Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

From Geometric Perfection to Flight Stability: The Development and Empirical Validation of a 36-Hole Pickleball Based on Archimedean Solid Principles

Peng Lin
Guangdong Industry Polytechnic University
Dan Huang
Beihua University
Yansheng Chen
Guangdong Industry Polytechnic University
Zejiong Zheng
2005101060@gdipu.edu.cn

Guangdong Industry Polytechnic University

Research Article

Keywords: Pickleball, Hole configuration, Landing dispersion, Bivariate probability ellipse, Flight stability

Posted Date: July 30th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10389714/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Sports Engineering on October 28th, 2026.
See the published version at https://doi.org/10.1007/s12283-026-00577-0.

Abstract

Objectives: This study compared landing dispersion between 36-hole and 40-hole pickleballs, focusing on directional stability and two-dimensional distribution patterns.

Design: A novel 36-hole ball based on regular polyhedron geometry was developed. Both ball types were launched 120 times each using a ball launcher under controlled conditions, with landing positions captured by high-speed camera system.

Methods: 240 trials (120 per type) were conducted at 50.0±0.2 km/h, 0±0.1°angle. Landing positions recorded by stereovision (300 fps, ±9 mm accuracy) under wind-controlled conditions (mean ≤2.0 m/s, gusts ≤3.0 m/s). Stability assessed via X/Y dispersion and 95% bivariate confidence ellipse.

Results: The 36-hole ball exhibited lower dispersion in both directions. Its 95% ellipse area (22,411 cm^2) was 29.3% smaller than the 40-hole ball (31,707 cm^2), with a lower eigenvalue ratio (1.95 vs. 2.81), indicating more isotropic distribution.

Conclusions: Hole configuration significantly influences landing dispersion. The 36-hole design demonstrates more compact and directionally consistent behavior, providing quantitative evidence for enhanced flight stability.

1. Introduction

Pickleball has experienced rapid global growth in recent years, prompting increased research interest in equipment design and performance optimization. As gameplay intensity and participation increase, ball flight stability has become a key determinant of competitive fairness and playability, particularly in outdoor environments where wind disturbances amplify trajectory variability. Despite this, limited scientific work has examined how geometric features of perforated polymer balls influence aerodynamic consistency.

Research on aerodynamics of sports balls has demonstrated that surface topology, perforation layout, and symmetry play critical roles in shaping drag, lift, and wake structures [1–4]. Studies on perforated spheres have further shown that variations in hole patterns can significantly alter airflow separation and pressure distribution [5, 6]. In addition, investigations into symmetry-driven aerodynamic behavior indicate that more uniform geometric structures generate more stable vortex shedding and reduced trajectory randomness [7]. However, despite the rapidly growing popularity of pickleball, scientific examination of its ball design remains limited, with only a few preliminary studies evaluating trajectory consistency under outdoor conditions [8].

Current outdoor pickleballs typically employ a 40-hole configuration characterized by irregular spacing and nonuniform angular distribution. Such asymmetry may introduce imbalanced aerodynamic forces, causing random deviations in flight paths. To address this problem, we designed a 36-hole pickleball with a more regular and symmetrical hole layout, designed to enhance aerodynamic balance. Yet, no

empirical study has quantitatively evaluated whether this symmetric configuration yields measurable improvements in real-world flight stability.

To fill this gap, the present research conducts a structural and empirical comparison of 36-hole and 40-hole pickleball designs. First, we examine baseline geometric characteristics—such as hole diameter, hole spacing, and the global uniformity of the layout—to identify potential sources of aerodynamic imbalance. Second, we conduct controlled outdoor landing-dispersion experiments to assess whether increased geometric regularity translates into more stable flight trajectories. Third, we use spatial distribution metrics, including standard deviations and 95% bivariate confidence ellipses, to quantify differences in stability.

2. Research methods

2.1. Theoretical Framework and Hypotheses

2.1.1. Aerodynamic Basis of Hole-Layout Effects

The aerodynamic behavior of perforated sports balls is governed by how surface openings disturb boundary-layer flow and influence wake formation. Prior studies indicate that perforation geometry alters drag, lift, and pressure distribution by modifying the point of airflow separation [9, 10]. Irregularly spaced holes can generate asymmetric pressure zones, increasing lateral deviations and inducing unpredictable flight behavior [11, 12].

Conversely, symmetric perforation layouts tend to enhance aerodynamic balance by promoting more uniform vortex shedding. Research has shown that geometric symmetry can reduce wake instability and decrease random trajectory fluctuation [13–15]. In outdoor settings—where stochastic wind forces amplify aerodynamic imbalances—such design-driven symmetry becomes even more critical for maintaining flight stability [16].

2.1.2. Structural Symmetry and Expected Flight Behavior

From a structural standpoint, the 36-hole configuration features a more regular and evenly distributed hole layout, which may enable more isotropic aerodynamic properties compared with the traditional 40-hole design. Theoretical and empirical research on perforated spheres suggests that balanced and evenly spaced openings help reduce variability in drag forces and improve trajectory consistency during flight [7, 17, 18].

Although actual flight behavior may deviate from theoretical expectations due to environmental and stochastic aerodynamic fluctuations, structural symmetry provides a reasonable basis for anticipating improved stability. The scientific question guiding this study is therefore: Does enhanced geometric regularity translate into measurable improvements in real-world flight stability?

2.2. Hypotheses

To guide empirical investigation while allowing flexibility for outcomes that may not fully align with theoretical expectations, the study proposes three directional—but not deterministically prescriptive—hypotheses:

H1: The 36-hole ball will exhibit lower lateral (X-axis) dispersion than the 40-hole ball.

H2: The 36-hole ball will exhibit lower longitudinal (Y-axis) dispersion than the 40-hole ball.

H3: The 36-hole ball will demonstrate smaller multivariate dispersion, as reflected by the 95% bivariate confidence ellipse, compared with the 40-hole ball.

These hypotheses reflect expected aerodynamic tendencies derived from geometric symmetry principles while allowing empirical results to confirm, refine, or contradict theoretical predictions.

2.3. Materials and Methods

2.3.1. Experimental Balls

Both types of balls were injection molded from the same batch of LLDPE (PB-2024-08) by the Polymer Materials Engineering Center of XX University shown in Fig. 1:

Fig. 1. Two different designs of pickleballs.

1. Green ball: a novel 36-hole ball designed by mapping the 36 vertices of a truncated icosahedron onto a sphere;
2. Yellow ball: a standard 40-hole ball produced by the authors' institution using a conventional ring-based layout.

Both balls were injection-molded from the same LLDPE batch using precision steel molds. All balls met official pickleball specifications (diameter 73.2 ± 0.4 mm; mass 24.5 ± 0.5 g). Crucially, hole diameter was identical (7.10 ± 0.02 mm) in the two designs. Consequently, total open area was 1462 mm² (40-hole, porosity $\tau = 7.98\%$) versus 1316 mm² (36-hole, $\tau = 7.18\%$), a deliberate 10.0% reduction. All other specifications (outer diameter 73.2 ± 0.2 mm, mass 24.5 ± 0.3 g, wall thickness 1.55 mm, 60-inch rebound) met current USA Pickleball standards. Five individually numbered balls of each type were selected. Each ball was launched 24 times, resulting in 120 trials per type.

2.3.2. Geometric Layout Assessment

A structural comparison was performed to examine potential aerodynamic implications arising from differences in hole-layout geometry. Without computational modeling, three practical geometric descriptors were assessed:

Hole Distribution Symmetry–qualitative comparison of global hole arrangement uniformity.

Hole Spacing Consistency–approximate measurement of distances between adjacent holes to identify irregular deviations.

Hole Diameter Uniformity–verification of consistent hole diameters within each ball type.

These structural observations help establish a theoretical basis for understanding how geometric asymmetry may affect aerodynamic balance during flight.

2.4. Outdoor Flight Experiment

2.4.1. Launch Procedure

Flight stability was tested on an outdoor asphalt court using a Lobster Pickle Champion serving machine.

Launch speed: 50.0 ± 0.2 km/h

Release height: 1.0 m

Launch angle: 0 ± 0.1°

Ball orientation was randomized before each launch.

2.4.2. Environmental Control

Tests were conducted between 07:30–08:30 (22 October 2025) to minimize environmental variation.

Two Gill WindMaster 3D anemometers monitored wind speed at court height.

Inclusion criteria:

mean wind ≤ 2.0 m/s,

gusts ≤ 3.0 m/s.

Trials exceeding criteria (4.4%) were discarded and repeated.

2.4.3 Landing-Point Tracking

A synchronized dual-camera high-speed stereovision system (Basler acA2040-120um; 300 fps) recorded trajectories. The system was calibrated daily using a standard DLT protocol.

Mean reprojection error: 0.18 ± 0.04 pixels

Landing-point accuracy: ±9 mm

Final landing coordinates were overlaid on a calibrated vector court grid (the same grid shown in Fig. 2) to produce the scatter plots.

2.4.4. Data Processing and Statistical Analysis

Trajectory data were smoothed using a Savitzky–Golay filter. Outliers (> 3 SD) accounted for < 2% of samples and were removed.

Flight stability was quantified using:

X-axis dispersion

Y-axis dispersion

Euclidean distance to centroid
95% bivariate confidence ellipse area

Coefficient of variation (CV)

Analysis software: Python (SciPy, statsmodels) and SPSS 27.0.

3. Results

This analysis is based on flight landing data from both 36-hole and 40-hole picks. 120 samples were collected for each type of pick, and flight stability was evaluated using three indicators: X-axis coordinates, Y-axis coordinates, and combined distance. The statistical results are as Table 1.

Table 1
Test data statistics (N = 120 per group)

Tpye	Metric	Mean ± SD	Min	Max	CV	σ^2
36-hole	X-axis	269.43 ± 37.64	181.35	363.4	0.1397	1417.05
	Y-axis	-119.63 ± 33.15	-284.33	-45.53	-0.2771	1099.06
40-hole	X-axis	294.08 ± 47.51	163.08	396.94	0.1616	2257.32
	Y-axis	-158.54 ± 39.63	-262.07	-77.08	-0.25	1570.53
Euclidean distance	36-hole	242.12 ± 33.53	169.25	408.4	0.1385	1124.46
	40-hole	320.53 ± 40.12	236.34	426.55	0.1252	1609.24

3.1. Comparison of stability across different dimensions

With respect to the x-axis, as summarized in Table 1, the mean landing position of the 36-hole ball (269.43 cm) was lower than that of the 40-hole ball (294.08 cm). More notably, the horizontal landing dispersion of the 36-hole ball was markedly reduced, with a standard deviation of 37.64 cm, representing a 20.8% decrease compared with the 40-hole ball (47.51 cm). These results suggest that the 36-hole geometry yields a more stable horizontal flight trajectory, thereby reducing unpredictable lateral deviations.

Regarding the y-axis, as shown in Table 1, the mean landing coordinate of the 36-hole ball was − 119.63 ± 33.15, whereas the 40-hole ball exhibited a more dispersed landing position (− 158.54 ± 39.63). The standard deviation along the y-axis for the 36-hole ball was 6.48 cm lower, corresponding to a 16.35% reduction relative to the 40-hole ball. This finding indicates that the 36-hole ball also demonstrates a more concentrated vertical landing distribution. Although the coefficient of variation (CV) of the 40-hole ball was slightly lower due to its larger mean distance, the absolute dispersion metrics more clearly demonstrate the superior directional stability associated with the 36-hole design.

Regarding overall distance, the mean value for the 36-hole ball was 242.12 ± 33.53, whereas the 40-hole ball exhibited a higher mean overall distance of 320.53 ± 40.12. Compared with the 40-hole ball, the 36-hole ball demonstrated a reduction of 78.41 units in mean overall distance, corresponding to a 24.46% decrease. In addition, the standard deviation of the overall distance for the 36-hole ball was 6.59 units lower, representing a 16.43% reduction, indicating reduced variability (as shown in Fig. 3).

3.2. Bivariate Landing Dispersion Analysis

To evaluate whether the two ball designs differ significantly in overall landing dispersion, we compared their bivariate landing distributions using both numerical dispersion metrics and the 95% confidence ellipse analysis (Fig. 4).

A 95% bivariate probability ellipse was constructed to quantify the two-dimensional landing dispersion under the assumption of bivariate normality (as shown in Fig. 4). Each ellipse enclosed approximately 95% of the landing points, corresponding to a Mahalanobis distance .

The ellipse area for the 36-hole ball was 22,411 cm^2, whereas that for the 40-hole ball was 31,707 cm^2. The ratio of ellipse areas (36-hole / 40-hole) was 0.707, indicating that the landing distribution of the 36-hole ball covered a 29.3% smaller area.

Ellipse shape was further characterized using the eigenvalue ratio of the covariance matrix, with lower values indicating greater circularity. The eigenvalue ratio was 1.95 for the 36-hole ball and 2.81 for the 40-hole ball, demonstrating a more elongated landing distribution for the 40-hole ball.

4. Discussion

4.1. Integration of Distribution-Level Findings and Their Scientific Significance

The present study advances pickleball aerodynamics research by demonstrating that landing stability is governed not only by mean flight characteristics but also by the structure and geometry of landing dispersion. Unlike previous studies that primarily focused on univariate indicators such as flight distance or drag-related metrics, this work reveals that two-dimensional dispersion geometry provides a more comprehensive and sensitive representation of flight predictability.

Across all spatial metrics, the 36-hole pickleball exhibited consistently reduced dispersion compared with the 40-hole design. Most notably, the substantially smaller 95% bivariate probability ellipse area and lower eigenvalue ratio indicate that the landing points of the 36-hole ball are not only more concentrated but also more evenly distributed across directions. This finding is particularly important because anisotropy in landing dispersion reflects directional sensitivity, which directly affects shot reliability in real gameplay. By capturing this anisotropy explicitly, the present study provides empirical evidence that cannot be obtained from one-dimensional analyses alone.

From a statistical perspective, the convergence of univariate (X- and Y-axis dispersion) and bivariate (ellipse area and shape) results strengthens the internal validity of the findings. Similar multi-metric convergence has been emphasized as a hallmark of robust inference in biomechanics and sports engineering studies [19–21]. Thus, the observed differences between hole configurations represent systematic design effects rather than measurement artifacts or random variability.

4.2. Cross-Sport Context: Parallels with Other Sports Projectile Systems

The implications of this study extend beyond pickleball and contribute to the broader understanding of perforated and textured sports projectiles. While golf balls and soccer balls rely primarily on surface roughness and panel seams to manipulate boundary layer behavior, pickleballs represent a distinct aerodynamic class in which through-holes dominate wake formation. Despite this difference, the present findings align with a recurring theme across sports: geometric regularity promotes directional consistency.

In golf ball research, symmetric dimple patterns have been shown to stabilize lift and reduce side-force fluctuations, leading to more predictable trajectories [22, 23]. Similarly, studies on soccer balls demonstrate that uniform panel arrangements minimize erratic lateral motion, particularly near critical Reynolds numbers [24]. The current results suggest that these principles generalize to perforated balls, despite the fundamentally different airflow pathways involved.

A particularly informative comparison can be drawn with badminton shuttlecocks. Although shuttlecocks differ markedly in shape and mass distribution, their aerodynamic behavior is highly sensitive to structural symmetry. Research has shown that asymmetric feather arrangements amplify yaw instability and lateral drift, even when mean drag characteristics remain unchanged [25]. The present study reveals a comparable phenomenon in pickleballs: improvements in lateral stability exceed those observed in the longitudinal direction, indicating that hole layout symmetry primarily mitigates cross-flow disturbances rather than altering global deceleration. This parallel highlights a shared aerodynamic mechanism across seemingly disparate sports equipment.

4.3. Methodological Contribution: Beyond Mean Performance Metrics

An important methodological contribution of this study lies in its demonstration that relative variability metrics alone may be insufficient for comparing equipment designs with differing mean performance levels. Although coefficients of variation are commonly reported, they inherently normalize dispersion by the mean and may therefore obscure absolute differences when mean distances differ substantially. In contrast, absolute dispersion measures and bivariate spatial analyses consistently differentiated the two ball designs in this study.

This observation echoes findings in movement variability and projectile motion research, where spatially explicit metrics have been shown to outperform normalized indices in detecting meaningful performance differences [26, 27]. By adopting a bivariate probability ellipse framework—widely used in biomechanics but rarely applied to sports equipment evaluation—the present study introduces a transferable analytical approach that can be extended to other sports involving projectile landing consistency.

4.4. Practical and Regulatory Implications

From an applied perspective, the reduced dispersion and increased isotropy of the 36-hole design have direct implications for equipment standardization and competitive fairness. In outdoor pickleball, where wind and environmental disturbances are unavoidable, improved directional consistency can reduce outcome variability unrelated to player skill. Similar motivations underlie equipment regulations in other sports, such as restrictions on golf ball dimple geometry and soccer ball panel configurations [16, 22].

Notably, the 36-hole design achieved improved stability despite a modest reduction in total open area relative to the 40-hole ball. This challenges the implicit assumption that increased porosity necessarily enhances outdoor performance. Comparable findings have been reported in soccer ball aerodynamics, where optimal rather than maximal surface roughness yields the most stable flight behavior [16, 28]. These results suggest that geometric optimization, rather than increased ventilation, should be the primary design focus for future pickleball development.

4.5. Reliability, Limitations, and Directions for Future Research

Several limitations should be acknowledged. The experiments were conducted at a fixed launch speed and under controlled spin conditions, whereas real gameplay involves a wide range of velocities and rotational states. Additionally, although environmental variability was minimized, outdoor testing inherently introduces small-scale turbulence that cannot be fully eliminated. Nevertheless, the large number of repeated trials and the consistency of results across multiple independent metrics mitigate these concerns.

Future research should integrate computational fluid dynamics simulations and wind tunnel experiments to directly quantify pressure distributions, wake structures, and lateral force coefficients associated with different hole layouts. Extending the analysis to include spin effects and player-generated variability

would further enhance ecological validity. Moreover, incorporating perceptual and performance-based assessments could help bridge the gap between measured aerodynamic stability and player experience.

5. Conclusion

This study demonstrates that a 36-hole pickleball designed using a truncated-icosahedron–based geometric framework achieves significantly greater flight stability than a conventional 40-hole ball. By integrating geometric uniformity analysis with controlled outdoor flight testing, we show that improved spherical isotropy reduces both horizontal and vertical landing dispersion, resulting in more predictable flight trajectories. These findings empirically validate the theoretical link between global hole symmetry and aerodynamic stability, extending prior research on perforated spheres into the context of pickleball equipment design.

The results highlight the potential of symmetry-driven engineering strategies to enhance the performance and standardization of outdoor pickleballs. While the study is limited by a single launch speed, uncontrolled spin conditions, and one control geometry, the observed stability improvements suggest that geometric optimization may represent a valuable direction for future equipment development.

Declarations

Funding information

This work was supported by the following grants: The 15th National Games and the National Paralympic Games Guangdong-Hong Kong-Macao Collaborative Development Theory and Practice Research Project (Grant No. 2025GBA-082); The Characteristic Innovation Project of Guangdong Provincial Department of Education (Grant No. 2025WTSCX173); The Teaching Reform Project of Guangdong Industry Polytechnic University (Grant No. KCSZ202418); The Doctoral Research Project of Guangdong Industry Polytechnic University (Grant No. BSKJ2025-42); Guangdong Artificial Intelligence Light Industry Innovation Application Engineering Technology Research Center (Grant No. 2025A020).

Confirmation of Ethical Compliance

This study did not involve human participants, biological samples, or animal subjects. The research focused exclusively on the aerodynamic stability testing of pickleballs with different hole configurations. As a purely mechanical/physical experiment, no ethical approval was required. All testing was conducted in compliance with standard laboratory safety regulations.

Acknowledgments

The authors sincerely thank Guangdong Industry Polytechnic University for providing the injection molding equipment and practical training facilities. The authors are also grateful to all participants for

contributing their valuable time to this study and facilitating the smooth progress of the work reported herein.

CRediT authorship contribution statement

Peng Lin: Conceptualization, Data curation, Writing – original draft, Funding acquisition. Yansheng Chen: Software, Formal analysis, Investigation (ball hole design and fabrication), Funding acquisition. Zejiong Zheng: Conceptualization, Methodology, Investigation (ball fabrication and testing), Project administration, Supervision. Dan Huang: Investigation (ball testing and data collection), Data curation.

References

1. Shi S, Zhang J. A Review on Aerodynamic Effects of Surface Texturing in Sports and Engineering. Highlights Sci Eng Technol. 2025 Dec 30;160:518–26. doi:10.54097/kck8h713
2. Emond K, Sun W, Swartz TB. Pickleball Flight Dynamics [Internet]. arXiv; 2024 [cited 2026 Jun 13]. Available from: http://arxiv.org/abs/2409.19000 doi:10.48550/arXiv.2409.19000
3. Achenbach E. The effects of surface roughness and tunnel blockage on the flow past spheres. Journal of Fluid Mechanics. 1974 Aug;65(1):113–25. doi:10.1017/S0022112074001285
4. Mehta RD, Pallis JM. Sports ball aerodynamics: effects of velocity, spin and surface roughness. Miner Met Mater Soc/AIME Mater Sci Sports(USA). 2001;185–97.
5. Afshari F, Sahin B, Marchetti B, Polonara F, Corvaro F, Leporini M, et al. NUMERICAL STUDY ON DRAG COEFFICIENT AND EVALUATION OF THE FLOW PATTERNS IN PERFORATED PARTICLES. Heat Transfer Res. 2021;52(14):47–61. doi:10.1615/HeatTransRes.2021038829
6. Tyagi H, Liu R, Ting DSK, Johnston CR. Experimental Investigation of Perforated Plate Turbulent Flow Past a Solid Sphere. In: Fluids Engineering [Internet]. Anaheim, California, USA; 2004 [cited 2026 Jun 13]. p. 577–85. Available from: https://asmedigitalcollection.asme.org/IMECE/proceedings/IMECE2004/47098/577/300616 doi:10.1115/imece2004-60340
7. Nedić J, Supponen O, Ganapathisubramani B, Vassilicos JC. Geometrical influence on vortex shedding in turbulent axisymmetric wakes. Phys Fluids. 2015 Mar 1;27(3):035103. doi:10.1063/1.4913573
8. Zhang YL, Huang HF, Xu XW, Zhao YJ. Precision calculation of the projectile trajectory of a spherical object considering air resistance. Journal of the Chinese Institute of Engineers. 2025 Aug 18;48(6):804–20. doi:10.1080/02533839.2025.2491433
9. Ambekar AS, Peters E, Hinrichsen O, Buwa VV, Kuipers JAM. Understanding the role of perforations on the local hydrodynamics of gas–liquid flows through structured packings. Chem Eng J. 2024 Apr;486:150084. doi:10.1016/j.cej.2024.150084
10. Kalugin VT, Epikhin AS, Chernukha PA, Kalugina MD. The effect of perforation on aerodynamic characteristics and the vortex flow field around a flat plate. In: IOP Conference Series: Materials

Science and Engineering [Internet]. IOP Publishing; 2021 [cited 2026 Jun 13]. p. 012007. Available from: https://iopscience.iop.org/article/10.1088/1757-899X/1191/1/012007/meta

11. Nayfeh AH, Saric WS. An Analysis of Asymmetric Rolling Bodies with Nonlinear Aerodynamics. AIAA J. 1972 Aug;10(8):1004–11. doi:10.2514/3.50285
12. Zhang W, Bi D, Wei Y. Effect of porosity on the kinematics of free-falling porous disks. Phys Fluids. 2023 Jan 1;35(1). doi:10.1063/5.0134073
13. Cadot O, Evrard A, Pastur L. Imperfect supercritical bifurcation in a three-dimensional turbulent wake. Phys Rev E. 2015;91(6):063005.
14. Chen RC, Wu JL. The flow characteristics between two interactive spheres. Chem Eng Sci. 2000;55(6):1143–58.
15. Rigas G, Morgans AS, Brackston RD, Morrison JF. Diffusive dynamics and stochastic models of turbulent axisymmetric wakes. J Fluid Mech. 2015;778:R2. doi:https://doi.org/10.1017/jfm.2015.390
16. Ward M, Passmore MA, Spencer A, Hanson H, Lucas T. The effect of surface geometry on the aerodynamic behaviour of a football. Sports Eng. 2023;26(1):33. doi:https://doi.org/10.1007/s12283-023-00409-5
17. Mehta RD. Aerodynamics of sports balls. Annu Rev Fluid Mech. 1985 Jan;17(1):151–89. doi:10.1146/annurev.fl.17.010185.001055
18. Nabizadeh M. Fluid Dynamics: From Geometric Formulations to Structure-Preserving Simulations [PhD Thesis] [Internet]. University of California, San Diego; 2025 [cited 2026 Jun 14]. Available from: https://search.proquest.com/openview/930ff066392ce465828034440646cfc6/1?pq-origsite=gscholar&cbl=18750&diss=y
19. Miqueleiz U, Aguado-Jimenez R, Lecumberri P, Garcia-Tabar I, Gorostiaga EM. Reliability of Inertial Measurement Unit-Based Spatiotemporal and Kinetic Variables in Endurance Runners during Treadmill Running. J Hum Kinet. 2025 May 12;97:65–76. doi:10.5114/jhk/195895
20. Lohse KR, Sainani KL, Taylor JA, Butson ML, Knight EJ, Vickers AJ. Systematic review of the use of “magnitude-based inference” in sports science and medicine. PLOS One. 2020 Mar 5;15(6):e0235318. doi:10.31236/osf.io/wugcr
21. You Y. Accelerometer-measured physical activity and sedentary behaviour are associated with C-reactive protein in US adults who get insufficient sleep: A threshold and isotemporal substitution effect analysis. J Sports Sci. 2024 Mar 18;42(6):527–36. doi:10.1080/02640414.2024.2348906
22. Abbas Z, Shah SIA, Javed A, Jamil M. Influence of dimple design on aerodynamic drag of golf balls. In: 2019 Sixth International Conference on Aerospace Science and Engineering (ICASE) [Internet]. Islamabad, Pakistan: IEEE; 2019 [cited 2026 Jun 14]. p. 1–7. Available from: https://ieeexplore.ieee.org/document/9059229/ doi:10.1109/icase48783.2019.9059229
23. Sajima T, Yamaguchi T, Yabu M, Tsunoda M. The Aerodynamic Influence of Dimple Design on Flying Golf Ball. In: Moritz EF, Haake S, editors. The engineering of sport 6 [Internet]. New York, NY:

Springer New York; 2006 [cited 2026 Jun 14]. p. 143–8. Available from: https://link.springer.com/10.1007/978-0-387-46050-5_26 doi:10.1007/978-0-387-46050-5_26

24. Alam F, Chowdhury H, Stemmer M, Wang Z, Yang J. Effects of surface structure on soccer ball aerodynamics. Procedia Eng. 2012;34:146–51. doi:10.1016/j.proeng.2012.04.026
25. Lin Zhou. Aerodynamic Characteristics and Trajectory Analysis of Badminton Shuttlecocks. Acta Bioeng Biomech. 2024;26(4). doi:10.37190/ABB-02508-2024-01
26. Hanono Cozzetti IA, Abdou A. A Visual Analytics Tool for Discovering Trajectory Patterns Using a Movement Taxonomy [Internet]. 2025 [cited 2026 Jun 14]. Available from: https://www.diva-portal.org/smash/record.jsf?pid=diva2:1973122
27. González-Millán S, Caparrós T, Toro-Roman V, Illera-Domínguez V, Albesa-Albiol L, Moras G, et al. Effect of ball inclusion in drop vertical jump test on performance and movement variability in basketball players. Appl Sci. 2024;14(2):505. doi:10.3390/app14020505
28. Hong S. The Impact of Surface Structure Changes on the Aerodynamic Characteristics of Modern Soccer Balls. Korean J Sport Sci. 2024 Jun 30;35(2):392–400. doi:10.24985/kjss.2024.35.2.392

Figures

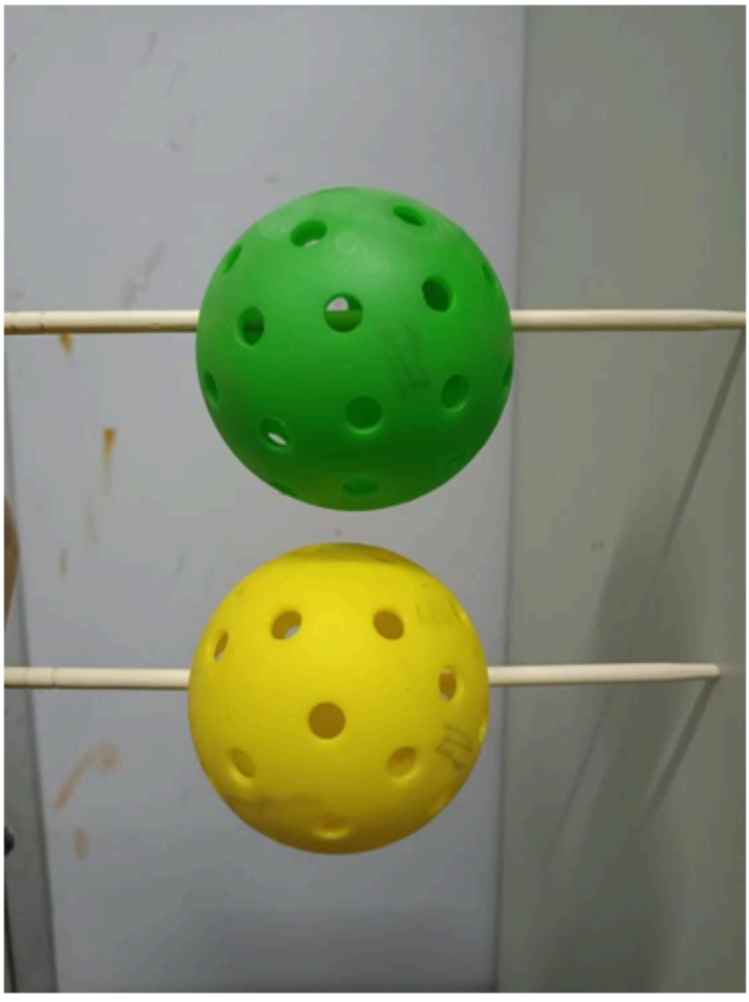


Figure 1

Two different designs of pickleballs.

(1) Green ball: a novel 36-hole ball designed by mapping the 36 vertices of a truncated icosahedron onto a sphere;

(2) Yellow ball: a standard 40-hole ball produced by the authors' institution using a conventional ring-based layout.

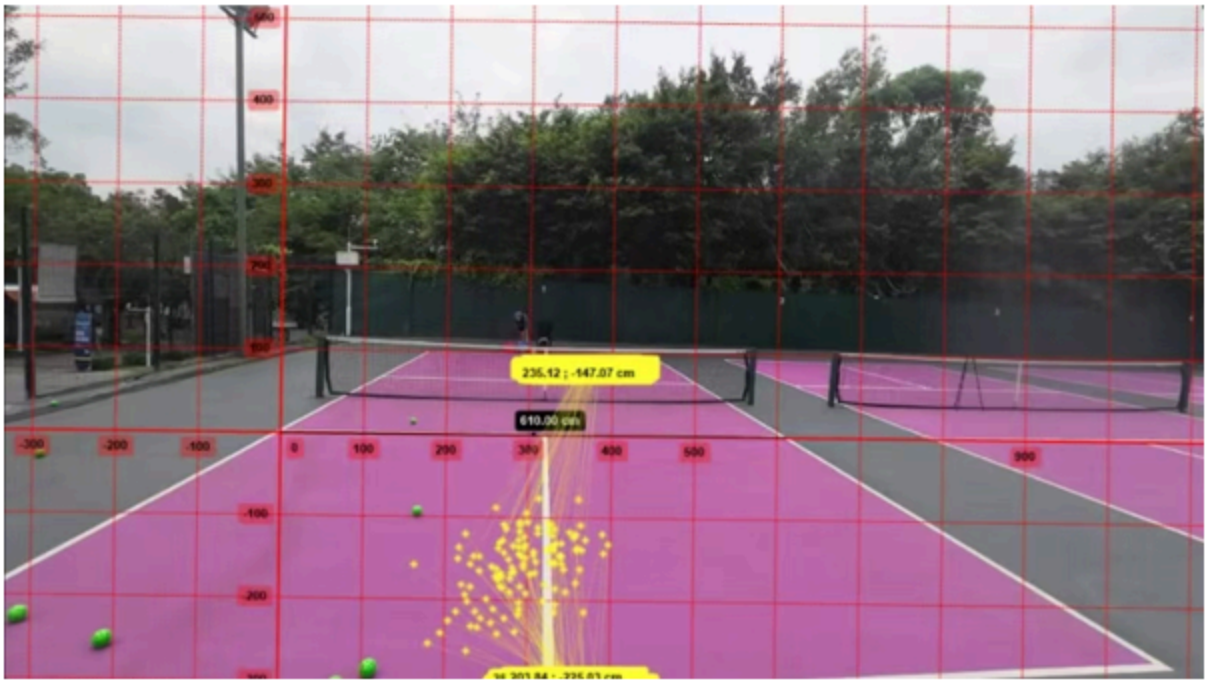


Figure 2

Landing point vector grid diagram

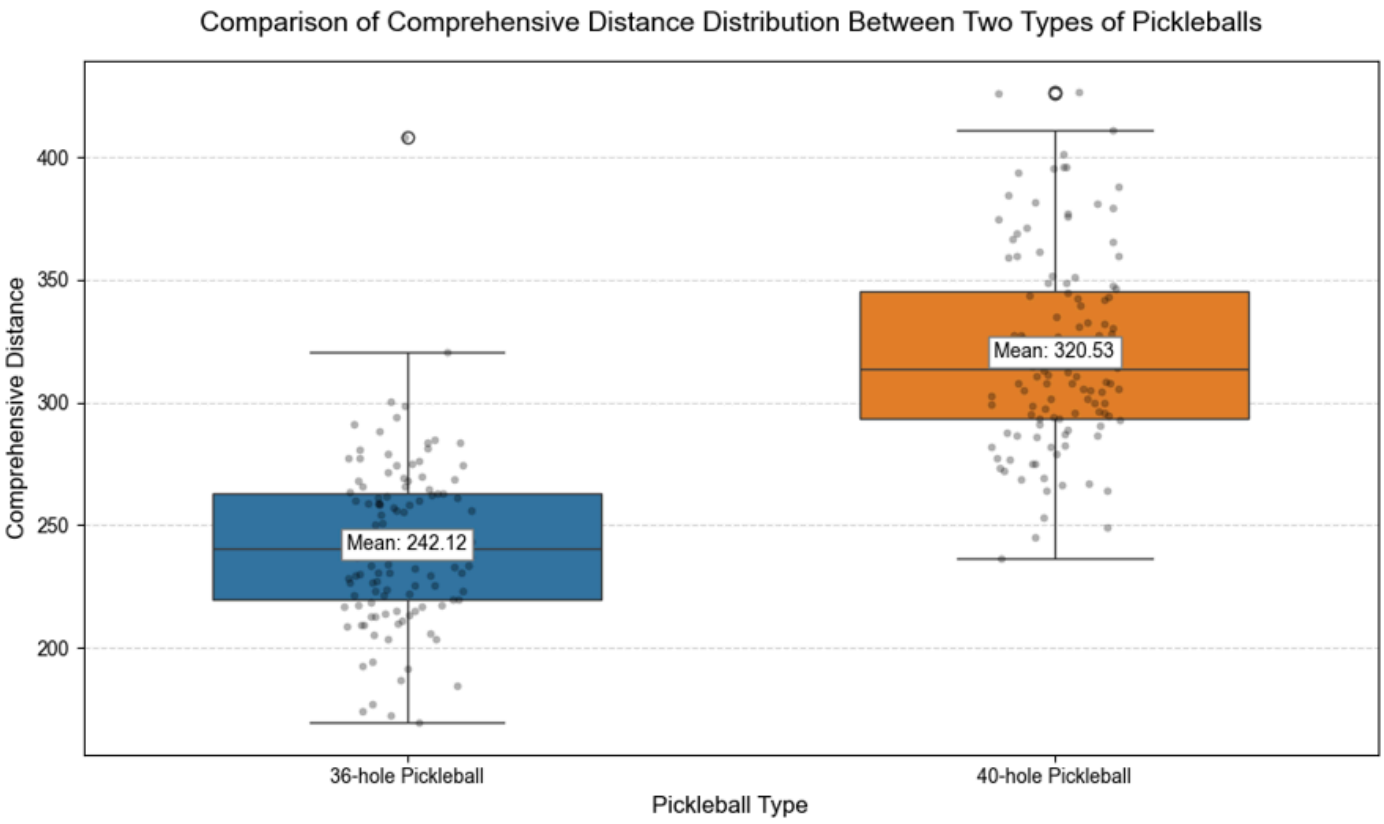


Figure 3

Overall Euclidean Distance from Centroid

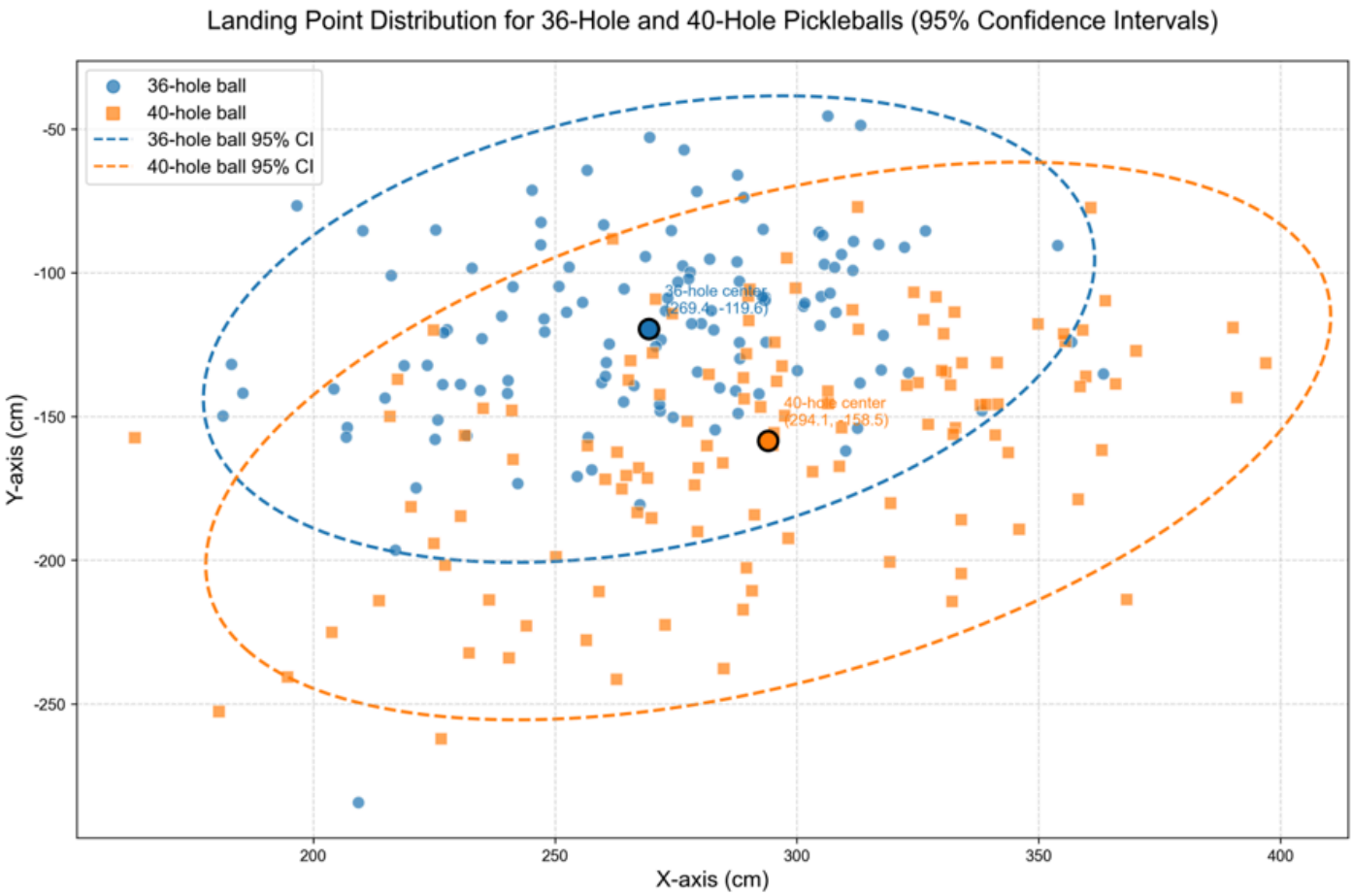


Figure 4

95% Bivariate Confidence Ellipse Comparison