



Effect of Dimple Topology and Ball Mass on the Aerodynamic and Flight Performance of Golf Balls

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Abstract. The flight performance of a golf ball is governed by its surface geometry, which controls boundary-layer transition, separation and wake formation, yet the effects of convex surface topology and of ball mass remain underexplored. This study experimentally compares three surface patterns of identical diameter and feature count: conventional circular dimples (baseline), hexagonal dimples and circular convex protrusions. Wake fields were characterised in a closed-loop water tunnel by Particle Image Velocimetry (PIV) and dye visualisation at $Re = 1.5 \times 10^3 - 6.7 \times 10^3$, and drag and lift were measured in a wind tunnel at $Re = 2.9 \times 10^4 - 1.12 \times 10^5$ with a combined uncertainty analysis. Over $Re = 5.8 \times 10^4 - 1.1 \times 10^5$ the baseline has the lowest drag at every test point, the convex and hexagonal patterns exceeding it by $5.8 \pm 0.9\%$ and $5.1 \pm 1.0\%$ on average, while the convex ball shows a pronounced negative-lift regime at intermediate Re . The measured $C_D(Re)$ and $C_L(Re)$ were applied to a two-dimensional, no-spin trajectory model with Monte Carlo uncertainty propagation at the regulation mass (45.93 g) and at 190 g. At regulation mass the ball decelerates into the negative-lift regime of the convex pattern, and the baseline carries 3.6 - 6.0 m farther than the convex ball for launch angles of $15.7^\circ - 46.8^\circ$; at 190 g the ball remains above this regime and the two patterns become indistinguishable at a shallow launch angle. This Reynolds-number-mediated pattern-mass coupling provides a fluid-mechanical rationale for the dominance of circular dimples on regulation balls.

Keywords: Golf-ball dimple pattern, Particle Image Velocimetry, Flow visualisation, Trajectory analysis, Uncertainty analysis

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1. Introduction

The flight performance of a golf ball, such as carry distance and directional stability, is governed primarily by its aerodynamic characteristics. Drag and lift determine how quickly the ball decelerates and how long it remains airborne, so surface geometry is a central design variable. Small changes in dimple geometry can substantially alter the drag crisis and the lift–drag balance over the Reynolds-number range of golf shots [1], and the interaction between spin and surface roughness can even reverse the sign of the lift force [2].

For concave dimples, systematic variation of diameter, depth, occupancy and shape shows that a larger dimple volume ratio generally reduces drag and enhances lift for spinning balls [3], [4]; laser-Doppler measurements and CFD have resolved the near-wake structure behind dimpled balls [5]; and wind-tunnel studies of golf balls and of dimpled or 3D-printed sports balls have quantified how surface parameters control the force coefficients [6], [7], [8]. Direct numerical simulation has further shown that dimples trip the boundary layer at the dimple lip and generate small-scale vortices that re-energise the near-wall flow and delay separation [9].

Two aspects remain only partially explored. First, almost all experiments concern concave dimples; balls with convex features of comparable size and coverage are rarely compared. Convex protrusions behave as distributed roughness elements; protruding biomimetic surfaces modify near-wall flow and drag differently from cavities [10], [11], and asymmetric roughness governs the separation and swing of cricket balls [12]. The effect of convex topology on a sphere at golf-ball Reynolds numbers, however, has not been isolated experimentally. Second, although aerodynamic coefficients have been linked to flight outcomes through CFD-plus-rigid-body models [13] and physics-informed deep-learning flight models [14], few studies combine flow visualisation, force measurement and trajectory analysis for golf balls, and the role of ball mass in modulating the aerodynamic ranking of surface patterns has, to our knowledge, not been examined.

This study addresses these gaps for circular-dimpled (baseline), hexagonal-dimpled and circular-convex balls (Figure 1): water-tunnel PIV characterises the wakes, wind-tunnel measurements provide drag and lift coefficients with quantified uncertainty, and the coefficients drive a trajectory model evaluated at two ball masses to test whether the inter-pattern ranking is mass-dependent.

2. Methods

2.1. Test models

Three test models were investigated (Figure 1): a circular-dimpled ball (baseline), a hexagonal-dimpled ball and a circular-convex ball. All models have the standard diameter $D = 42.68$ mm and approximately 308 surface features. Each dimple has a diameter $d = 4$ mm and a depth $h = 0.5$ mm, and each convex element has the same diameter and height (Figure 1d–f). A cylindrical hole ($D_{\text{hole}} = 3$ mm, $l_{\text{hole}} = 16$ mm) at the bottom of each model is used for mounting in both tunnels (Figure 1g). The models were 3D-printed in rigid polymer and are heavier than a regulation ball ($m_{\text{conv}} = 0.206$ kg, $m_{\text{base}} = 0.1863$ kg, $m_{\text{hex}} = 0.179$ kg versus $m_{\text{reg}} = 0.04593$ kg). Because C_D , C_L and the PIV wake structure depend only on geometry, fluid properties and free-stream velocity, the aerodynamic results apply to a regulation ball at the same Reynolds number; only the trajectory analysis (Section 2.4) depends on mass and is therefore performed at two mass levels. Feature coverage, print roughness and dimensional tolerances were not measured, so the comparison refers to these specimens.

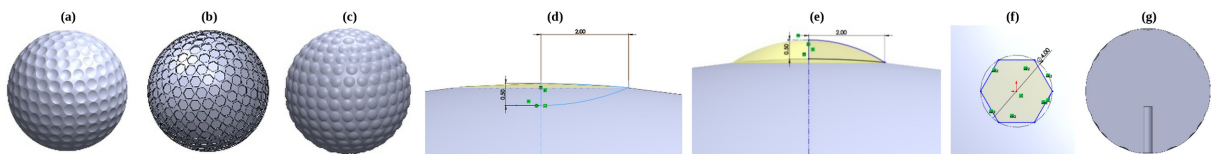


Figure 1. Test models: (a) circular-dimpled (baseline), (b) hexagonal-dimpled, (c) circular-convex; geometry of (d) a circular dimple, (e) a convex element and (f) a hexagonal dimple (dimensions in mm); (g) mid-section showing the support hole.

2.2. Water-tunnel PIV and flow visualisation

Wake measurements were performed in a closed-loop water tunnel (test section $0.16 \text{ m} \times 0.25 \text{ m} \times 0.75 \text{ m}$, $0.05\text{--}2 \text{ m s}^{-1}$) equipped with a PIV system (Figure 2a). Water at 15°C ($\rho = 999 \text{ kg m}^{-3}$, $\mu = 1.1375 \times 10^{-3} \text{ Pa s}$) was seeded with plastic tracer particles of $\approx 30 \mu\text{m}$, a size typical of liquid-phase PIV [15], [16]. A laser sheet illuminated the vertical mid-plane through the ball centre and a CCD camera normal to the sheet recorded the particle images [16], [17]. For each model, about 300 images were captured at five flow speeds; at each condition 100 frames recorded at $100 \text{ frames s}^{-1}$ were processed by cross-correlation in PIVlab and time-averaged to obtain the velocity field and the out-of-plane vorticity ω_z . Velocity and vorticity profiles were extracted along vertical lines at $X/D = 0.6, 0.8$ and 1.0 downstream of the ball centre. The Reynolds number is defined as

$$Re = \frac{\rho U D}{\mu} \quad (1)$$

where U is the free-stream velocity. The three lowest pump settings (2.5, 5 and 7.5 Hz) gave $U = 0.040, 0.104$ and 0.180 m s^{-1} , i.e. $Re = 1499, 3898$ and 6747 , referred to below as $Re = 1500, 3900$ and 6700 ; these are analysed here. Dye injected upstream of the ball provided qualitative visualisation at $Re = 1500$.

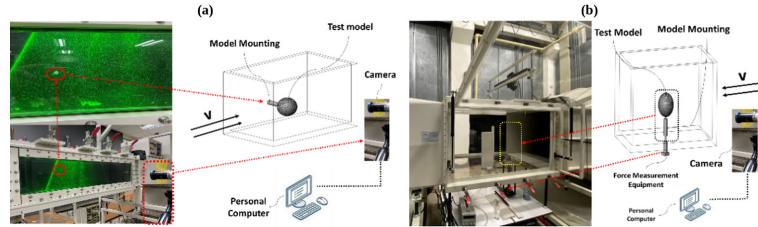


Figure 2. Experimental set-ups: (a) water tunnel with PIV system; (b) wind tunnel with sting-mounted model, force balance and visualisation camera.

2.3. Wind-tunnel force measurements

Drag and lift were measured in an open-circuit, suction-type wind tunnel with a $0.7 \text{ m} \times 2 \text{ m} \times 2 \text{ m}$ test section (Figure 2b). The model was mounted on a slender vertical sting connected to a multi-component force balance beneath the test-section floor, a configuration commonly used for static sports-ball testing [18], [19], and the free-stream velocity was measured upstream of the ball. Each run was normalised by the velocity recorded with it: one value per setting for the baseline and convex runs ($10.0\text{--}38.2 \text{ m s}^{-1}$) and individual values for the two hexagonal runs ($10.0\text{--}38.8 \text{ m s}^{-1}$); at equal fan frequency the two velocity records differ by r.m.s. 1.1 % (maximum 2.5 %). Forces were recorded at nine settings in air at 15°C ($\rho_a = 1.225 \text{ kg m}^{-3}$, $\mu_a = 1.8 \times 10^{-5} \text{ Pa s}$), giving $Re = 2.90 \times 10^4\text{--}1.12 \times 10^5$, which overlaps the lower part of the on-course range. Each condition was measured twice (Test 1 and Test 2), except four high-velocity convex settings with a single valid run (50 runs in total). Smoke streaklines illuminated by a laser sheet were recorded at fan frequencies of 1.8, 3 and 4.7 Hz ($U_a = 0.5, 1.25$ and 2.3 m s^{-1} ; $Re = 1452, 3631$ and 6680), the settings closest to the water-tunnel Reynolds numbers. All measurements were made on stationary models, which isolates the effect of surface geometry from the spin-coupled Magnus mechanism, as is common when characterising new ball surfaces [18], [19], [20]; spin is discussed in Section 3.5.

2.4. Data reduction and trajectory model

Time-averaged forces of each run were converted into coefficients with the run's own velocity and then averaged over the runs,

$$C_D = \frac{2F_D}{\rho_a A U^2} \quad (2)$$

$$C_L = \frac{2F_L}{\rho_a A U^2} \quad (3)$$

where $A = \pi D^2/4 = 1.4307 \times 10^{-3} \text{ m}^2$ is the frontal area and forces recorded in gram-force were converted

with $1 \text{ gf} = 9.80665 \times 10^{-3} \text{ N}$. The coefficients drive a two-dimensional point-mass flight model that assumes motion in the vertical plane, no spin (zero Magnus force) and quasi-steady aerodynamics:

$$m \frac{d\mathbf{V}}{dt} = -\frac{1}{2} \rho_a A C_D |\mathbf{V}|^2 \hat{\mathbf{V}} + \frac{1}{2} \rho_a A C_L |\mathbf{V}|^2 \hat{\mathbf{n}} - mg \mathbf{e}_y \quad (4)$$

where $\mathbf{V}$ is the velocity vector, $\hat{\mathbf{V}}$ the unit vector along $\mathbf{V}$, $\hat{\mathbf{n}}$ the unit vector normal to $\hat{\mathbf{V}}$ in the vertical plane (positive upward for $C_L > 0$), $\mathbf{e}_y$ the upward unit vector, $g = 9.81 \text{ m s}^{-2}$ and m the ball mass. Equation (4) was integrated with an adaptive Runge–Kutta (RK45) scheme (relative and absolute tolerances 10^{-10}) until the ball returned to launch height, for $U_0 = 40 \text{ m s}^{-1}$ and launch angles $\theta = 15.74^\circ$, 31.33° , 46.83° and 59.83° ($u_0 = U_0 \cos \theta = 38.50, 34.17, 27.37$ and 20.10 m s^{-1}). The primary model uses Re-dependent coefficients obtained by linear interpolation of the measured $C_D(\text{Re})$ and $C_L(\text{Re})$ at the instantaneous Re; the in-flight Re (3.2×10^4 – 1.16×10^5) lies almost entirely within the measured range (end values are held outside it). For comparison, a constant-coefficient model using the values at $\text{Re} = 1.12 \times 10^5$ was also run. Coefficient uncertainties were propagated by Monte Carlo sampling (500 realisations, each C_D and C_L point drawn from a normal distribution with its combined standard uncertainty); a carry difference is considered significant when it exceeds twice its standard deviation. To isolate the aerodynamic effect from mass differences, the same mass was assigned to all patterns in each scenario: $m = 190 \text{ g}$ (close to the 190.4 g mean of the test models) and $m = 45.93 \text{ g}$ (maximum permitted by the Rules of Equipment [21]). This approach follows ball-in-flight models [6], [22].

2.5. Uncertainty analysis

The combined standard uncertainty was evaluated following the GUM [23]. The Type A repeatability uncertainty of each mean force was estimated from the duplicate runs as

$$u(F) = \frac{|F_{T1} - F_{T2}|}{2} \quad (5)$$

i.e. the standard error of the mean for $n = 2$, applied to the run-normalised coefficients. For the four convex settings with a single valid run, the Type A term was taken from the pooled repeatability of the five duplicated convex settings (7.7 % of C_D ; 2.6 gf in lift). Type B contributions are $u(U)/U \approx 1 \%$ (velocity measurement, consistent with the 1.1 % r.m.s. difference noted in Section 2.3), $u(\rho)/\rho \approx 0.5 \%$ and $u(A)/A \approx 0.2 \%$, combined by root-sum-square propagation:

$$\frac{u(C_D)}{C_D} = \sqrt{\left(\frac{u(F_D)}{F_D}\right)^2 + \left(\frac{2u(U)}{U}\right)^2 + \left(\frac{u(\rho)}{\rho}\right)^2 + \left(\frac{u(A)}{A}\right)^2} \quad (6)$$

The 1 gf recording resolution adds a rounding term of $1 \text{ gf}/\sqrt{12}$ per reading in quadrature. Because C_L is often close to zero, its absolute uncertainty $u(C_L)$ is reported. For the PIV, a typical correlation-peak error of $\approx 0.1 \text{ px}$ [24] implies velocity errors of a few per cent, so the PIV fields are used comparatively. Averaged results are listed in Table 1; per-point values are given in the Supplementary Data.

Table 1. Combined standard uncertainty of C_D and C_L , averaged over all tested Re.

Pattern	$u(C_D)/C_D$ (avg)	$u(C_D)/C_D$ (range)	$u(C_L)$ (avg)
Baseline	2.60 %	2.08–3.98 %	± 0.018
Hexagonal	6.24 %	4.15–10.04 %	± 0.014
Convex	7.99 %	5.11–10.04 %	± 0.047

3. Results and Discussion

3.1. Wake structure

Figure 3a shows the time-averaged velocity-magnitude fields with streamlines in the mid-plane. All three models form a recirculation region bounded by two shear layers, with separation (red circles) just downstream of the crest. At these Reynolds numbers the boundary layer is laminar, so the shorter, reorganised recirculation region at higher Re reflects transition of the separated shear layers rather than dimple-induced boundary-layer transition, which occurs at much higher Re [9], [25]. The wake

organisation depends on topology: at $Re = 6700$ the baseline wake contains a pair of large, coherent counter-rotating vortices, the convex wake is less ordered and the hexagonal wake is intermediate. The vorticity fields (Figure 3b) confirm that high vorticity is confined to the shear layers and show that, for the convex model, the high-vorticity region extends further downstream and is less coherent.

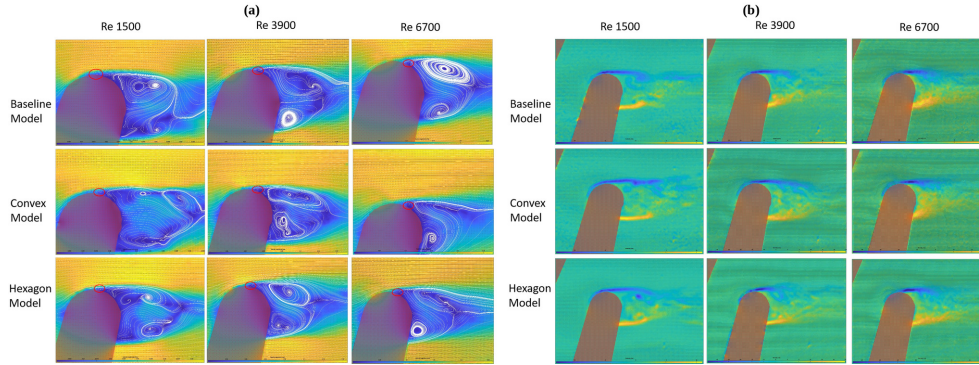


Figure 3. Time-averaged water-tunnel PIV fields for the three models (rows) at $Re = 1500$, 3900 and 6700 (columns): (a) velocity magnitude with streamlines, red circles marking the separation region; (b) out-of-plane vorticity.

Dye visualisation in the water tunnel (Figure 4a) and smoke visualisation in the wind tunnel (Figure 4b) show vortex-shedding wakes for all models, with the broadest and most dispersed wake behind the convex ball.

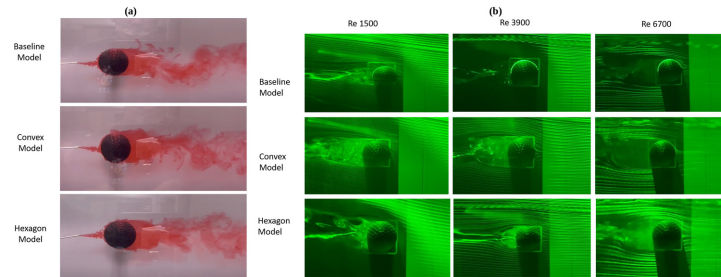


Figure 4. Flow visualisation: (a) dye in the water tunnel at $Re = 1500$; (b) smoke-laser sheet in the wind tunnel at $Re = 1452$, 3631 and 6680 (panel labels give the nominal values 1500 , 3900 and 6700).

In Figure 5a–c the velocity deficit widens downstream at all Re , without a consistent ordering of the minimum velocity among the patterns. The vorticity profiles at $Re = 6700$ (Figure 5d–f) show a negative and a positive peak marking the two shear layers. Close to the ball ($X/D = 0.6$ – 0.8) the convex peaks are 9–27 % weaker than the baseline peaks, but the convex ball carries clearly non-zero vorticity in the wake core between them (mean 5 – 7 s^{-1} over the central 20 mm , versus ≈ 0 for the baseline). At $X/D = 1.0$ the trend reverses: the convex peaks are $\approx 48 \%$ (negative, -21.8 versus -14.7 s^{-1}) and $\approx 28 \%$ (positive, 11.4 versus 8.9 s^{-1}) stronger than the baseline peaks, and the hexagonal ball shows similarly strong shear layers (-20.5 and $+19.3 \text{ s}^{-1}$). Convex vorticity is therefore not uniformly the strongest; rather, the baseline wake decays fastest, whereas both textured patterns retain vortical energy further downstream.

3.2. Aerodynamic coefficients

Figure 6 shows $C_D(Re)$ and $C_L(Re)$ with combined-uncertainty error bars. C_D lies between 0.59 and 0.74 (sub-critical values, no drag crisis within the range) and is similar for all patterns, within uncertainty, at the lowest Re . From $Re = 5.8 \times 10^4$ upward the baseline has the lowest drag at all seven test points. At the highest setting it gives $C_D = 0.706 \pm 0.015$, against 0.736 ± 0.059 for the convex and 0.738 ± 0.036 for the hexagonal pattern; these single-point differences lie within the uncertainties. Averaged over the seven points, however, the convex and hexagonal drag exceed the baseline by $5.8 \pm 0.9 \%$ and $5.1 \pm 1.0 \%$.

% (mean $\pm$ standard error), whereas the two textured patterns differ by only -0.6 % and are regarded as comparable. Lift shows a stronger pattern dependence. The convex ball generates negative lift over $Re = 4.4 \times 10^4 - 8.0 \times 10^4$ (minimum $C_L = -0.32 \pm 0.17$), a regime measured in both repeated runs, and positive lift ($C_L \approx +0.04$ to $+0.05$) from $Re = 8.7 \times 10^4$ upward, where only one valid run is available. At the highest setting the convex lift exceeds the baseline value by $\Delta C_L = +0.015 \pm 0.022$ ($C_L = +0.038 \pm 0.020$ versus $+0.023 \pm 0.008$), a difference not resolved by the data, whereas the hexagonal lift is essentially zero (-0.008 ± 0.008).

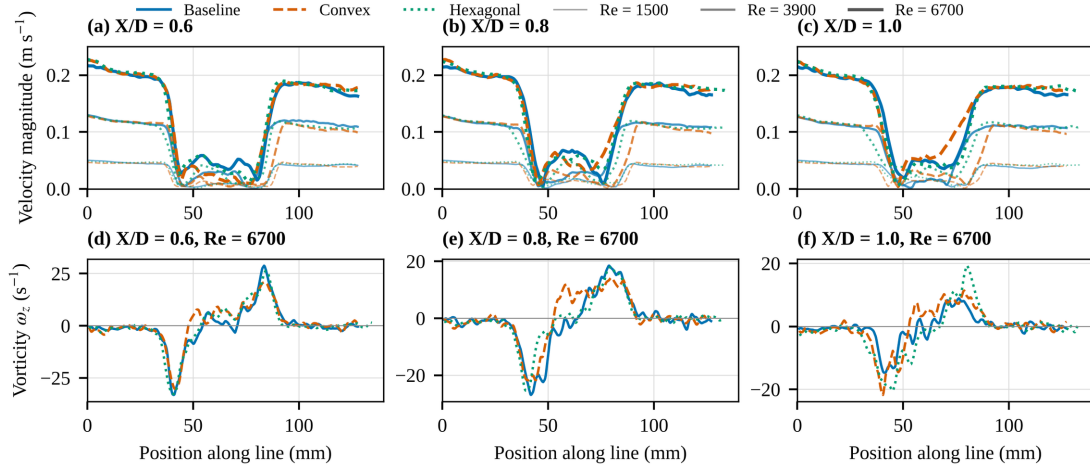


Figure 5. Wake profiles along vertical lines at $X/D = 0.6, 0.8$ and 1.0 downstream of the ball centre: (a–c) velocity magnitude at $Re = 1500, 3900$ and 6700 ; (d–f) vorticity at $Re = 6700$. Curves are re-plotted from the PIVlab profile exports.

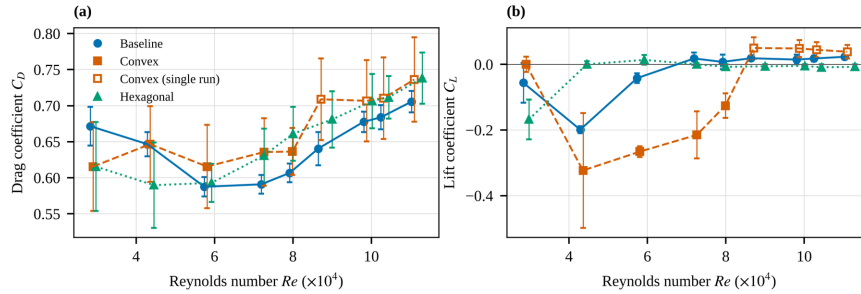


Figure 6. (a) Drag and (b) lift coefficients versus Reynolds number. Error bars show the combined standard uncertainty; open symbols mark convex settings with a single valid run; symbols are offset slightly in Re for legibility.

3.3. From wake to forces

The wake observations are consistent with the force trends, although they were obtained at Reynolds numbers about 17 times lower than the force data, so the links proposed here are qualitative. The baseline wake, with coherent vortices and the fastest vorticity decay, corresponds to the lowest C_D . In the hexagonal configuration the dense, space-filling tessellation leaves little smooth surface between cavities; its persistent downstream shear layers (Figure 5f) are consistent with its higher drag and with numerical evidence that dimples in unfavourable locations or with excessive depth can increase rather than reduce drag by promoting premature separation [26], [27]. The convex protrusions act as distributed roughness, producing a broader, less ordered wake (Figures 3 and 4) with vorticity spread into the wake core, which enlarges the pressure deficit and explains the drag penalty.

Lift reflects wake asymmetry: at $X/D = 1.0$ the two shear layers of the convex ball differ most in strength (Figure 5f). At intermediate Re , earlier separation on one side biases the wake and yields negative lift; as Re increases, the separation lines move rearward and the asymmetry inverts, switching

the sign of C_L between $Re \approx 8.0 \times 10^4$ and 8.7×10^4 . Comparable lift-sign changes linked to separation-line repositioning are reported for golf balls under reverse-Magnus conditions [2], cricket balls with asymmetric roughness [12] and static footballs and volleyballs [18], [19]. The more symmetric wake of the hexagonal ball is consistent with its near-zero lift.

3.4. Flight performance and pattern–mass coupling

Table 2 lists the carry distances with their Monte Carlo uncertainties, and Figure 7 shows the effect of ball mass. With the Re -dependent coefficients and regulation mass, the ball decelerates from $Re = 1.16 \times 10^5$ to about 6.4×10^4 ($\theta = 15.74^\circ$) or lower, i.e. into the regime where the convex pattern has negative lift. The baseline therefore carries significantly farther than the convex ball at $\theta = 15.74^\circ$, 31.33° and 46.83° (by 3.7 ± 1.0 , 6.0 ± 1.1 and 3.6 ± 1.8 m), and farther than the hexagonal ball at $\theta = 15.74^\circ$ (2.1 ± 0.6 m). The baseline–hexagonal differences at the three steeper angles ($|\Delta| \leq 1.6$ m) and all differences at $\theta = 59.83^\circ$ are not significant.

Table 2. Computed carry distance (m) for $U_0 = 40 \text{ m s}^{-1}$: nominal value $\pm$ one standard deviation from Monte Carlo propagation of the coefficient uncertainties (500 realisations).

θ ($^\circ$)	Pattern	Re-dependent C, 45.93 g	Re-dependent C, 190 g	Constant C, 45.93 g	Constant C, 190 g
15.74	Baseline	52.8 ± 0.4	73.0 ± 0.3	51.9 ± 0.6	73.0 ± 0.4
	Convex	49.1 ± 1.0	73.5 ± 0.7	51.9 ± 1.9	73.1 ± 1.1
	Hexagonal	50.7 ± 0.4	71.7 ± 0.3	49.4 ± 1.0	71.4 ± 0.6
31.33	Baseline	69.8 ± 0.4	112.1 ± 0.4	67.9 ± 0.7	110.9 ± 0.6
	Convex	63.9 ± 1.0	109.7 ± 1.1	66.9 ± 2.6	110.3 ± 2.1
	Hexagonal	69.2 ± 0.6	110.1 ± 0.6	65.5 ± 1.5	108.8 ± 1.1
46.83	Baseline	68.2 ± 0.4	119.6 ± 0.3	66.8 ± 0.8	117.1 ± 0.7
	Convex	64.6 ± 1.7	115.0 ± 1.1	65.3 ± 2.8	115.9 ± 2.5
	Hexagonal	69.8 ± 0.9	118.3 ± 0.6	65.1 ± 1.6	115.3 ± 1.5
59.83	Baseline	57.5 ± 0.3	102.0 ± 0.3	55.4 ± 0.7	99.9 ± 0.6
	Convex	56.7 ± 1.3	99.5 ± 0.9	53.8 ± 2.4	98.6 ± 2.3
	Hexagonal	58.4 ± 0.8	102.1 ± 0.5	54.7 ± 1.4	98.9 ± 1.4

With constant high- Re coefficients, which ignore the intermediate- Re lift of the convex ball, the baseline–convex differences shrink to 0.0–1.6 m and fall within their uncertainty (± 2.0 – 2.9 m); only the shorter carry of the hexagonal ball at $\theta = 15.74^\circ$ (2.5 ± 1.1 m at 45.93 g, 1.6 ± 0.7 m at 190 g) remains significant. Constant coefficients thus hide the effect that controls the ranking.

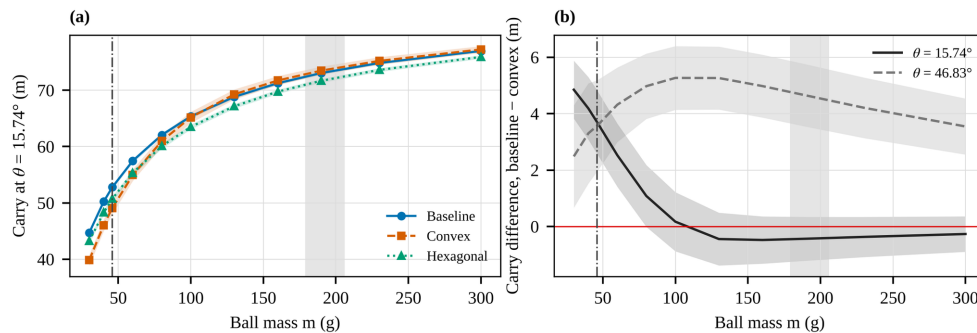


Figure 7. Effect of ball mass (same mass for all patterns, Re -dependent coefficients, $U_0 = 40 \text{ m s}^{-1}$): (a) carry at $\theta = 15.74^\circ$; (b) baseline-minus-convex carry difference at $\theta = 15.74^\circ$ and 46.83° . Shaded bands show $\pm$ one standard deviation; the vertical line marks the regulation mass and the grey band the test-model masses.

Ball mass changes this picture through the same Reynolds-number mechanism. A heavier ball decelerates less: at 190 g and $\theta = 15.74^\circ$ its Re stays above 9.2×10^4 , within the positive-lift regime of the convex pattern, so the convex and baseline carries become indistinguishable (73.5 ± 0.7 versus 73.0

± 0.3 m). Figure 7b shows that at this angle the baseline advantage of 3.7 m at regulation mass decreases steadily and vanishes at $m \approx 105$ g, whereas at $\theta = 46.83^\circ$, where the longer flight always reaches low Re, the baseline remains ahead by 3.5–5.3 m for all masses between 45.93 and 300 g. To our knowledge, this Reynolds-number-mediated pattern–mass coupling has not been reported for golf balls: circular dimples are the best of the three patterns for a regulation ball, whereas convex protrusions become competitive only for heavier projectiles (e.g. cricket balls ≈ 160 g) on shallow trajectories. Because the positive high-Re lift of the convex ball rests on single-run data, this heavier-ball result should be confirmed by repeated measurements.

3.5. Limitations and the role of spin

Five limitations bound these conclusions. (i) The PIV Reynolds numbers ($\leq 6.7 \times 10^3$) are far below on-course values, and the wind-tunnel range ($\leq 1.12 \times 10^5$) covers only the lower end of the on-course range. The absolute C_D values exceed those of commercial golf balls beyond the drag crisis [7], so the results should be read as relative comparisons; sting interference (which also breaks top–bottom symmetry) may contribute, and the projected blockage (3.6 % in the water tunnel, 0.1 % in the wind tunnel) was not corrected. (ii) The water-tunnel calibration showed slightly different velocities in the upper and lower parts of the test section, attributed to the boundary layer on the test-section floor; this may contribute to the vertical wake asymmetry, so wakes are compared between models only. (iii) Spin was not represented; at 3000 rpm and $Re = 10^5$ the spin parameter $S = \omega D/(2U) \approx 0.19$, at which golf-ball lift coefficients reach about 0.15–0.25 [2], exceeding the static inter-pattern lift differences, so spin could alter the ranking. (iv) The 2D model neglects side forces, roll and unsteady effects. (v) Only two runs were made per condition, four high-velocity convex settings have a single valid run, and balance calibration records were not available.

4. Conclusion

All patterns form a recirculation region whose organisation depends on topology: the baseline wake is the most coherent and decays fastest, whereas the textured patterns retain stronger shear layers downstream. Over $Re = 5.8 \times 10^4$ – 1.1×10^5 the baseline has the lowest drag at every test point, the convex and hexagonal patterns exceeding it by 5.8 ± 0.9 % and 5.1 ± 1.0 % on average and being comparable to each other. The convex ball shows a pronounced negative-lift regime at intermediate Re. With Re-dependent coefficients and Monte Carlo uncertainty propagation, a regulation-mass baseline ball carries 3.6–6.0 m farther than the convex ball for launch angles of 15.7° – 46.8° , because a light ball decelerates into the convex negative-lift regime; at 190 g this disadvantage vanishes at shallow launch angles. Ball mass therefore acts through the in-flight Reynolds number on surface-pattern selection. Future work should (i) repeat the high-velocity convex measurements and measure spinning balls at 2000–3000 rpm, (ii) extend PIV to $Re > 10^5$ using mass-matched, regulation-equivalent balls, and (iii) couple the dataset with high-fidelity LES/DNS and CFD modelling [28] to design and test hybrid patterns.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the authors used Claude to assist with structuring the reasoning and with language editing of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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