covers*", carbon fibre shafts fastened by weightless strings and a polyester wrapping around the cork. However, the dimples have been reported to be actual holes, suggesting that the wind may flow through (Dynamic Badminton, 2017). One discrepancy between the feather and synthetic shuttlecocks is that feather shuttlecocks consist of no openings other than in the stem/rachis portion segmented by the two strings (Woo and Alam 2017).

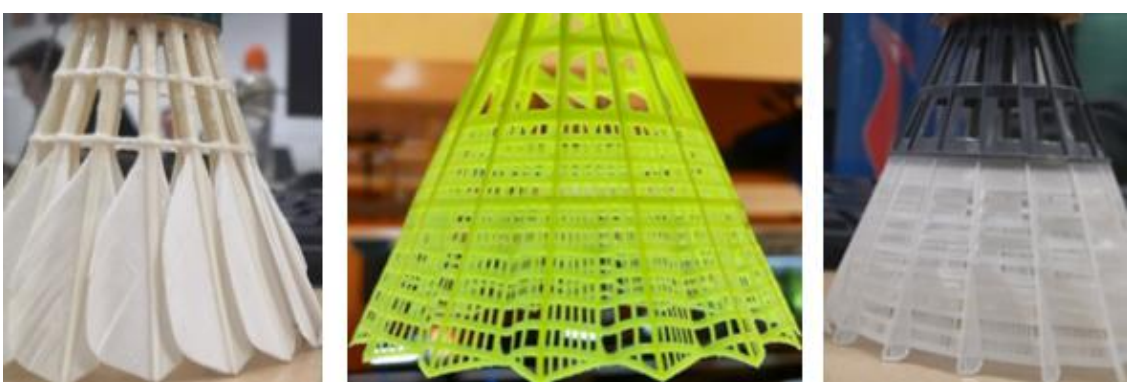

Figure 6. Comparison of skirt patterns of: a) Feather shuttlecock, b) Single-piece synthetic skirt and c) Two-piece synthetic skirt. Clear discrepancies can be observed not only between the feather and synthetic skirts, but also between the different synthetic shuttlecock brands.

As illustrated in Figure 6a-c, all synthetic shuttle designs feature netted patterns at the top skirt portion where gaps are evidently not present in the original feather product; the pattern of gaps also differs from brand to brand. From the smoke visualisation studies conducted (Cooke, 1999; Alam, Nutakom and Chowdhury, 2015), air jets would bleed through the gaps through the porous skirt, whereas the air would strike the solid vane of a feather and be deflected off. This observation accentuates the inadequate design regulation between synthetic and feather shuttlecocks.

Despite constant changes to the sporting equipment of many other sports (Carlol 2004; National Public Radio 2008; Hanson and Harland 2012; Daily Mail Reporter 2013; Ucantseeme 2015), most current designs of synthetic shuttlecocks create minimal traction.

Rationale for developing a synthetic alternative

In the period of 2015 to 2017, the official initial smash velocity of badminton increased from 408 km/h in 2015 to 426 km/h (≈118 m/s) in 2017 (Liew, 2017). As Proposed by Zhu (2013), the total mechanical energy in a badminton power stroke is attributable to the sum of the kinetic energy (K_E) generated from a racquet swing and the strain energy (SE) caused by the string's deformation at the point of impact represented by:

$$E = K_E + S_E = \frac{1}{2}mv^2 + \frac{1}{2}kx^2 \qquad (1)$$

Where k is the stiffness of the string bed (tension), and x is the displacement of the string bed. For elite players, using effective techniques to generate the racquet swing with a high-tension string (k = 0) is the most desirable—as this gives opponents minimum time to react to the returning shot. Increasing the smash velocity will greatly increase the amount of energy experienced by the shuttlecock and therefore a need for improvement in shuttlecock technology is apparent.

FLIGHT CHARACTERISTICS OF SHUTTLECOCKS

Although natural feather shuttles are generally considered to be the gold-standard for a quality gameplay experience as they offer consistent flight, they are not without their drawbacks. The major disadvantage of feather shuttlecocks is its lack of durability, due to the inherently brittle nature of the biological feathers, chips and breakages quickly accumulate during a rally leading to the need for rapid replacements. Thus, playing with feather shuttlecocks regularly at a recreational level becomes considerably costly. In most circumstances, a single "*birdie*" will seldom last one game at any level—from novice to elite—before being replaced; in some cases, it may not even endure a single mistimed "*frame shot*" or powerful smash. Given the high cost that could quickly amount to through rapid shuttle replacements, playing with natural shuttles are customarily reserved for official competitions receiving sponsorships or passionate players who seek the authenticity of badminton.

In the first rigorous study on shuttlecocks conducted by Cooke (1992), she likened a shuttlecock's flight to a javelin or discus than spherical balls (e.g. soccer, basketball or tennis). The flight characteristics of shuttlecocks depart significantly from that of typical ball sports mainly due to four factors: the open design of the shuttle allowing air to flow through the projectile during flight; the single axis of symmetry resembling that of an isosceles triangle; the partially overlaying of feathers causing a gyroscopic spin during flight; the uneven distribution of mass giving rise to the projectile's asymmetrical trajectory.

Despite its high-drag characteristics, the badminton shuttlecock holds the title of the highest initial velocity amongst all racquet-ball sports (Peastrel, Lynch and Armenti 1980; Tong 2004). This is a result of the myriads of materials being used in its construction; which, in turn, gave rise to its characteristic "*parachute trajectory*" (Morgan 1996; White 2010). It is described as a rapid deceleration resulting in a near-vertical drop as the projectile reaches its peak height (Figure 7). This flight path is most noticeable when launched in the upward direction at high speed such as a clear or lift shot. The shuttlecock must flip over upon being launched to stabilise its flight (Lin, Chua and Yeo 2013b). In the process, the shuttlecock rapidly decelerates because of its high-drag property thereby coming to a near-vertical drop when reaching peak height (White 2010).

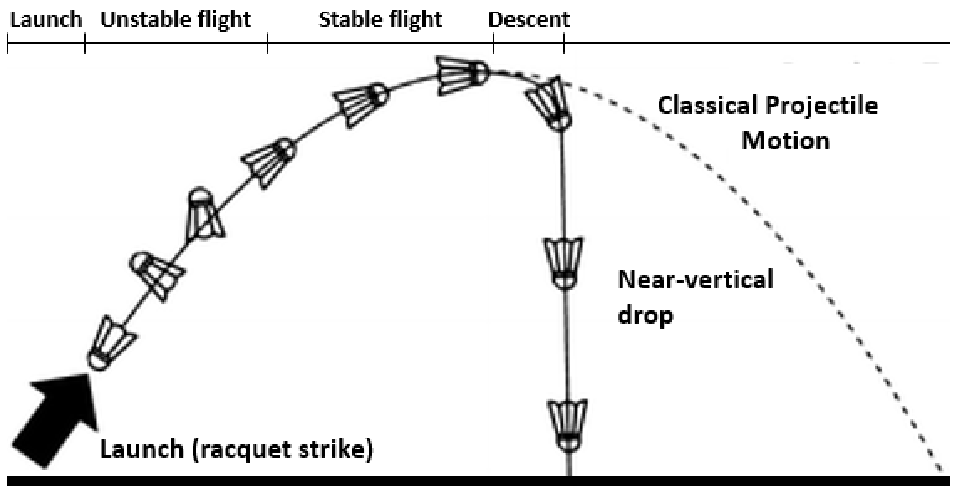

Figure 7. Schematic of a badminton shuttlecock's flight in comparison to the classical projectile motion. Vertical lines illustrate the distinct phases of flight: launch, unstable flight, stable flight and rapid deceleration.

In contrary, this netted/meshed synthetic shuttles design wobbles in flight causing it to sway resembling a "*knuckleball*" pitch in baseball (Texier, Cohen, Quéré and Clanet 2016). Synthetic shuttles are, thus, avoided by much of the badminton community, due to the variable flight from rally-to-rally.

The above factors give rise to the following two major considerations, i) drag and ii) spin:

Drag force

The shuttlecock's atypical trajectory has been coined as hitting an "*aerodynamic wall*", describing the tendency of any projectiles with high launching-velocity-to-terminal-velocity ratio (Cohen et al. 2013). For a badminton feather shuttlecock, this ratio has been reported to be 17.5, which is much higher than most sport balls like: soccer (1.7), golf (1.9) and tennis (3.3); with tennis balls having a projected frontal area (≈6.5 cm) closest to a shuttlecock (≈6.0 cm).

Within the range of 25 - 200 km/h, it has been reported that the drag force experienced by a shuttlecock can reach up to 50 times the gravitational force (Phomsoupha and Laffaye 2015). A shuttlecock, despite its high-drag profile, has reported to maintain 80% of its original speed during high-level play (SciFri 2014), implying the enormous stress sustained by the projectile.

The shuttlecock's velocity and its deceleration produced by the drag exhibits an inversely logarithmic relationship based on the flight path observed by Subramaniyan (2008).

Spin

The badminton shuttlecock naturally exhibits gyroscopic spin, or precession, during flight due to a pressure difference from the partial overlay of feathers (Figure 8a-b) (Cohen, Texier, Quèrè and Clanet 2015). This contrasts with the Magnus (side-spin) effect observed among other ball sports. To achieve precession, a forward momentum must be applied to propel the projectile forward but, at the point of release, also imparted a torsional force is at the spin axis parallel to the direction of motion (Nathan and Baldwin 2007; Petchesky 2013). This is mechanically difficult to achieve in most sport contexts; however, the shuttlecock's construction enables such spin to be imparted when launched.

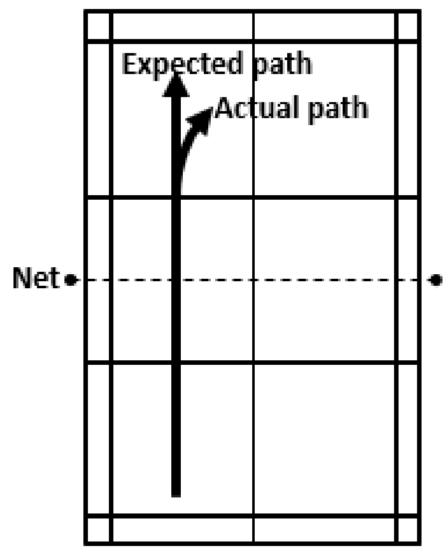

Figure 8. Schematic of the effect of precession causing a horizontal deviation in shuttlecock flight.

As a result, shuttlecocks can be seen to veer towards the right-hand side due to a lateral pressure difference—commonly known as "*righting*" of the shuttle (Figure 8) (Willis 2014a).

While there are no academic studies to support the claims, anecdotally, the community reported that the "*righting*" phenomenon of synthetic shuttles significantly differ from feather shuttlecocks thus preventing players altering between playing with the two shuttlecock types (Commins 2016; Dynamic Badminton 2017; XH Badminton 2017; Swift Badminton School 2018).

CURRENT BODY OF LITERATURE

This review will emphasise on the technological and sport performance aspects of badminton and will not discuss the user perception of different shuttlecock types or issues relating in general to sports science.

Flight path research

Experimental fluid mechanics of badminton shuttles came about after the publication of Cooke's (1992) PhD dissertation. Subsequently, she reported on the design of the badminton shuttlecock (Cooke, 1996); the distinctive drag reduction behaviour exhibited by synthetic shuttlecocks largely due to their readily collapsible skirt—which after more than 20 years remains unresolved—and shuttlecock ballistics (Cooke, 2002), specifically how aerodynamic parameters influence the shuttlecock trajectory. Her research efforts led to the development of one of the earliest commercial synthetic shuttlecocks (Cooke, 2017).

Regarding sports engineering research in badminton shuttles, areas that are commonly examined include:

a) Wind tunnel testing.
b) Video analysis.
c) Analytical and numerical simulation.

These topic areas are further discussed the sections below:

Wind tunnel testing

To observe sport projectile aerodynamics, experiments that require large-scale technical modifications (i.e. sport fields or courts) are generally deemed logistically impractical (financial and human resources) to conduct. For this reason, wind tunnel testing is commonly implemented.

The two key parameters in sport aerodynamics are:

The drag force (F_D) given by:

$$F_D = C_D \cdot \frac{1}{2} \rho v^2 \cdot A \qquad (2)$$

Where,
$\rho =$ Density of air (1.225 kg/m^3 for standard atmosphere conditions)
$v =$ Relative velocity of the fluid (m/s)
$A =$ Shuttlecock's projected frontal area (m^2)
$C_D =$ Coefficient of aerodynamic drag

These parameters are the classical drag force and drag coefficient used in fluid dynamics. The classical Reynolds number is also used to characterise the fluid flow:

$$Re = \frac{\rho v D}{\mu} \qquad (3)$$

Where,
$\rho =$ Density of air
$v =$ Relative velocity of the fluid (m/s)
$D =$ Shuttlecock skirt Diameter (m)
$\mu =$ Dynamic viscosity of the fluid (Pa.s)

In his recent simulation study, Hart, Pott and James (2018) raised the concern regarding sting mount-based wind tunnel studies suggesting the potential interference of wake formation at the rear end of shuttles, which is believed to have led to inconsistent reporting by different studies.

One major challenge in aerodynamic studies on badminton shuttlecocks has been to map out the fundamental flow regimes, namely the subcritical, supercritical and trans-critical regions (Roshko, 1960; Mehta, 2008). There is limited data documenting a shuttlecock's flow regime at low Reynolds numbers (Re) (13,000 < *Re* < 30,000) apart from one study that reported a C_D at Re ≈ 0.48 (Cooke, 1999). One reason is that, at low speeds, the contribution of the aerodynamic drag becomes negligible compared to the effect of gravity. Consequently, conducting wind tunnel tests at low *Re* for shuttlecocks become less prioritised compared to studying drag at high *Re* ranges ($3.7 \times 10^4 > Re > 2.6 \times 10^5$).

While the average C_D for shuttles generally ranges between 0.5 and 0.6 (Cooke, 1999; Alam et al. 2009; Alam et al. 2010; Cohen et al. 2013), discrepancy has also been observed (Kitta, Hasegawa, Murakami and Obayashi, 2011 vs Alam, Nutakom and Chowdhury, 2015) where shuttlecocks from the same brands were used yet ranges varying from $0.55 < C_D < 0.58$ to $0.49 < C_D < 0.54$, respectively, was reported. It is difficult to pinpoint the exact reasons leading to the discrepancy, and casting technical errors aside, within shuttlecocks itself lie a plethora of variables—both structural and environmental—that may have led to the conflict.

Given that rapid changes in speed is one of the defining features of the badminton shuttlecock, many studies are investigated its unique aerodynamics where different factors, such as skirt deformation and altitude, are altered.

Structural factors and Environmental factors

In sport designs, it is generally desirable to lower the C_D and this can be achieved by roughening an object's surface like adding dimples to golf balls (Alam et al. 2010). In contrary, a shuttlecock's high-drag profile has been documented as an intentional design:

> "*The spin consumes a great deal of flight energy, so that even if the shuttle is strongly hit, it cannot fly too far… it is desirable that the delicate shuttle should fall to the ground very gently, so that it will not be damaged.*"(Schoberl 1954, para. 5-6).

The degree of which the skirt deforms is generally agreed to be the most influential factor dictating a shuttle's trajectory. As the netted design of the current synthetic shuttlecocks is more porous than feather shuttlecocks, it has been conjectured that the synthetic skirt's high tendency to collapse greatly lessens the drag during flight (Cooke 1999). Consequently, synthetic shuttles are a poor alternative to its feathered counterpart (Kitta, Hasegawa, Murakami, and Obayashi 2011; Nakagawa, Hasegawa, Murakami, and Obayashi 2012).

In a 2015 study (Cohen, Texier, Quèrè and Clanet 2015), it was reported that between 0°C - 40°C—a range deemed realistic for badminton to be played under globally—a 10% increase in landing distance (13.1 m vs 14.7 m) was observed with increase in temperature; a 10% increase in relative humidity accounted for up to 5% of increase in overall weight due to moisture being trapped within micro-structures of feathers. It was reported that a 0. 9km increase in altitude above sea-level also increases travelling distance and flight time by up to 10% and 5%, respectively (Subramaniyan 2008). Anecdotally, it has been observed that the durability and strength of the shuttle's adhesive deteriorate after prolonged storage (>1 year) compared to newly purchased shuttles, leading to speculations that rate of degradation may be dependent on storage conditions (Bluejeff 2004).

Video analysis

Video and motion analyses are often associated with technique correction however, recently, it has been implemented by engineers and aerodynamicists to gain a more in-depth understanding on shuttlecock trajectories by capturing the transient changes of shuttlecock flight such as skirt deformation at high speed (Post et al. 2009) and in-flight phases (Lin, Chua & Yeo 2013b). However, these observations can only be made under strict laboratory and even then, it is challenging to consistently capture the moment. Hence, shuttlecock video analysis during actual games would be even more complex and has yet to be officially documented.

To address the above, motion-tracking algorithms have been used to enhance the video capture of shuttlecock trajectories, however at the time of writing, all of the methods used have not yet produced useful analytical data (Shishido, Kitahara, Kameda and Ohta 2014; Yoshikawa, Kobayashi, Watanabe and Otsu 2010; Shishido, Kitahara, Kameda and Ohta 2015; Shishido, Kitahara, Kameda and Ohta 2016).

Numerical studies and simulations

Several years ago, Goff (2013) indicated that more simulations would benefit the understanding of shuttlecock aerodynamics but pointed out that it would be challenging to construct scientifically sound simulation models due to the complex geometry of a shuttlecock.

Hart (2014) subsequently conducted a CFD study on a synthetic shuttle and compared two different simulation methods: Reynolds Average Navier Stokes simulation (RANS) and Scale-Resolving Simulation (SRS). It was concluded that while both methods generated similar C_D estimates, RANS was unable to simulate low-speed flows that exist in the region behind the skirt making SRS a more desirable method. This study revealed the viability of performing CFD on highly sophisticated sport projectiles such as badminton shuttlecocks.

In 2018, Hart, Potts and James (2018) performed a computational fluid dynamics (CFD) analysis on natural feather shuttlecocks in the range of 45,000 > *Re* > 271,000 (approx. 36 km/h to 216 km/h), testing two modelling approaches: unsteady RANS (uRANS) and SRS. These settings were applied to both the conventional feather shuttlecock model and a "*closed rachis cage*" model where the porous area of the shuttlecock was covered, similar to the study conducted by Alam, Nutakom and Chowdhury (2015). Based on results, Hart, Potts and James (2018) presented the complex fluid movement that occurs within the feather rachis gaps which would otherwise be difficult to display using conventional wind tunnel testing methods due to the obstruction of the sting mount.

In the same year, a Japanese cohort proposed a new aspect of shuttlecock research by marrying the extent of camber of the feathers with aerodynamics (Konishi et al. 2018).

Table 1. Literature table illustrating the lack of understanding in the structural mechanics of shuttlecocks.

Literature	**Samples**	**Wind Tunnel**	**Video Analysis**	**Structural Mechanics**	**CFD**	**Proto-typing**
Cooke (1992)	Feather & Synthetic	X	X		X	
Cooke (1999)	Feather & Synthetic	X				X
Lin et al. (2013a)	Feather, Synthetic & Artificial feather		X			
Lin et al. (2013b)	Feather & Synthetic	X			X	X
Hasegawa et al. (2013)	Feather & Modified feather	X	X			
Cohen (2013)	Synthetic	X	X		X	
Cao et al. (2014)	Feather & Synthetic	X			X	
Hart (2014)	Synthetic				X	
Alam et al. (2015)	Feather, Synthetic, modified F&S shuttles	X				
Woo (2017)	Feather & Synthetic	X				
Hart et al. (2018)	Feather				X	
Konishi et al. (2018)	Feather				X	

It was reported that the concavely shaped feather at its vane portion reduced drag and increased lift due to reduction in skirt diameter towards the rear end. Conversely, convex vanes increased drag. This phenomenon is believed to resemble that of the landing manoeuvre performed by birds—wings are spread and tilted to increase lift (Dvrák 2016). If one were to consider the camber effect as the vertical plane deviation, then a curvature deviation in the horizontal plane should also be accounted for (Yue et al. 2016). Hence, further study into the aerodynamic contribution of such horizontal deviations on the shuttlecock's flight would be warranted.

The findings from the above research points to another aspect that suggesting the skirt deformation may not be the only contributor regarding shuttlecock aerodynamics.

CONCLUSIONS

Several concluding remarks are made from the current body of literature regarding badminton research:

- 30 years since emerging as an academic field of study, a considerable amount of knowledge has been gained regarding shuttlecocks. The frequent shuttle change in competitions is a glaring concern that has been long neglected. In many cases, shuttlecocks can become unusable after an insignificant number of racquet strikes making the game unsustainable.
- There exist areas with a clear disconnect warranting further attention, such as the correlation between aerodynamics and structural mechanics which may be the key to designing a viable synthetic shuttlecock product.
- Regarding structural and environmental factors, several areas of research are worth considering, such as, the effect of ambient conditions (temperature, altitude and humidity etc.) on the storage of natural shuttles.

Future research

To date, no study has yet to measure the percentage change regarding drag decrease and skirt deformation. Experiments conducted by Cohen, Texier, Quèrè and Clanet (2015) and Subramaniyan (2008) suggest that the shuttlecock mass can be affected by its ambient environment; hence, affects the landing distance.

In addition, emerging interests on feather camber (Yue et al. 2016; Konishi et al. 2018) indicates a need to gain an in-depth understanding into the badminton feather's structure. Only with better understanding on the feathers, can research into the more subtle aspects of shuttlecock, such as improvement in cork or foam bases, can be performed.

Hart, Potts and James (2018) raised a valid concern in regard to the sting-mount setup of wind tunnel testing. It should be noted that mount-less experiments have been attempted using the magnetic suspension and balance system (MSBS) (Higuchi 2005; Takagi, Sawada and Obayashi 2016). In fact, an MSBS Wind Tunnel study has been previously conducted for archery (Miyazaki et al. 2012); it is also compatible with multi-component force sensing (Lee, Lee, Han and Kawamura 2013). Therefore, the adoption of this new experimental setup should be mostly compatible with the traditional wind tunnel test.

AUTHOR CONTRIBUTIONS

This article was co-written by Dr Woo, Prof Alam and Dr Kootsookos. Dr Woo was the primary contributor aggregating and reviewing the development of badminton shuttlecocks. Dr Kootsookos assisted in the initial content arrangement and draft submission processes. Prof Alam provided his guidance and expertise in aerodynamics. All authors were involved in the finalisation of the manuscript submission.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ACKNOWLEDGEMENTS

The authors would like to thank the RMIT technical officers for their assistance in providing many helpful advices and feedback during the data collection phase of this study.

REFERENCES

Alam F, Chowdhury H, Theppadungporn C, Subic A, Masud M, & Khan K (2009) Aerodynamic properties of badminton shuttlecock. International Journal of Mechanical and Material Engineering, 4(3): 266 - 272.

Alam F, Chowdhury H, Moria H, Brooy RL, & Subic A (2010) A comparative study of golf ball aerodynamics. In 17th Australian Fluid Mechanics Conference, Auckland, New Zealand 5 - 9 December 2010.

Alam F, Nutakom C, & Chowdhury H (2015) Effect of Porosity of Badminton Shuttlecock on Aerodynamic Drag. Procedia Engineering, 112, 430-435. https://doi.org/10.1016/j.proeng.2015.07.220

Badminton World Federation (2018) Laws of badminton: BWF Statutes, Section 4.1.2: Shuttle.

Badminton Oceania Confederation. (n.d.). Shuttle speeds [Shuttlecock speed conversion chart].

Basu, T. (16 Aug 2016). "Shuttlecocks can only be made of the left wings of geese" [online article]. Inverse. Retrieved from [Accessed 2024, June 12]: https://www.inverse.com/article/19768-2016-rio-olympics-goose-geese-left-wing-badminton-shuttlecock

Bluejeff. (2004, October 16). Storing shuttlecock [Online forum comment]. Retrieved from [Accessed 2024, June 12]: https://www.badmintoncentral.com/forums/index.php?threads/storing-shuttlecock.18963/#post-188123

Carlol. (2004, July 13). New resources for visual cognition [Online forum comment]. Retrieved from [Accessed 2024, June 12]: http://www.badmintoncentral.com/forums/index.php?threads/avian-flu-affecting-shuttle-prices.15801/page-2

China Network Television (CNTV). (2011, April 9). "Badminton from a different perspective" [Documentary]. Retrieved from [Accessed 2024, June 12]: http://sports.cntv.cn/20110421/104877.shtml

Cohen C, Texier BD, Dupeux G, Brunel E, Quéré D, & Clanet C (2013) The aerodynamic wall. Proceedings of the Royal Society A, 470(2161): 1 - 20. https://doi.org/10.1098/rspa.2013.0497

Cohen C, Texier BD, Quèrè D, & Clanet C (2015) The physics of badminton. New Journal of Physics, 17, 1-17. https://doi.org/10.1088/1367-2630/17/6/063001

Commins, D. (2016). The best plastic synthetic shuttle: A review of the Bird2 [Video file]. Retrieved from [Accessed 2024, June 12]: https://www.youtube.com/watch?v=0GebY4Bp2wo

Cooke AJ (1992) The Aerodynamics and Mechanics of Shuttlecocks [Dissertation]. Cambridge University.

Cooke AJ (1996) Shuttlecock Design and Development, Sports Engineering - Design and development (Haake, S.J. ed.), In Proceedings 1st International Conference on The Engineering of Sport. Blackwell Science, Oxford.

Cooke AJ (1999) Shuttlecock Aerodynamics, Sports Engineering Journal (Haake, S.J. ed.), 2(2): 85-96. https://doi.org/10.1046/j.1460-2687.1999.00023.x

Cooke AJ (2002) Computer Simulation of Shuttlecock Trajectories, Sports Engineering Journal (Haake, S.J. ed.), 5(2), pub. Blackwell Science, Oxford. https://doi.org/10.1046/j.1460-2687.2002.00100.x

Cooke AJ (2017) Research to Retail: A Striking Difference [Online Media, last updated 2017]. Retrieved from [Accessed 2024, June 12]: http://www.cookeassociates.com/publications/research.php

Daily Mail Reporter. (2013). Could bird flu kill off BADMINTON? Daily Mail Australia. Retrieved from [Accessed 2024, June 12]: http://www.dailymail.co.uk/femail/article-2314564/Will-bird-flu-kill-badminton-Indonesia-bans-importation-shuttlecocks-China-avian-virus.html

Dvorák, R. (2016). Aerodynamics of bird flight. EPJ Web of Conference, 114, 1-8. https://doi.org/10.1051/epjconf/201611401001

Dynamic Badminton. (Jul 7, 2017). Victor Carbonsonic No.2 (REVIEW) [Product Review Video]. Retrieved from [Accessed 2024, June 12]: https://www.youtube.com/watch?v=haPLwxeYqlg

Efstathios, K., & Bouris, D. (2012). Bluff Body Aerodynamics and Wake Control. In Applied Aerodynamics (pp. 63-78). Rijeka, Croatia: IntechOpen [Digital book chapter]. Retrieved from [Accessed 2024, June 12]: http://www.intechopen.com/books/applied-aerodynamics/bluff-body-aerodynamics-and-wake-control

Goff, J.E. (2013). A review of recent research into aerodynamics of sport projectiles. Sports Engineering, 16(3): 137-154. https://doi.org/10.1007/s12283-013-0117-z

Hanson, H., & Harland, A. (2012). The 16th century football: 450 year old sports technology assessed by modern standards. Procedia Engineering, 34: 373-378. https://doi.org/10.1016/j.proeng.2012.04.064

Hart, J. (2014). Simulation and understanding of the aerodynamic characteristics of a badminton shuttle. Procedia Engineering, 72, 768-773. https://doi.org/10.1016/j.proeng.2014.06.130

Hart JH, Potts JR, & James DJ (2018) Comparison of turbulence modelling approaches in simulation of a feather shuttle: A porous conical bluff body. Sports Engineering, 21:465-478. https://doi.org/10.1007/s12283-018-0293-y

Higuchi, H. (2005). Passive and active controls of three-dimensional wake of bluff-body. JSME International Journal Series B Fluids and Thermal Engineering, 48(2): 322-327. https://doi.org/10.1299/jsmeb.48.322

Kitta S, Hasegawa H, Murakami M, & Obayashi S (2011) Aerodynamic properties of a shuttlecock with spin at high Reynolds number. Procedia Engineering, 13, 271-277. https://doi.org/10.1016/j.proeng.2011.05.084

Konishi Y, Matsushima Y, Misaka T, Okuizumi H, Tanaka K, & Obayashi S (2018) Effect of camber on badminton shuttlecock. Proceedings, 2(6):266. https://doi.org/10.3390/proceedings2060266

Lee, D.K., Lee, J.S., Han, J.H., & Kawamura, Y. (2013). Dynamic calibration of magnetic suspension and balance system for sting-free measurement in wind tunnel tests. Journal of Mechanical Science and Technology, 27(7): 1963-1970. https://doi.org/10.1007/s12206-013-0513-0

Liew V. (Jan 16, 2017). "Mads Pieler Kolding unleashes 426 km/h smash". Retrieved from [Accessed 2024, June 12]: http://www.badmintonplanet.com/badminton-news/4785-mads-pieler-kolding-unleashes-426-km-h-smash-4-videos.html

Lin CSH, Chua CK., & Yeo JH. (2013a). Design of high-performance badminton shuttlecocks: virtual and rapid prototyping approach. Virtual and Physical Prototyping, 8(2):165-171. https://doi.org/10.1080/17452759.2013.812738

Lin CSH, Chua CK., & Yeo JH. (2013b). Turnover stability of shuttlecocks-transient angular response and impact deformation of feather and synthetic shuttlecocks. Procedia Engineering, 60, 106-111. https://doi.org/10.1016/j.proeng.2013.07.024

Mehta R.D. (2008) Sports Ball Aerodynamics. In: Nørstrud H. (eds) Sport Aerodynamics. CISM International Centre for Mechanical Sciences, vol 506. Springer, Vienna. https://doi.org/10.1007/978-3-211-89297-8_12

Miyazaki, T., Mukaiyama, K., Komori, Y., Okawa, K., Taguchi, S., & Sugiura, H. (2012). Aerodynamic properties of an archery arrow. Sports Engineering, 16(1): 43-54. https://doi.org/10.1007/s12283-012-0102-y

Morgan JE (1996) The design and development of a shuttlecock hitting machine for training badminton players at all levels of the game. In The Engineering of Sport (Vol. 3, pp. 103-111). CRC Press. https://doi.org/10.1201/9781003078098-17

Nakagawa K, Hasegawa H, Murakami M, & Obayashi S (2012) Aerodynamic properties and flow behavior for a badminton shuttlecock with spin at high Reynolds numbers. Procedia Engineering, 34, 104-109. https://doi.org/10.1016/j.proeng.2012.04.019

Nathan, A., & Baldwin, D. (2007). An analysis of the gyroball. Baseball Research Journal, 36, 77-80.

National Public Radio. (2008). Baseball: From child's play to America's pastime [Website]. Retrieved from [Accessed 2024, June 12]: https://www.npr.org/templates/story/story.php?storyId=88752540

Peastrel M, Lynch R, & Armenti A (1980) Terminal velocity of a shuttlecock in vertical fall. American Journal of Physics, 48(7): 511-513. https://doi.org/10.1119/1.12373

Petchesky, B. (2013). Unspinning the mythical gyroball, the demon miracle pitch that wasn't. Deadspin [Sport Media]. Retrieved from [Accessed 2024, June 12]: https://deadspin.com/unspinning-the-mythical-gyroball-the-demon-miracle-pit-1451016294

Phomsoupha M, & Laffaye G (2015) The science of badminton: game characteristics, anthropometry, physiology, visual fitness and biomechanics. Sports Medicine, 45(4): 473-495. https://doi.org/10.1007/s40279-014-0287-2

Post SL, McLachlan J, Lonas T, Dancs J, Knobloch D, Darrow C, Sinn E, Davis S, Neilly D, Funk A, Golz J, Phelps A, & Goers B (2009) Aerodynamics of a badminton shuttlecock. [IMECE2009-10266]. Proceedings of the ASME 2009 International Mechanical Engineering Congress & Exposition, Florida, USA. https://doi.org/10.1115/IMECE2009-10266

Roshko, A. (1960). Experiments on the flow past a circular cylinder at very high Reynolds number [ID code: 10105]. Journal of Fluid Mechanics, 10 (3). pp. 345-356. https://doi.org/10.1017/S0022112061000950

Schoberl H (1958) U.S. Patent No. US2830817. Washington, DC: U.S. Patent and Trademark Office.

SciFri. (2014 Dec 26). Birdie in flight: The science of badminton [Documentary]. Retrieved from [Accessed 2024, June 12]: https://www.youtube.com/watch?v=Y4B1SoFKnBo

Shishido H, Kitahara I, Kameda Y, & Ohta Y. (2014). A trajectory estimation method for badminton shuttlecock utilizing motion blur. In Image and Video Technology (pp. 325-336). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-53842-1_28

Shishido H, Kitahara I, Kameda Y, & Ohta Y (2015) Trajectory Estimation of a Fast and Anomalously Moving Badminton Shuttle. In Joint Conference of IWAIT and IFMIA. Retrieved from [Accessed 2024, June 12]: http://www.kameda-lab.org/research/publication/2015/201501_IWAIT/201501_IWAIT_ShishidoH.pdf

Shishido H, Kameda Y, Kitahara I, & Ohta Y (2016) 3D position estimation of badminton shuttle using unsynchronized multiple-view videos. In Proceedings of the 7th Augmented Human International Conference 2016, 47-48. ACM. https://doi.org/10.1145/2875194.2875235

Subramaniyan R (2008) Effect of local conditions on the flight trajectory of an indoor badminton shuttlecock [Dissertation].

Swift Badminton School. (Sep 28, 2018). Half feather, half plastic HYBRID shuttle?! Kawasaki King Kong 500 Review. Retrieved from [Accessed 2024, June 12]: https://www.youtube.com/watch?v=9f61ubO7VD0

Taneepak. (2005, Jul 27). Question about the Shuttlecocks [Online forum comment]. Retrieved from [Accessed 2024, June 12]: https://www.badmintoncentral.com/forums/index.php?threads/question-about-the-shuttlecocks.25466/

Takagi, Y., Sawada, H., & Obayashi, S. (2016). Development of magnetic suspension and balance system for intermittent supersonic wind tunnels. American Institute of Aeronautics and Astronautics Journal, 54(4): 1277-1286. https://doi.org/10.2514/1.J054411

Texier BD, Cohen C, Quéré D, & Clanet C (2016) Physics of knuckleballs. New Journal of Physics, 18(7): 1-14. https://doi.org/10.1088/1367-2630/18/7/073027

Tong GF (2004) Mechanics analysis of a shuttlecock terminal velocity [Master's Thesis]. National Kaohsiung Normal University.

Ucantseeme. (2015, Apr 8). Shuttlecock price increased again?? (Penang Malaysia) [Online forum comment]. Retrieved from [Accessed 2024, June 12]: http://www.badmintoncentral.com/forums/index.php?threads/shuttlecock-price-increased-again-penang-malaysia.152684/

White C (2010) Chapter 15: Some assorted sporting projectiles. In Projectile dynamics in sport: Principles and applications (pp. 281-307). Abingdon, Oxon, England: Routledge. Retrieved from [Accessed 2024, June 12]: https://tinyurl.com/White-2010

Willis G (1996) U.S. Patent No. WO1996031260A2. Washington, DC: U.S. Patent and Trademark Office.

Willis G (2014a) Bird2 shuttlecock updates: The right-handed shuttlecock. Retrieved from [Accessed 2024, June 12]: http://goode-sport.co.uk/buy/ashaway-bird-2-shuttlecock/

Willis G (2014b) Buy Bird Shuttlecocks [Sales page]. Retrieved from [Accessed 2024, June 12]: http://www.birdsports.net/buy.html

Woo TMT, Alam F (2017) Comparative aerodynamics of synthetic badminton shuttlecocks. Sports Engineering, 21(1):21-29. https://doi.org/10.1007/s12283-017-0241-2

XH Badminton. (Jul 7, 2017). Carbonsonic Shuttlecock unbox and review [Product Review Video]. Retrieved from [Accessed 2024, June 12]: https://www.youtube.com/watch?v=lrdL4HXJexo

Yonex (2012) Shuttlecock facts: "The flight trajectory naturally veers to the right.". In Yonex Shuttle News (published 29 June, 2012). Retrieved from [Accessed 2024, June 12]: https://www.yonex.hu/shuttle_news/knowledge/index.html

Yonex (2019) Mavis 350: Playing condition [Product Information]. Retrieved from [Accessed 2024, June 12]: https://www.yonex.com/m-350

Yoshikawa F, Kobayashi T, Watanabe K, & Otsu N. (2010) Automated service scene detection for badminton game analysis using CHLAC and MRA. International Journal of Computer, Electrical, Automation, Control and Information Engineering, 4(2): 331 - 334.

Yue H, Cai K, Dong C, Cao L, & Zeng Z (2016) Development and Production of multi-parameter measurement device for feather pieces. DYNA Ingeniería e Industria, 91(4). 413-422. https://doi.org/10.6036/8007

Zhu Q (2013) Expertise of using striking techniques for power stroke in badminton. Perceptual and Motor Skills: Learning and Memory, 117(2): 427 - 441. https://doi.org/10.2466/23.25.PMS.117x24z2