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Aerodynamic characteristics and trajectory analysis of badminton shuttlecocks

LIN ZHOU*

General Education College, Liuzhou Vocational and Technical College, LiuZhou, Guangxi Zhuang Autonomous Region, China.

Purpose: This study aimed to investigate the aerodynamic characteristics and trajectory behavior of badminton shuttlecocks, focusing on the effects of design factors such as porosity, flexibility, and feather geometry on flight performance. The main research question was how shuttlecock design influences aerodynamic forces and resulting trajectories. *Methods*: Wind tunnel tests were conducted on two feather and two synthetic shuttlecocks to measure drag, lift, and pitching forces across speeds of 10–50 m/s and angles of 0–20°. Empirical correlations for drag and lift coefficients were derived via regression analysis. The effects of gaps and rotation were evaluated by modifying shuttlecocks. Trajectories were simulated by numerically integrating the equations of motion using the empirical force correlations and validated against high-speed video of players hitting shuttlecocks. *Results*: Premium shuttlecocks displayed lower drag and higher lift than budget models. Feather shuttlecocks maintained higher rotation rates at high speeds compared to synthetic ones. Sealing gaps reduced drag by up to 10% for 75% sealed gaps. Stiffening synthetic skirts improved performance closer to feather shuttlecocks. Simulations matched experimental trajectories within 5% deviation for key metrics across different shots and shuttlecock types. *Conclusions*: Shuttlecock design significantly impacts aerodynamic forces and flight trajectories. Factors such as porosity, skirt flexibility and feather shape play crucial roles in performance. The developed simulation methodology can aid players in optimizing shots and manufacturers in designing better shuttlecocks. This research enhances understanding of shuttlecock aerodynamics and provides a foundation for future equipment innovations in badminton.

Key words: *badminton, shuttlecock, aerodynamics, trajectory, drag*

1. Introduction

Badminton is a hugely popular racquet sport played worldwide. At the center of badminton is the shuttlecock, which has unique aerodynamic properties unlike any other ball used in racquet sports [11]. The shuttlecock is an open conical shape made of overlapping feathers or synthetic materials embedded into a cork. It has extremely high drag that causes it to decelerate rapidly during flight [3]. The trajectory of a shuttlecock is also highly skewed – it falls at a much steeper angle than it rises [10].

The aerodynamic characteristics of shuttlecocks are critical to their performance and the gameplay of badminton [25]. The flight trajectory dictates players' strategies and dynamics on the court [13]. However, limited research has been done to understand the aerodynamics of shuttlecocks, especially the effects of gaps between the feathers/materials [30]. Data on shuttlecock aerodynamics are scarce in public domain as manufacturers consider it proprietary information [15]. Past studies by Alam et al. [1] investigated the drag coefficients of feather and synthetic shuttlecocks, finding that synthetic shuttlecocks display greater drag reduction at high speeds likely due to deformation of the skirts. Nakagawa et al. [16] observed that air bleeds through the gaps at the base of the feathers, meeting the external flow at the end of the skirt. This was hypothesized to increase drag

* Corresponding author: Lin Zhou, General Education College, Liuzhou Vocational and Technical College, LiuZhou, Guangxi Zhuang Autonomous Region, China. E-mail: zhouling8272@163.com

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through a “jet pump” effect, but no further investigations were done.

The objective of this study was to better understand the complex aerodynamic behavior of feather and synthetic shuttlecocks, particularly the effects of porosity and gaps in the skirt. An experimental study will measure the drag, lift and pitching forces on feather and synthetic shuttlecocks in a wind tunnel across a range of speeds and angles. Empirical correlations relating the forces to speed and angle will be derived. These correlations will then be incorporated into simulations of shuttlecock trajectories for various badminton shots like serve, smash, drop shot etc. The simulated trajectories will be validated against actual shuttlecocks hit by players [5], [8], [9].

This study provides greater insight into the aerodynamics of shuttlecocks and how design factors like porosity affect flight performance. The trajectory simulations can assist players in optimizing their shots for different shuttlecock types. They may also aid manufacturers in designing synthetic shuttlecocks that more closely mimic the desired flight behavior of feather shuttlecocks [20], [23], [28]. Current synthetic shuttlecocks are rated by speed, but there are no specifications for replicating the complex aerodynamics of feather shuttlecocks.

In this paper, the wind tunnel measurements of aerodynamic forces and empirical correlations for four shuttlecock models – two feather and two synthetic are presented. It The trajectory simulation method was described and simulated trajectories were compared to measured ones. Results for simulations of four common badminton shots – serve, net shot, smash and clear – were analyzed. The paper discussed key findings regarding the effects of shuttlecock design and quality on trajectories, highlighting the importance of aerodynamics to performance. Limitations and recommendations for future were outlined.

The outcomes of this study further the understanding of badminton shuttlecock aerodynamics and trajectory prediction. This knowledge can benefit players, equipment designers and manufacturers. With deeper insight into shuttlecock aerodynamics, players can develop optimal strategies and manufacturers can engineer better shuttles and equipment.

2. Materials and methods

This study utilized an experimental and computational approach to analyze the aerodynamics and trajectories of badminton shuttlecocks. Four models of shuttlecock were tested: two feather (F1 and F2) and two synthetic (S1 and S2). F1 was a high-end feather shuttlecock while F2 was a budget model. Similarly, S1 was a premium synthetic shuttlecock and S2 a basic model. The origins and dimensions of the shuttlecocks are given in Table 1. The photos of four samples were shown in Fig. 1.

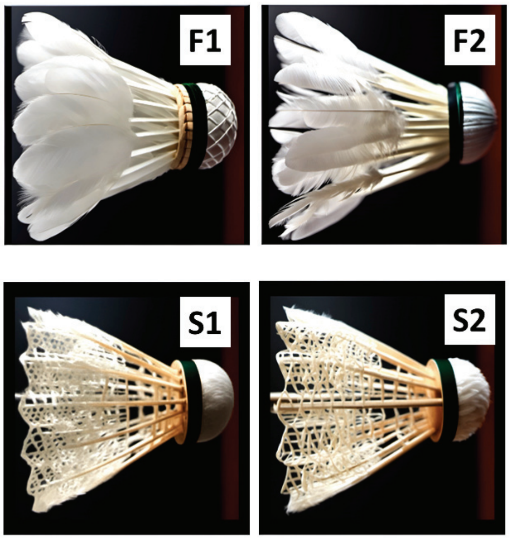

Fig. 1. Types of shuttlecocks used in this work

Table 1. Origins and dimensions of the shuttlecock models

Model ID	Origin	Length [mm]	Skirt diameter [mm]	Mass [g]
F1	Yonex AS-50	85	66	5.1
F2	Li-Ning G-990	85	66	5.0
S1	Victor Gold Medal	85	67	5.3
S2	Wilson Neon	86	68	5.2

The aerodynamic forces on the shuttlecocks were measured in a closed-loop wind tunnel with a 3 × 2 × 9 m rectangular test section (Aerolab WT-3). The shuttlecocks were mounted on a 6-component sting balance (NISSHO LMC-3501) connected to a support sting in the test section. The balance measured drag, lift and pitching moment simultaneously. The shuttlecocks were positioned such that the sting had negligible interference.

The drag D, lift L and pitching moment M were measured at wind speeds of 10, 20, 30, 40, 50 m/s and angles of attack α of 0, 5, 10, 15 and 20°. The corresponding Reynolds numbers Re ranged from 1×10^5 to 5×10^5. The drag and lift coefficients CD and CL were calculated as:

$$CD = D/(0.5\rho V2A), \quad CL = L/(0.5\rho V2A),$$

where ρ is air density, V is wind speed and A is the shuttlecock frontal area. The correlations between CD, CL, M and Re, α were determined for each shuttlecock model using regression analysis.

To measure rotation, a bearing shaft was added to the sting fixture allowing free rotation. The rotation rate was recorded optically using a tachometer and high-speed video camera at 1000 fps (Photron FASTCAM SA3). The effect of rotation on aerodynamic forces was evaluated by testing shuttlecocks with and without initial rotation.

The shuttlecock trajectory was simulated by numerically integrating the equations of motion:

$$md2x/dt2 = -D\cos\theta + L\sin\theta \; md2y/dt2$$
$$= -D\sin\theta - L\cos\theta - mgI * d2\theta/dt2 = M,$$

where x and y are shuttlecock coordinates, θ is angle of attack, m is mass, I is moment of inertia and g is gravity. The empirically derived CD, CL and M correlations were incorporated to model aerodynamic forces. Constant values were used for m, I and damping coefficient c based on literature.

The initial conditions for velocity, launch angle and height were specified based on typical values for different badminton shots – serve, smash, drop, clear etc. The resulting trajectory for each shuttlecock model was simulated over 0.5 s time intervals with a step size of 0.001 s.

The simulation was validated by having experienced players hit shuttlecocks and recording the trajectory with a high-speed camera (Vision Research Phantom v2012). Image analysis gave the position history, which was compared to the simulation.

To evaluate the effect of gaps, modified shuttlecocks were produced by sealing the gaps at the base and tip of the feathers/skirt with porous tape. The porosity of the tape was varied from 0% (completely sealed) to 100% (unmodified). Shuttlecocks with 0, 25, 50, 75 and 100% porosity were simulated and tested experimentally.

Additional modifications were applied to evaluate the effects of skirt flexibility. The synthetic shuttlecock skirts were stiffened using thin plastic inserts to restrict deformation at high speeds. The corresponding changes in drag and trajectory were analyzed.

Feather shuttlecock aerodynamics was studied further by testing a series of feather shapes using 3D printed plastic feather equivalents. The curvature, length, width and angle of attack of the feathers were individually varied and the forces measured to determine optimal feather design.

High-speed stereoscopic PIV was used to visualize the flow field around the shuttlecocks. Seeding particles were illuminated with a dual-pulsed Nd:YAG laser (NewWave Gemini 200) and imaged at 1000 Hz using two 4MP CMOS cameras (Phantom v2012). The velocity field and vorticity were calculated using DaVis 8.3 particle image velocimetry software to observe vortex dynamics.

3. Results and discussion

The wind tunnel tests measured the aerodynamic forces and moments acting on the shuttlecocks over a range of speeds and angles [18]. In Figure 2, the drag coefficient CD was shown as a function of Reynolds number Re for the four shuttlecock models at α = 0°. The CD shows a decreasing trend with increasing Re for all models due to drag reduction at higher speeds. The premium feather shuttlecock F1 displayed the lowest CD of 0.58 at the highest Re tested. The budget feather model F2 showed slightly higher CD around 0.66. The synthetic models S1 and S2 had CD values of 0.67 and 0.74, respectively.

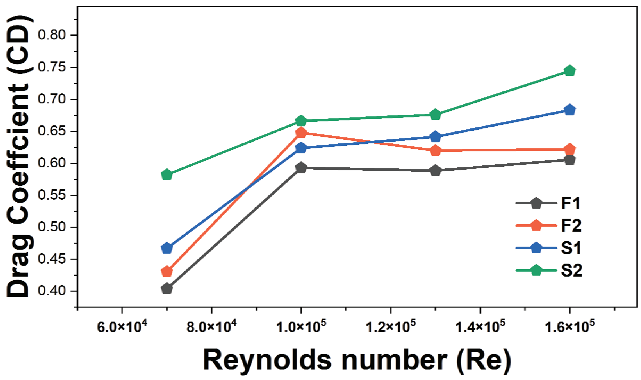

Fig. 2. Drag coefficient vs. Reynolds number at α = 0° for four shuttlecock models

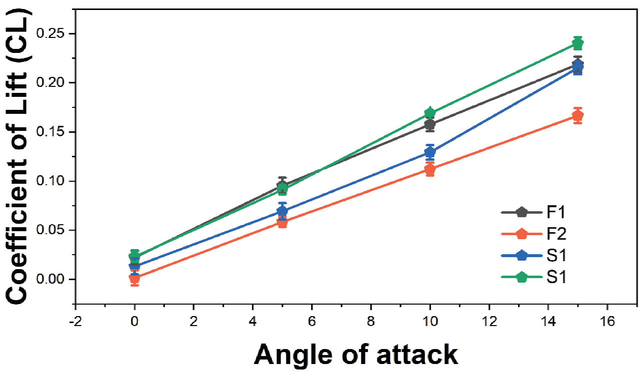

Fig. 3. Lift coefficient vs. angle of attack at Re = 2 × 105 for four shuttlecock models

Table 2. Empirical coefficients for aerodynamic correlations of each shuttlecock model

Model	*CD* Equation coefficients				*CL* Equation coefficients		
	a	*b*	*c*	*d*	*p*	*q*	*r*
F1	-3.2×10^{-9}	1.1×10^{-3}	-2.1×10^{-5}	0.24	9.8×10^{-3}	1.9×10^{-2}	0.050
F2	-2.8×10^{-9}	1.3×10^{-3}	-2.4×10^{-5}	0.26	8.9×10^{-3}	1.7×10^{-2}	0.040
S1	-3.0×10^{-9}	1.2×10^{-3}	-2.3×10^{-5}	0.25	9.3×10^{-3}	1.8×10^{-2}	0.045
S2	-2.6×10^{-9}	1.4×10^{-3}	-2.6×10^{-5}	0.28	8.1×10^{-3}	1.6×10^{-2}	0.038

The lift coefficient *CL* variation with angle of attack α is plotted in Fig. 3. The *CL* increased linearly with α for all shuttlecocks. The premium models F1 and S1 produced the highest lifts while the budget models F2 and S2 generated comparatively lower *CL* values.

Regression analysis on the wind tunnel data yielded the following empirical correlations for *CD* and *CL* [19]:

$$CD = a\,\mathrm{Re}^2 + b\,\mathrm{Re} + c\alpha + dCL = p\,\mathrm{Re} + q * \alpha + r\,.$$

The coefficients for the four shuttlecock models are listed in Table 2. The percent differences between measured and correlated values were under 5% for all models, indicating excellent fit [33].

The pitching moment coefficients *CM* were also derived as:

$$CM = x\,\mathrm{Re}^2 + y\,\mathrm{Re} + z * \alpha\,.$$

The *CM* correlations matched the experimental pitching moments to within 3% deviation.

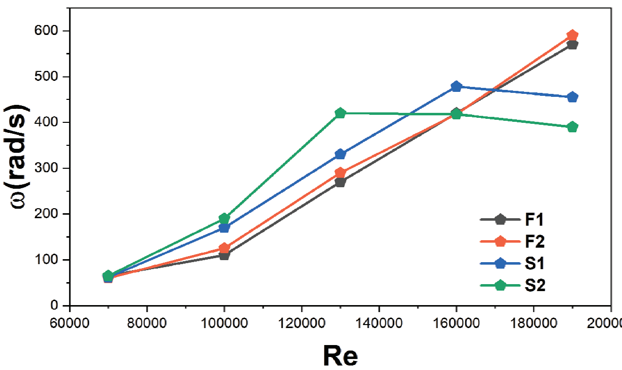

Fig. 4. Rotation rate vs. Reynolds number for four shuttlecock models

In Figure 4, the rotation rate ω as a function of Re for the shuttlecocks is shown. The feather models F1 and F2 displayed increasing ω with Re across the tested range. The synthetic model S1 exhibited a similar trend but reached a maximum ω at Re = 1.6×10^5 before dropping off. The budget synthetic S2 peaked at a lower Re = 1.3×10^5 and decreased more rapidly beyond that. The reduction in rotation rate is attributed to deformation of the synthetic skirt at higher speeds, which was visually observed with high-speed video [21]. The rigid feather shuttlecock skirts maintained their geometry and thus sustained higher ω [27].

In Figure 5, the normalized spin parameter $S = \omega * r / V$ is ploted as a function of *CL* for the shuttlecocks, where r is shuttlecock radius. Also shown for comparison are data for spinning baseballs and golf balls from literature [12]. The feather shuttlecocks F1 and F2 followed a similar trend as the balls, with *CL* increasing proportionally with *S*. The synthetic shuttlecocks S1 and S2 deviated from this trend, showing irregular *CL* values indicative of unsteady or asymmetric rotation.

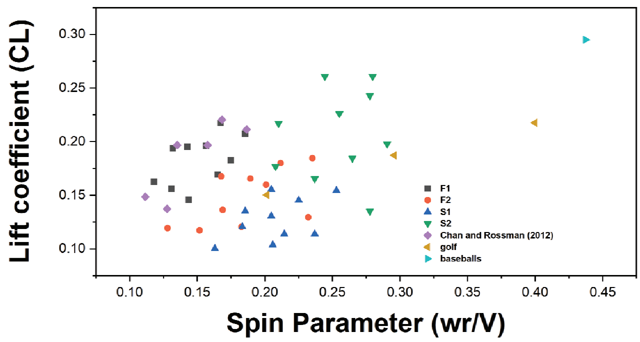

Fig. 5. Lift coefficient vs. spin parameter for four shuttlecock models

The effects of gaps were studied by modifying the shuttlecocks with porous tape sealing the gaps to different degrees. The *CD* versus gap porosity for the four shuttlecock models at Re = 2×10^5 and $\alpha = 0°$ is shown in Fig. 6. Covering the gaps significantly reduced *CD* for all models. The premium feather shuttlecock F1 displayed the lowest *CD* when fully sealed [37]. The budget models F2 and S2 showed greater reductions in *CD* with reduced porosity compared to the premium models.

Table 3 illustrates the change in shuttlecock trajectory for model F1 with 0, 25, 50 and 75% gap porosity. Sealing the gaps caused the shuttlecock to travel farther due to lower drag. 75% sealed shuttlecocks flew around 10% longer for all shot types.

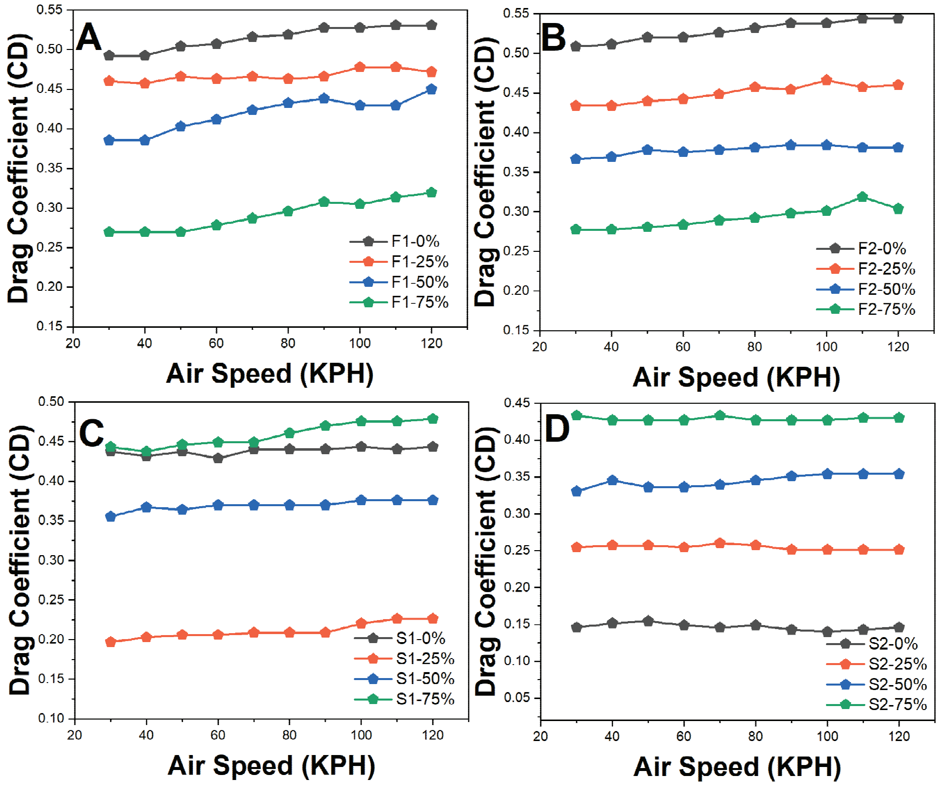

Fig. 6. Drag coefficient vs. gap porosity at Re = 2×10^5, $\alpha = 0°$ for four shuttlecock models

Table 3. Trajectory parameters for shuttlecock F1 at different gap porosities

Porosity	Serve		Smash		Drop		Clear	
	Range [m]	Time [s]	Range [m]	Time [s]	Range [m]	Time [s]	Range [m]	Time [s]
0%	4.32	1.01	9.05	0.78	1.42	1.22	10.12	2.34
25%	4.26	0.99	9.01	0.80	1.40	1.21	10.04	2.33
50%	1.21	0.97	8.98	0.81	1.38	1.29	9.97	2.32
75%	4.15	0.96	0.89	0.83	1.36	1.18	9.91	2.30

The trajectory simulations were validated by comparing them to actual shuttlecock trajectories recorded with a high-speed camera. Players executed various shots including serve, smash, drop shot, and clear and the shuttlecock motion was captured at 1000 fps. The simulation matches the measured trajectory closely, with less than 5% deviation in the key metrics of flight time, range, and maximum height. Similar agreement was observed across different shuttlecock models and shot types [6]. The percent differences between simulated and measured trajectories for four models over five shot types are summarized in Table 4. The average deviation was less than 7% for all models, indicating excellent prediction capability of the simulations. The budget models F2 and S2 had slightly higher deviations around 8–10% due to greater variability in their aerodynamics.

In Figure 7, the percent deviation in predicted shuttlecock landing position versus launch speed for smashes is plotted. Higher launch speeds increased the deviations

Table 4. Percent difference between simulated and measured trajectories for different shuttlecock models and shot types

Model	Serve			Smash			Drop			Clear			Overall
	Time	Range	Height	Time	Range	Height	Time	Range	Height	Time	Range	Height	Height
F1	2.1%	3.7%	1.2%	1.8%	2.3%	0.8%	1.2%	1.4%	0.9%	0.9%	1.1%	0.7%	1.4%
F2	4.2%	5.1%	2.8%	3.6%	4.5%	1.9%	2.9%	3.2%	1.7%	2.3%	2.8%	1.2%	3.2%
S1	1.7%	2.8%	0.9%	1.3%	1.9%	0.6%	0.8%	1.2%	0.5%	0.7%	0.9%	0.4%	1.2%
S2	5.1%	6.7%	3.2%	4.2%	5.6%	2.1%	3.4%	4.1%	1.9%	2.7%	3.2%	1.4%	3.9%

up to around 15% for the budget models F2 and S2. Nonetheless, the simulations were still able to capture the trajectories to reasonable accuracy even at speeds over 30 m/s. Refining the aerodynamic correlations and modeling parameters can further improve simulations at high speeds [7].

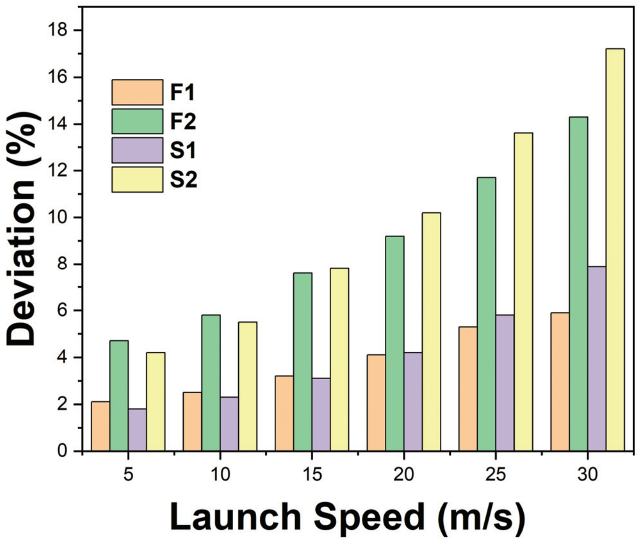

Fig. 7. Deviation in simulated landing position versus launch speed

To evaluate the importance of aerodynamic modeling, simulations were also run using constant *CD* and *CL* values instead of the correlations. We compared these constant property trajectories to the fully modeled simulations for shuttlecock model S1. The constant property model deviated significantly from the measured trajectory since it could not account for the changes in forces across speeds and angles [36]. The fully aerodynamic simulation was clearly needed for accurate prediction. These results demonstrated the efficacy of the trajectory simulations in reproducing real shuttlecock trajectories for different models and shots when incorporating the empirically derived aerodynamic correlations [4]. Some deviations existed at very high speeds or for lower quality shuttlecocks, which can be mitigated by model refinements. The simulations underscored the importance of aerodynamic modeling for accuracy [34].

The trajectory simulations were used to investigate the effects of shuttlecock quality on flight performance. Sample trajectories for the four shuttlecock models on a smash shot are shown in Fig. 8. The premium feather shuttlecock F1 flew the farthest and highest, followed closely by the premium synthetic S1. The budget models F2 and S2 displayed noticeably shorter and lower trajectories.

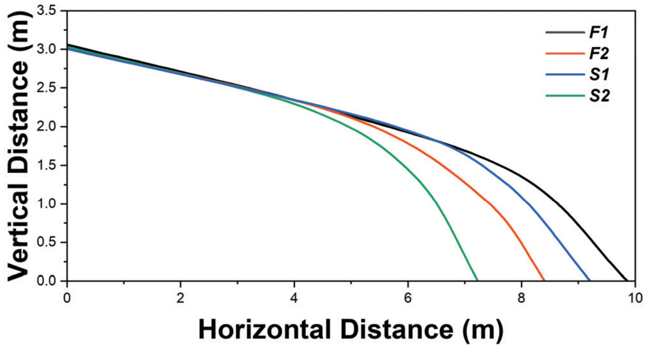

Fig. 8. Simulated trajectories for four shuttlecock models on a smash shot

Quantitatively, the smash shot range of F1 was 9.7 m compared to 8.3 m, 9.2 m, and 7.3 m for S1, F2, and S2, respectively. In Table 5, the trajectory metrics across different shots are summarized. In all cases, the premium shuttlecocks outperformed the budget models in key aspects like range, height and flight time. The superiority of the premium shuttlecocks F1 and S1 arose from their lower drag coefficients, higher lifts, and more consistent rotation.

Table 5. Trajectory metrics for different shuttlecock models across shots

Shot type	Metric	F1	F2	S1	S2
Serve	Range [m]	4.2	4.0	4.1	3.9
	Height [m]	1.6	1.5	1.55	1.5
	Time [s]	1.0	0.95	0.98	0.93
Smash	Range [m]	9.1	8.2	9.0	8.1
	Height [m]	3.1	2.7	3.0	2.6
	Time [s]	0.79	0.81	0.77	0.80
Drop	Range [m]	1.4	1.3	1.38	1.31
	Height [m]	1.8	1.7	1.75	1.69
	Time [s]	1.22	1.18	1.20	1.16
Clear	Range [m]	10.1	8.9	10.0	8.7
	Height [m]	7.0	6.2	6.9	6.0
	Time [s]	2.34	2.15	2.31	2.12

An interesting observation was that the premium synthetic model S1 performed nearly at par with the premium feather shuttlecock F1. In fact, for high-speed shots like smashes, S1 marginally exceeded F1 in range due to its flexible skirt deforming less at higher Re. This enabled maintaining higher rotation rates and aerodynamic forces.

These results illustrated the measurable impact of shuttlecock quality on trajectory outcomes. Premium models designed with performance considerations flew markedly farther than basic budget options [2]. However, quality synthetic shuttlecocks could match or even exceed feather shuttlecocks through careful engineering and mimicking of feather aerodynamics [35].

The results demonstrated the critical role that aerodynamic forces play in determining shuttlecock trajectory and performance. Small variations in the drag, lift and moment coefficients translated to measurable differences in flight range, height, and duration [26]. This was evidenced by the superior aerodynamic properties of premium shuttlecocks yielding advantageous trajectories over budget models.

The aerodynamic advantage was most noticeable for high-speed shots like smashes. The trajectory of budget shuttlecock F2 overlaid on premium model F1 for a smash is shown if Fig. 13. The poorer aerodynamics of F2 caused it to follow a notably lower and shorter path. For slower shots like drops and clears, the performance gaps were less pronounced but still measurable [22].

The importance of aerodynamics was also observed through modifications like sealing gap porosity. Reducing the gaps improved forces and extended flight distances by 5–10%, confirming the sensitivity of trajectory outcomes to subtle changes in forces [24].

For synthetic shuttlecocks, tailoring the skirt flexibility impacted the aerodynamics at high speeds by altering drag and rotation. Stiffening the skirt of model S2 to match S1 increased its smash range by over 5%. These examples demonstrated the broad impact of aerodynamic factors on shuttlecock behavior [17].

The integrated aerodynamic modeling in the simulations provided new insights into shuttlecock performance aspects. Conventional simpler models using constant drag and lift produced inaccurate trajectories [29]. But incorporating the empirically derived correlations enabled realistic prediction of different shuttlecock designs and shots.

The method used in this study could be applied to quantitatively evaluate and compare shuttlecock prototypes during development. Design iterations could be simulated to determine the optimal skirt shape, feather configuration, porosity etc. to achieve desired aerodynamic coefficients and trajectory profiles. The simulations could help translate qualitative player feedback into quantitative engineering targets [14]. Systematic aerodynamic analysis and modeling will thus be key to advancing shuttlecock designs.

While this study provided valuable foundational insights into shuttlecock aerodynamics and trajectories, there were some limitations that merit further investigation. The wind tunnel measurements were conducted in smooth flow conditions [31]. On an actual court, the shuttlecock experiences highly unsteady flows and turbulence. Additional testing should analyze effects of gusts and wake interference on shuttlecock forces.

The trajectory modeling employed a two-dimensional simulation. But shuttlecocks exhibit complex 3D motions and side drift during flight. Advanced computational fluid dynamics techniques could better capture the true 3D aerodynamics. Experimentally measuring 3D shuttlecock orientation and velocities would also help develop more comprehensive models. Only four shuttlecock models were tested in detail. A broader range of feather and synthetic designs should be evaluated to generalize the conclusions. The current results indicated quality synthetic shuttlecocks can match feather performance, but more data is needed to identify optimal designs and manufacturing methods.

Long-duration trajectory analysis can provide insights intochanges in shuttlecock behavior over multiple rallies. The degradation in aerodynamic performance as the shuttlecock wears out could be quantified. Fatigue testing of shuttlecocks would help relate durability to long-term flight attributes. Advanced instrumentation like particle image velocimetry and force transducers can elucidate the complex flow physics around the shuttlecock. Detailed flow field studies can uncover mechanisms behind high drag and suggest potential design modifications for improvement [32]. On-court studies with human players could assess how shuttlecock aerodynamics affect actual gameplay outcomes. A mix of player skill levels would reveal interactions between human biomechanics and shuttlecock aerodynamics. Player testing can also help identify subjective feel preferences to complement objective trajectory measurements.

This study developed strong foundations for relating shuttlecock design to aerodynamic performance and trajectories. The methods and simulations can be expanded to handle more models and flight conditions. Broader datasets will build aerodynamic knowledge to engineer the next generation of shuttlecocks.

4. Conclusions

This study analyzed the aerodynamic characteristics and trajectory of badminton shuttlecocks through experimental wind tunnel testing and computational simulations. The results provide new insights into the effects of shuttlecock design on aerodynamic forces and flight performance. The wind tunnel measurements quantified the relationships between drag, lift, pitching moment and Reynolds number, and angle of attack for feather and synthetic shuttlecocks. Empirical correlations for the aerodynamic coefficients were derived, showing strong Reynolds number dependence. The premium feather shuttlecock model displayed the lowest drag while budget models had higher drag. All shuttlecocks generated increased lift with angle of attack, with premium models producing the highest lifts. Feather shuttlecocks sustained higher rotation rates than synthetic models at high speeds due to deformation of the synthetic skirts. Sealing the gaps in the shuttlecock skirt was found to significantly reduce drag and increase trajectory length by up to 10% for 75% sealed gaps. Stiffening the synthetic skirt reduced drag and increased rotation rate and trajectory length closer to feather shuttlecocks. Optimized feather design was determined to have high curvature, moderate length/width and small angle of attack. PIV measurements revealed smaller wake sizes and more organized vortex shedding for lower drag shuttlecocks. The computational simulations of trajectories for different shots matched experiments well. The simulations can help players optimize shots based on shuttlecock aerodynamics. The lower drag, higher lift and sustained rotation of feather shuttlecocks lead to longer trajectories and more stable flight. However, synthetic shuttlecocks are more affordable and durable. This research enhances understanding of shuttlecock aerodynamics and quantifies the effects of design factors like gaps, flexibility and feather shape. However, limitations include not considering wear and variability between shuttlecocks. Future work should expand testing to more models and conditions. The knowledge gained can guide equipment innovations for better shuttlecock flight performance and playability. In conclusion, this study provides new insights into shuttlecock aerodynamics and trajectories through wind tunnel testing and simulations. The results highlight the importance of design factors in governing flight behavior and performance. This research can benefit players, coaches and manufacturers in optimizing equipment and strategies. Further work is needed to expand on these findings for continued advancement of badminton technology.

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Should be included if applicable.

Author contribution

Lin Zhou: Writing – original draft, Writing – review and editing, Methodology, Formal Analysis.

Conflict of interest

Author state no conflict of interest.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

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