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Numerical Simulation of Shuttlecock Dynamics: Effects of String Tension, Impact Force, and Launch Angle

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Abstract

The performance of a badminton stroke is governed by a complex interplay between racket string properties, impact force, launch angle, and aerodynamic effects. In this study, we present a numerical simulation framework to investigate the influence of string tension, impact force, and launch angle on shuttlecock exit speed, flight distance, and trajectory. Idealized elastic models are first introduced to establish theoretical upper bounds, followed by more realistic simulations incorporating aerodynamic drag and player-dependent efficiency. The results reveal that while increased string tension enhances shuttlecock exit speed in an idealized model, the effective performance exhibits a non-monotonic behavior when human factors are considered. Furthermore, aerodynamic drag significantly alters optimal launch angles and flight distances. These findings provide physical insight into racket-string optimization and practical implications for player performance and equipment design.

Keywords: Badminton, Shuttlecock Dynamics, Numerical Simulation, String Tension, Impact Force.

Introduction

Badminton shuttlecock dynamics differ substantially from those of spherical projectiles due to the shuttlecock's asymmetric geometry and exceptionally high aerodynamic drag. Despite this, many discussions of racket performance still rely on simplified elastic collision models that neglect aerodynamic effects and player-dependent variability [1].

Previous studies have examined shuttlecock aerodynamics and racket–shuttle interactions independently. However, a unified framework that links string tension, impact force, launch angle, and aerodynamic drag remains limited. This study aims to bridge that gap by employing numerical simulations to analyze shuttlecock exit speed, flight trajectory, and distance under progressively realistic assumptions [2].

The objectives of this paper are threefold

1. To quantify the relationship between string tension and shuttlecock exit speed.
2. To evaluate the impact of aerodynamic drag on shuttlecock trajectory and optimal launch angle.
3. To examine combined effects of impact force and launch angle on achievable flight distance [3].

Physical Model and Simulation Method

Shuttlecock Exit Speed Model

The racket–shuttle interaction is modeled using an effective elastic response, where the shuttlecock exit speed v_0is assumed to scale with string tension T:

$$v_0 \propto \sqrt{T}$$

This assumption reflects the increase in effective stiffness of the string bed with higher tension. Figure 1 illustrates the resulting relationship between string tension and shuttlecock exit speed [4].

Impact Force and Initial Velocity

The impact force Fapplied during the stroke is assumed to determine the initial velocity magnitude through energy transfer:

$$\frac{1}{2}mv_0^2 \propto F$$

This simplified relation allows investigation of flight distance under varying impact forces in the absence of aerodynamic drag, serving as a theoretical upper bound [5].

Aerodynamic Drag Model

The shuttlecock experiences a drag force proportional to the square of velocity:

$$\vec{F}_d = -\frac{1}{2} C_d \rho A v^2 \hat{v}$$

where C_d is the drag coefficient, ρis air density, and Ais the effective cross-sectional area. Numerical integration of the equations of motion is performed to obtain trajectories with drag.

Launch Angle and Trajectory Simulation

The initial velocity vector is decomposed according to the launch angle θ. Trajectories are computed both with and without aerodynamic drag to highlight their qualitative differences.

Player Efficiency and Non-Ideal Effects

To account for human factors such as control, timing, and energy loss at high string tensions, a Gaussian efficiency function is introduced:

$$\eta(T) = \exp\left(-\frac{(T - T_{\mathrm{opt}})^2}{2\sigma^2} \right)$$

The effective exit speed becomes $v_{\mathrm{eff}} = \eta(T) v_0$, producing a non-monotonic performance curve [6].

Results

Effect of String Tension on Exit Speed

Figure 1 shows a monotonic increase in shuttlecock exit speed with string tension under ideal elastic assumptions. This trend represents a best-case scenario in which all stored elastic energy

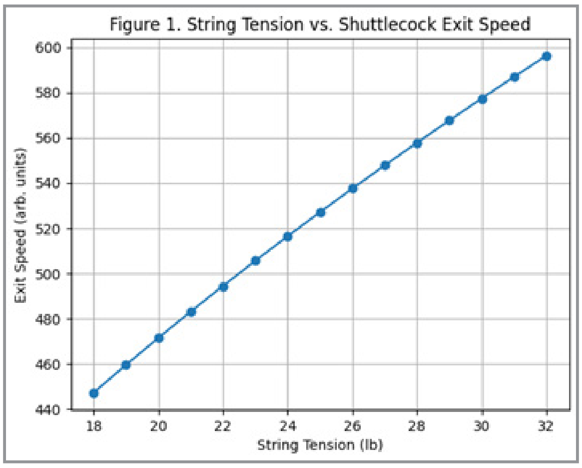

Figure 1: Impact Force and Flight Distance Without Drag

As shown in Figure 2, flight distance increases rapidly with impact force when aerodynamic drag is neglected. This result provides a theoretical upper limit and highlights the inadequacy of drag-free models for realistic shuttlecock motion.

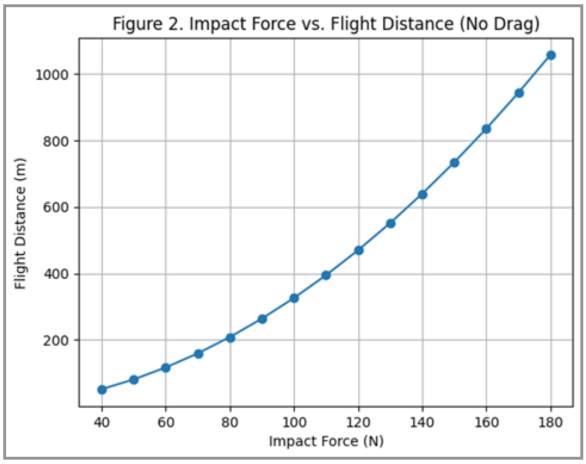

Figure 2: Trajectory Comparison with and Without Drag

Figure 3 compares shuttlecock trajectories under identical initial conditions. The drag-free trajectory follows a conventional parabolic path, whereas the trajectory with drag exhibits a steep ascent and rapid descent. The dramatic reduction in horizontal range underscores the dominant role of aerodynamic drag.

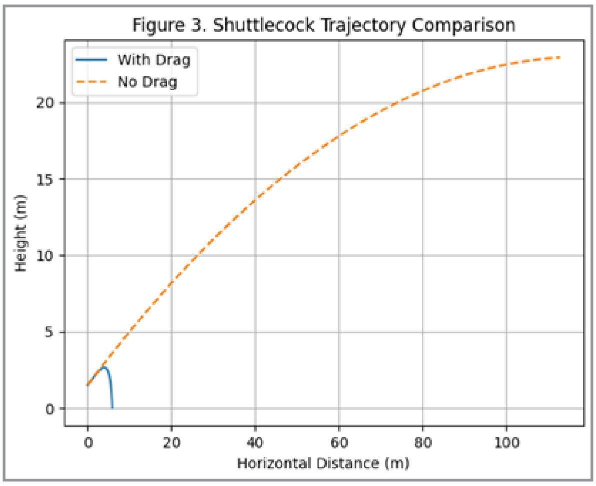

Figure 3: Non-Monotonic Dependence on String Tension

Figure 4 demonstrates that when player efficiency is incorporated, shuttlecock exit speed reaches a maximum at an optimal string tension. Beyond this point, increased tension reduces effective performance due to decreased control and timing accuracy.

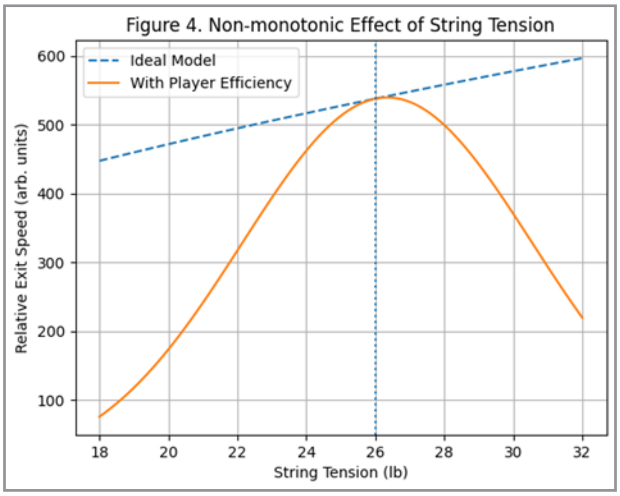

Figure 4: Optimal Launch Angle under Aerodynamic Drag

Figure 5 shows the relationship between launch angle and flight distance in the presence of drag. Unlike classical projectile motion, the optimal angle is significantly lower than 45°, typically in the range of 15–25°.

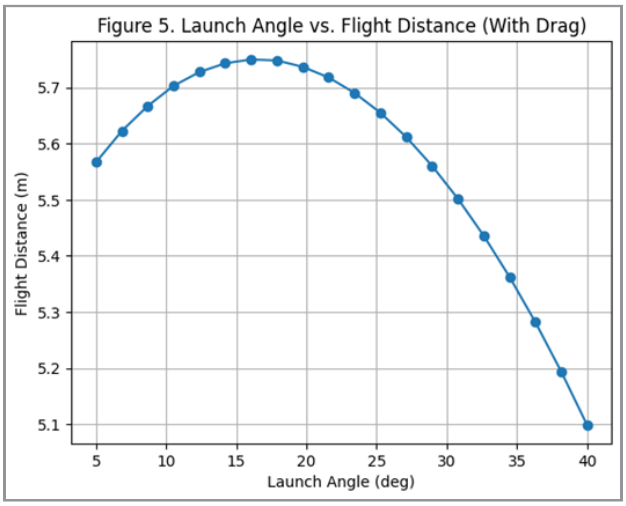

Figure 5: Combined Effects of Impact Force and Launch Angle

Figure 6 presents a contour map of flight distance as a function of impact force and launch angle. The results indicate that higher impact forces expand the optimal angle range, but aerodynamic drag continues to constrain achievable distances.

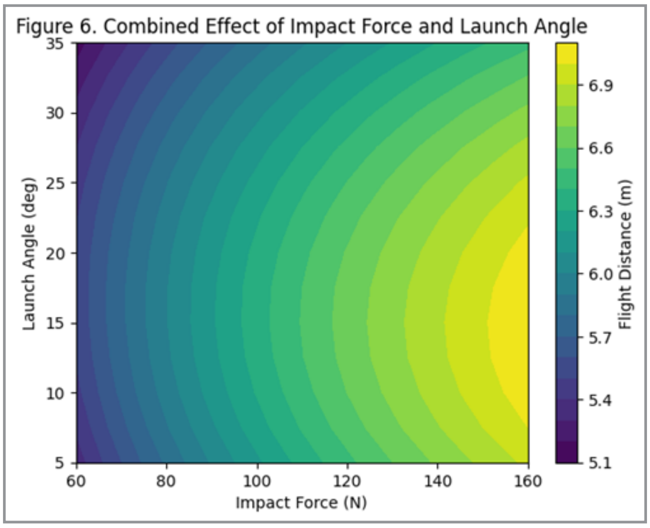

Figure 6: Combined Effect of Impact Force and Launch Angle

Discussion

The simulations reveal several important insights. First, idealized elastic models overestimate the benefits of increased string tension. When player-dependent efficiency is considered, an optimal tension emerges, consistent with empirical observations among competitive players.

Second, aerodynamic drag fundamentally alters shuttlecock motion, invalidating classical projectile assumptions. The strong dependence of optimal launch angle on drags highlights the necessity of sport-specific modeling.

Finally, the combined force–angle analysis suggests that performance optimization cannot rely on a single parameter. Instead, effective stroke execution depends on a balance between impact force, launch angle, and controllability.

Limitations and Future Work

The present study employs simplified models for racket–shuttle interaction and player efficiency. Future work may include:

- Experimental validation using high-speed motion capture
- Player-specific parameter calibration
- Three-dimensional trajectory modeling
- Integration with real-time coaching or smart racket systems [7-10].

Conclusion

This study provides a comprehensive numerical investigation of shuttlecock dynamics in badminton. By incorporating string tension, impact force, launch angle, and aerodynamic drag, the simulations demonstrate that optimal performance arises from a balance between physical properties and human factors. The framework presented here offers a foundation for equipment optimization, player training, and future experimental studies.

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