

Surface texture, boundary-layer transition, and drag on a swimmer's head: a computational study across the sphere drag crisis

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Abstract

A competitive swimmer's head, approximated as a sphere, travels at 1.6–2.2 m/s ($Re = 3.2\text{--}4.4 \times 10^5$), spanning the sphere drag crisis. Ridged caps are marketed as tripping the boundary layer to trigger the crisis at lower velocity. Whether they do is unknown: towing experiments cannot isolate the head, and, to our knowledge, no computational study has examined a cap surface. This study performed the first controlled computational comparison of a smooth sphere and an idealized crown-textured cap, using unsteady Langtry–Menter transition-model simulations at four velocities with identical meshing parameters and a fixed time step. At 1.6–2.0 m/s, no drag difference was resolved; at 1.8 and 2.0 m/s, differences above 2.5 % were excluded. At 2.2 m/s, near sprint pace, the cap's drag was $31 \pm 21\%$ ($k = 2$) higher, owing to intermittent high-drag, high-lateral-force episodes absent on the sphere. Pressure drag exceeded 92 % of the total. In the model's first assessment against the sphere drag crisis, both boundary layers remained laminar yet separated at $102\text{--}105^\circ$, the turbulent value measured above the crisis, not at the expected laminar $79\text{--}82^\circ$. The drag difference thus arose in the wake, not through boundary-layer transition. These results suggest that effective cap relief would need to alter the separation or the wake rather than merely reduce skin friction; for simulation practice, the intermittency field, not the separation angle, shows whether transition is predicted. Agreement in separation angle alone can therefore give a false impression that the drag-crisis physics has been captured.

Keywords: swim cap; passive flow control; Langtry–Menter transition model; separation control; unsteady Reynolds-averaged simulation; competitive swimming

1. Introduction

At the elite level, small changes in hydrodynamic drag can affect swimming performance. After polyurethane full-body suits were introduced in 2008 and followed by an exceptional number of world records, the international governing body of the sport banned non-textile materials and restricted suit coverage, thickness, and buoyancy. The swim cap covers the head, the swimmer's leading bluff body, but has received far less study than the suit.

The physical premise behind textured caps is the sphere drag crisis, which is an abrupt fall in drag over a narrow range of Reynolds numbers. Below this range, the laminar boundary layer separates at approximately 82° from the front stagnation point, producing a wide wake and a drag coefficient near 0.5. Above this range, the boundary layer becomes turbulent before separating. The additional near-wall momentum delays separation to $100\text{--}110^\circ$, the wake narrows, and the drag coefficient falls below 0.1. Achenbach [1] placed this transition at $Re \approx 3.7 \times 10^5$ for a free-stream turbulence intensity of 0.45 %.

A swimmer's head, approximated as a sphere of diameter $D = 0.2$ m moving through water ($\nu = 1.0 \times 10^{-6}$ m²/s) at $U = 1.6\text{--}2.2$ m/s, has $Re = UD/\nu = 3.2\text{--}4.4 \times 10^5$. This interval brackets the critical Reynolds number; consequently, a cap that tripped an otherwise laminar boundary layer could initiate the crisis at a lower velocity. Two considerations limit the possible gain. First, the drag on a bluff body at these Reynolds numbers is dominated by pressure, and any reduction must therefore come from delayed separation rather than from a smoother surface. Second, roughness lowers the critical Reynolds number but raises the minimum attainable drag coefficient [2]. A treatment that reduces drag at low velocity may thus increase it at high velocity.

Forced transition on spheres has been well documented. Son et al. [3] measured the drag, surface pressure, and boundary-layer profiles on a sphere with a trip wire at $20\text{--}70^\circ$, for $Re = 0.5$ to 2.8×10^5 . The wire locally separated the laminar boundary layer; transition in the separated shear layer and reattachment then added near-wall momentum, which delayed the main separation. Choi et al. [4] identified the same mechanism for distributed dimples. In both cases, the relief lay well upstream of laminar separation, and its height-to-diameter ratio k/D was of order 10^{-2} , an order of magnitude larger than that of a competition cap.

Direct evidence on caps is sparse and limited to whole-body measurements. Gatta et al. [5] towed 10 swimmers at 1.5, 1.7, and 1.9 m/s and found no significant difference between smooth and dimpled caps. An earlier study by the same group [6] found 5–6.5 % lower passive drag with a seamless silicone helmet cap than with a conventional silicone cap, which it attributed to material and fit rather than to texture. Neither experiment isolated the head. Computational evidence is also scarce because simulating the drag

crisis is expensive. Li et al. [7] reproduced it using large-eddy simulation on meshes of up to approximately 1.45×10^8 cells and noted that the earlier large-eddy simulation of Muto et al. [8] predicted turbulent separation at $Re = 2.4 \times 10^5$, where experiments showed laminar separation [1]. Transition-sensitive unsteady Reynolds-averaged Navier–Stokes (URANS) closures are far less expensive, and the four-equation Langtry–Menter model [9] has been well validated on flat plates, airfoils, and turbomachinery. To our knowledge, however, it has not been assessed against the sphere drag crisis, and no computational study has examined a swim-cap surface as a transition-control device.

This study has two objectives. The first is to determine whether a crown-textured cap changes head drag across the competitive Reynolds number range when both bodies are meshed with the same parameters and advanced with the same fixed time step. The second is to assess whether a transition-sensitive URANS closure reproduces the sphere drag crisis and to identify diagnostics that distinguish a correct prediction from a merely plausible one.

This study makes three contributions. First, to our knowledge, it provides the first controlled computational comparison between a swim-cap surface and a smooth sphere at swimming Reynolds numbers. Unlike towing experiments, it isolates the head, and both bodies share meshing parameters and a fixed time step, so that the surface is the only deliberate difference between them. Second, it shows that the drag difference between the bodies arose in the wake rather than through boundary-layer transition: no difference was resolved at 1.6–2.0 m/s, whereas at 2.2 m/s the cap sustained intermittent high-drag episodes that the sphere did not. Third, it provides the first assessment of the Langtry–Menter model against the sphere drag crisis, showing that the intermittency field, rather than the separation angle, indicates whether the model predicts transition; it also shows that a coarse time step suppresses the wake episodes.

2. Methods

2.1. Geometries and meshes

Two axisymmetric bodies of nominal diameter $D = 0.2$ m were simulated (Fig. 1). Geometry 1, hereafter referred to as the sphere, was smooth (Fig. 1a). Geometry 2, hereafter referred to as the cap, was an idealized crown-textured cap on the same base sphere (Fig. 1b). Its concentric ridges had a nominal radial relief of ± 0.5 mm and a meridional period of 5.96° . They extended to a polar angle $\varphi = 43.8^\circ$ from the front stagnation point. Beyond this angle, the cap was spherical to within $0.1 \mu\text{m}$; therefore, the two bodies coincided over the rear 136° . Within the textured band, the relief reached $\pm 478 \mu\text{m}$ at $8\text{--}16^\circ$ and decayed to $\pm 68 \mu\text{m}$ at 40° (Fig. 1c, d).

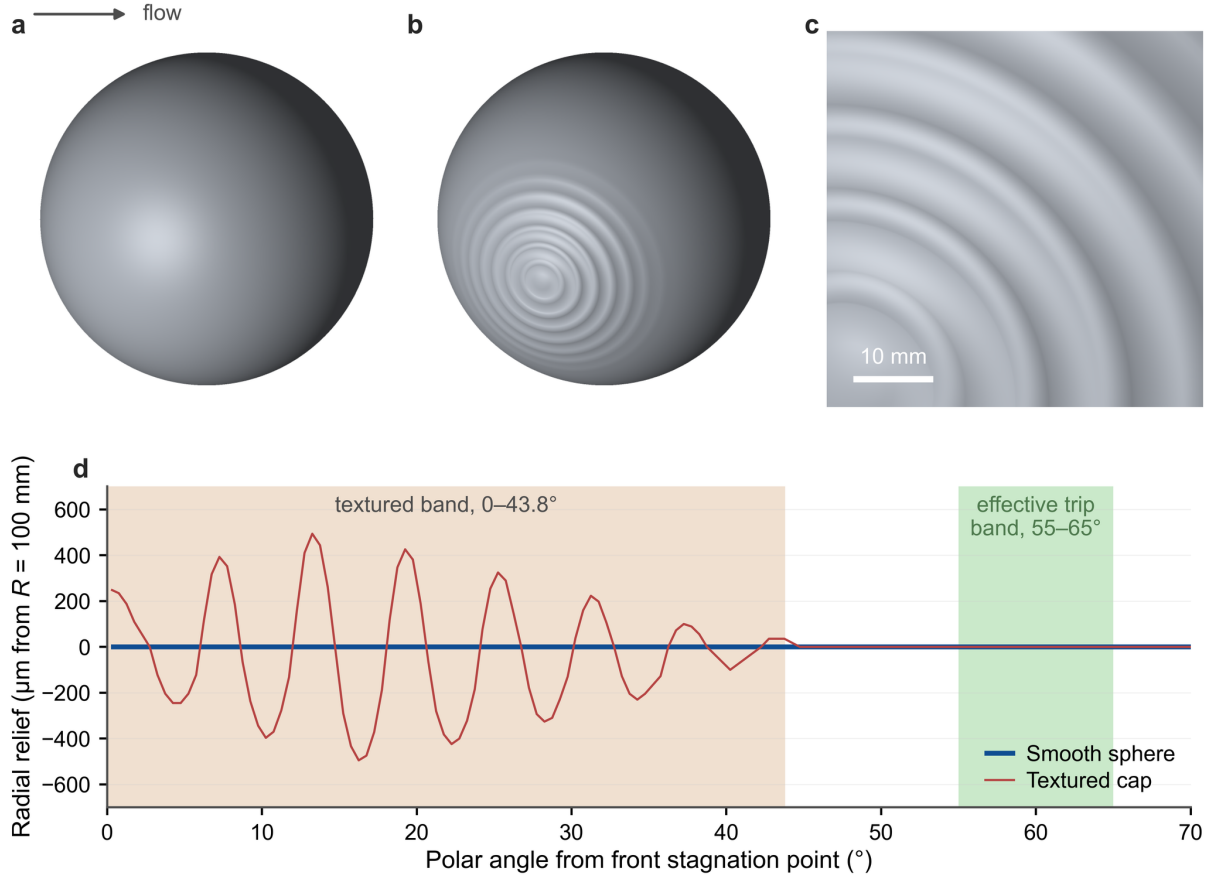


Fig. 1 The two bodies, both 0.2 m in diameter. (a) Geometry 1, the sphere, and (b) geometry 2, the crown-textured cap, rendered with identical camera, lighting, and scale. (c) Ridges at a polar angle of 18°, viewed along the surface normal. Grazing illumination makes the shading follow the slope of the 0.5 mm relief; no geometry is exaggerated. (d) Radial relief against polar angle; beyond the textured band, the two surfaces coincide to within 0.1 μm

Both geometries were meshed using snappyHexMesh with the same parameters and refinement strategy (Fig. 2). The surface cells were refined to 1.25 mm, and 15 prism layers were added with an expansion ratio of 1.15 and a first-layer thickness of 1.36×10^{-5} m. The far-field and boundary-layer resolutions therefore matched, and the cell counts, 4 847 403 and 4 812 263, differed by 0.7 % solely because of the surface shape. The mesher generated all prism layers on the sphere, but only 94.28 % of them on the cap, because it truncated layers over the steepest ridge flanks. Section 3.3 quantifies the consequences for the wall resolution.

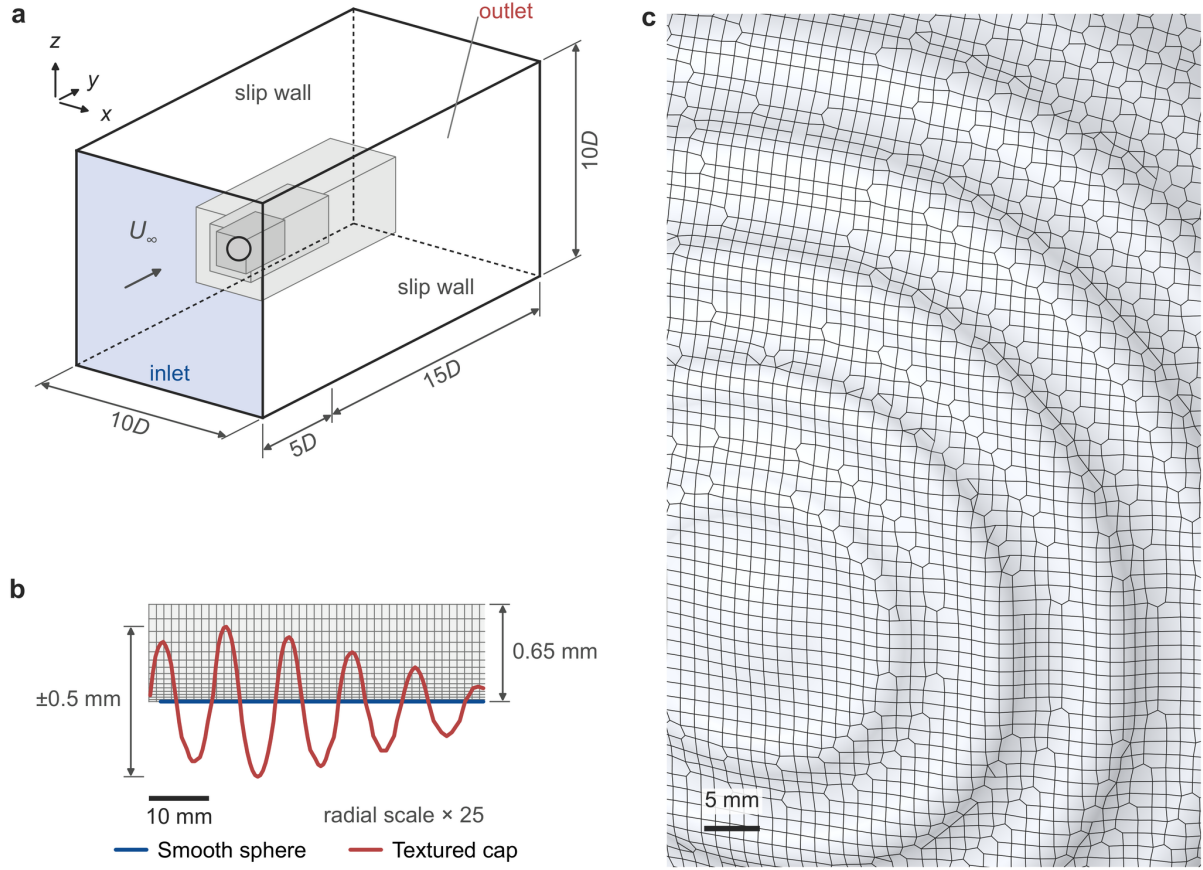


Fig. 2 Computational domain and mesh. (a) Domain to scale in orthographic isometric projection, with hidden edges dashed; nested boxes are the wake refinement volumes (levels 4 to 2), and all four lateral boundaries are slip walls. (b) Wall-normal detail at the crown, with the surface unwrapped: the 15 prism layers of the sphere mesh against the relief of the cap, with radial distances exaggerated 25 times. (c) Surface faces of the cap mesh over the textured band

2.2. Numerical method

Governing equations and solver. The incompressible URANS equations were solved using `pimpleFoam`, the transient solver of OpenFOAM v2512. They were closed using the four-equation Langtry–Menter transition shear-stress transport model [9], hereafter referred to as the transition model. This model adds transport equations for the intermittency γ and the transition-onset momentum-thickness Reynolds number Re_{θ_t} to those for the turbulence kinetic energy k and the specific dissipation rate ω . The fluid was water ($\nu = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$, $\rho = 998 \text{ kg/m}^3$).

Boundary and initial conditions. The domain was rectangular, with the body at the origin, the inlet $5D$ upstream, the outlet $15D$ downstream, and the four lateral boundaries $5D$ from the flow axis (Fig. 2a). The blockage ratio was 0.79 %. A uniform velocity U_∞ was imposed at the inlet, the lateral boundaries were slip walls, the outlet pressure was fixed, and the body was a no-slip wall. At all velocities, the inlet turbulence intensity was $Tu = 1\%$ and the eddy-viscosity ratio was $\nu_t/\nu = 10$, so that $k = 1.5 (0.01 U_\infty)^2$ and $\omega = k/(10\nu)$. The transition variables entered at $\gamma = 1$ and $Re_{\theta_t} = 584$ in all cases. Every case was started from a uniform field and run to $t = 80 \text{ s}$.

Spatial and temporal discretization. Time was advanced using a second-order backward scheme. Convection was discretized using linear-upwind differencing and a cell-limited gradient for momentum, and using upwind differencing for k and ω for robustness. The transition equations used bounded limited-linear differencing because upwind differencing smeared the transition front. A steady formulation was tested first and rejected: its residuals settled into a limit cycle, and its mean lift and side-force coefficients, C_l and C_s , were nonzero, although both must vanish for an axisymmetric body.

Both geometries were advanced with the same time step, 1.5×10^{-3} s. It was set as the upper limit for adaptive stepping, allowing each run to start from a uniform field. The Courant number limit of 20 was never reached; therefore, the step was constant throughout every averaging window. A Courant-limited step was avoided because the thinner prism layers over the ridges would have given the cap a smaller step than the sphere. Section 3.4 reports the sensitivity to the step.

Numerical stability. Each time step used three outer correctors, two pressure correctors, and one non-orthogonal corrector. With two outer correctors, the solution was stable only at much lower Courant numbers.

2.3. Convergence, averaging, and uncertainty

A run was accepted as converged only when all five of the following criteria were met: (i) the mean was formed over at least 12 cycles of the drag signal; (ii) the running mean drifted by less than 1 % over the last five cycles; (iii) the difference between the means over the first and second halves of the averaging window, hereafter referred to as the split-half difference, was less than 1 %; (iv) the mean lift and side-force coefficients satisfied $|C_l| < 0.01$ and $|C_s| < 0.01$, as required for an axisymmetric body; and (v) the mean changed by less than 0.5 % when the start of the averaging window was moved from 30 to 40 s.

Five of the eight runs met these tolerances (Online Resource 1: Table S1). The other three, the sphere and the cap at 1.6 m/s and the cap at 2.2 m/s, contained intermittent high-drag episodes (Section 3.3), and their standard errors were 5–8 %. The fixed tolerances of 0.5–1 % lie below the statistical resolution of such signals. For these runs, each tolerance in criteria (ii) to (v) was replaced by twice the standard error of the tested quantity, and all three runs met the criteria in this form.

The lateral force coefficients oscillated at a dominant frequency f corresponding to a Strouhal number $St = fD/U_\infty \approx 0.02$ – 0.03 , an order of magnitude below the classical shedding value. This oscillation reflected a precessing asymmetric wake: global stability analysis has predicted a stationary asymmetric mode for axisymmetric bodies [10], and its lateral-force signature has been observed on a sphere at $Re = 300$ [11]. The flow became statistically stationary only at $t \approx 15$ – 30 s; therefore, a window defined by shedding cycles alone would have been approximately an order of magnitude too short. Accordingly, every run was averaged over the same window, $t = 30$ – 80 s.

For each run, the sampling uncertainty was the standard error of the mean. It was estimated from the integral timescale of the autocorrelation of the drag signal and by batch means, and the larger of the two estimates was adopted. The standard error was 0.33–0.60 % of the drag coefficient for the five runs without high-drag episodes and 5.1–8.0 % for the other three. Uncertainties on differences between the geometries were propagated to first order and expressed with a coverage factor $k = 2$, as approximately 95 % intervals.

3. Results

3.1. Drag, separation, and the pressure–friction split of the sphere

Table 1 lists the converged force coefficients for the sphere. The drag coefficient decreased by 18.7 % over a 38 % increase in Reynolds number. Most of this decrease occurred between 1.6 and 1.8 m/s, where the root-mean-square drag fluctuation also decreased from 0.051 to 0.007. The separation remained near 104° at every velocity because the boundary layer remained laminar over the body (Section 3.2). Consequently, the computed coefficients did not reproduce the drag crisis measured by Achenbach [1] (Fig. 3). His drag coefficient decreased from 0.45 to 0.06 across the simulated range. The computed value was approximately one-third of the measured value at the lowest Reynolds number and approximately twice the measured value at the highest. Pressure drag accounted for 92.6 to 93.2 % of the total in all cases.

Table 1 Force coefficients, separation angle, and wall resolution of the sphere, averaged over $t = 30$ – 80 s. SE is the standard error of the time average; separation angle and y^+ are from the surface sample at $t = 80$ s. Mean lift and side-force coefficients were within 0.014 of zero (the largest value in the 1.6 m/s run, which was assessed against twice its standard error; Section 2.3), and split-half differences were 0.00–1.80 %

U (m/s)	Re	C_d	SE	C_d rms	Separation	y^+ mean / max
1.6	3.2×10^5	0.1531	5.08 %	0.0507	104.3°	0.45 / 0.88
1.8	3.6×10^5	0.1341	0.53 %	0.0070	104.3°	0.49 / 0.97
2.0	4.0×10^5	0.1276	0.60 %	0.0075	104.5°	0.53 / 1.05
2.2	4.4×10^5	0.1245	0.60 %	0.0075	104.6°	0.57 / 1.14

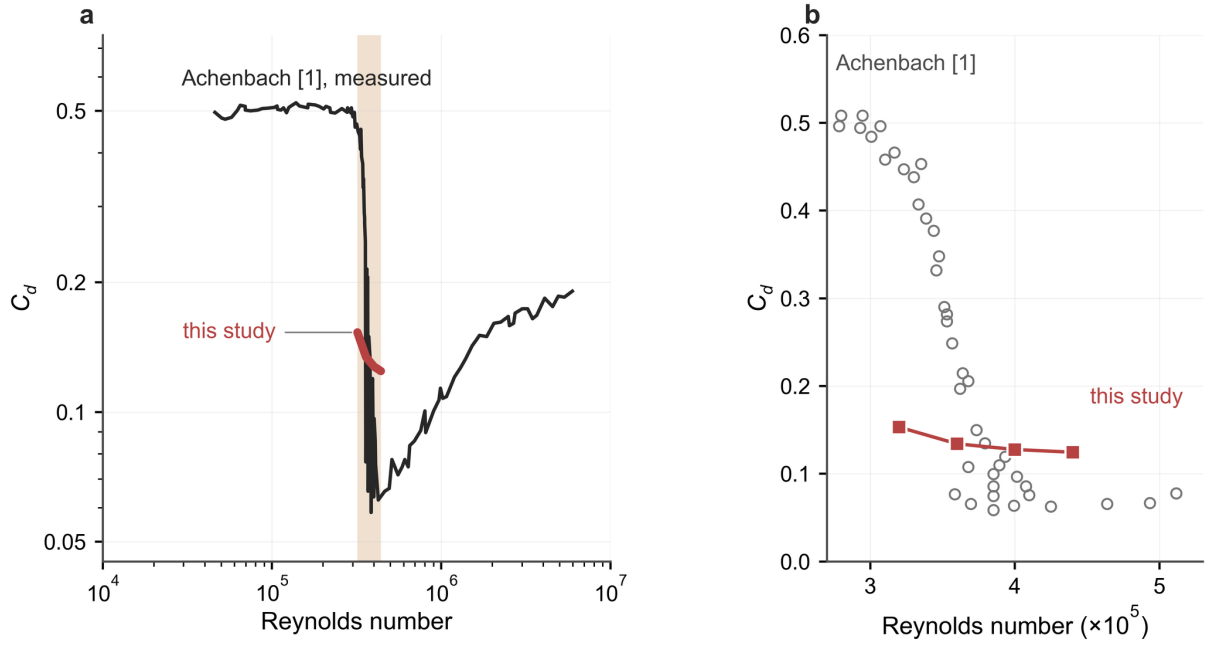


Fig. 3 Drag coefficient of the sphere against Reynolds number. (a) Full measured range; shading marks the simulated range, in which the computed values form a short segment. (b) Simulated range, with measured values (circles) and computed values (squares). Computed values are averages over $t = 30\text{--}80$ s, and their standard errors are smaller than the symbols. Measured values were digitized from figure 4 of [1] (Online Resource 1: Section S7)

In the meridional surface distributions (Fig. 4), the time-averaged pressure coefficient followed potential-flow theory to approximately 80° and reached its suction minimum near 90° (Fig. 4a). The wall shear stress crossed zero at separation (Fig. 4b). The main discrepancy with the experiment lay in the separated region. Averaged over $120\text{--}180^\circ$, the computed pressure coefficient was -0.01 to -0.05 , compared with -0.24 digitized from Achenbach's figure 7(b) at the same Reynolds number. The computed suction peak, -1.17 to -1.20 , did not match Achenbach's value at the simulated Reynolds number (-0.98). Instead, it was close to his transcritical measurement at $Re = 5 \times 10^6$ (-1.18). The digitization uncertainty (± 0.02) was much smaller than these discrepancies.

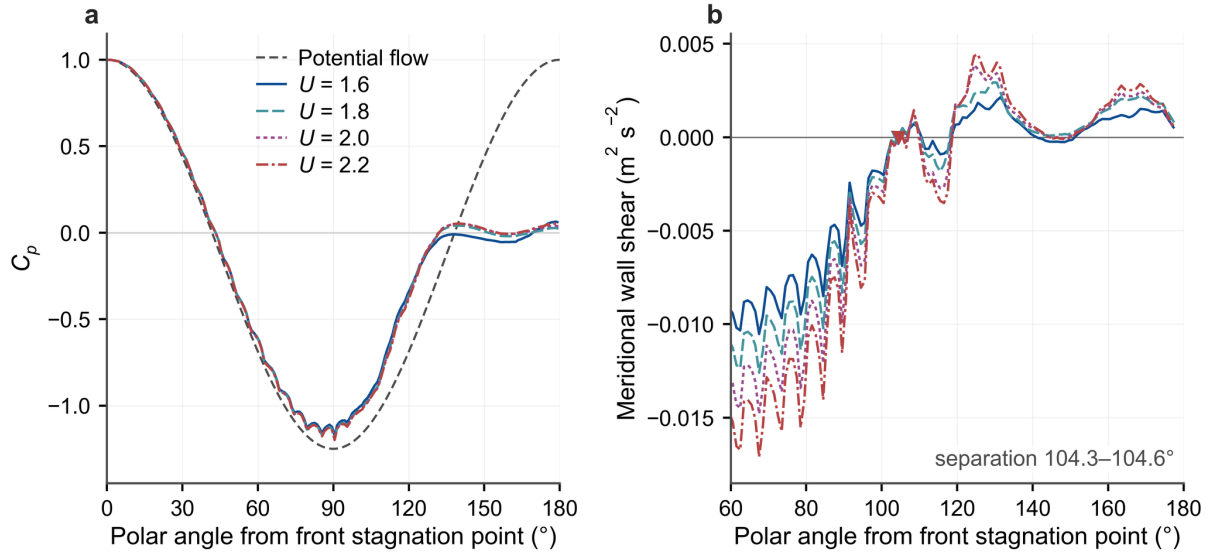


Fig. 4 Meridional surface profiles of the sphere at the four velocities (U in m/s). (a) Pressure coefficient, time-averaged over $t = 5\text{--}80$ s and rebased to 1 at the stagnation point, with potential-flow theory (dashed). (b) Meridional wall shear stress at $t = 80$ s; triangles mark the separation angle. The sawtooth modulation is a discretization artifact of per-face storage, not a flow feature

3.2. Absence of boundary-layer transition on the body

Near the wall on the forebody, between 50° and 100° , the intermittency was $\gamma \approx 0.02$ and the eddy-viscosity ratio was $\nu_t/\nu = 0.04\text{--}0.6$ (Fig. 5), both indicating a laminar boundary layer. The boundary layer separated while laminar at 104° , and transition was predicted only at approximately 110° , in the detached shear layer. Experiments and higher-fidelity simulations have placed laminar separation much further upstream. Achenbach [1] inferred approximately 82° from his subcritical surface measurements, and the large-eddy simulation of Li et al. [7] gave 79° . The computed drag coefficient therefore reflected excessively delayed laminar separation, not the transition-and-reattachment mechanism of the drag crisis.

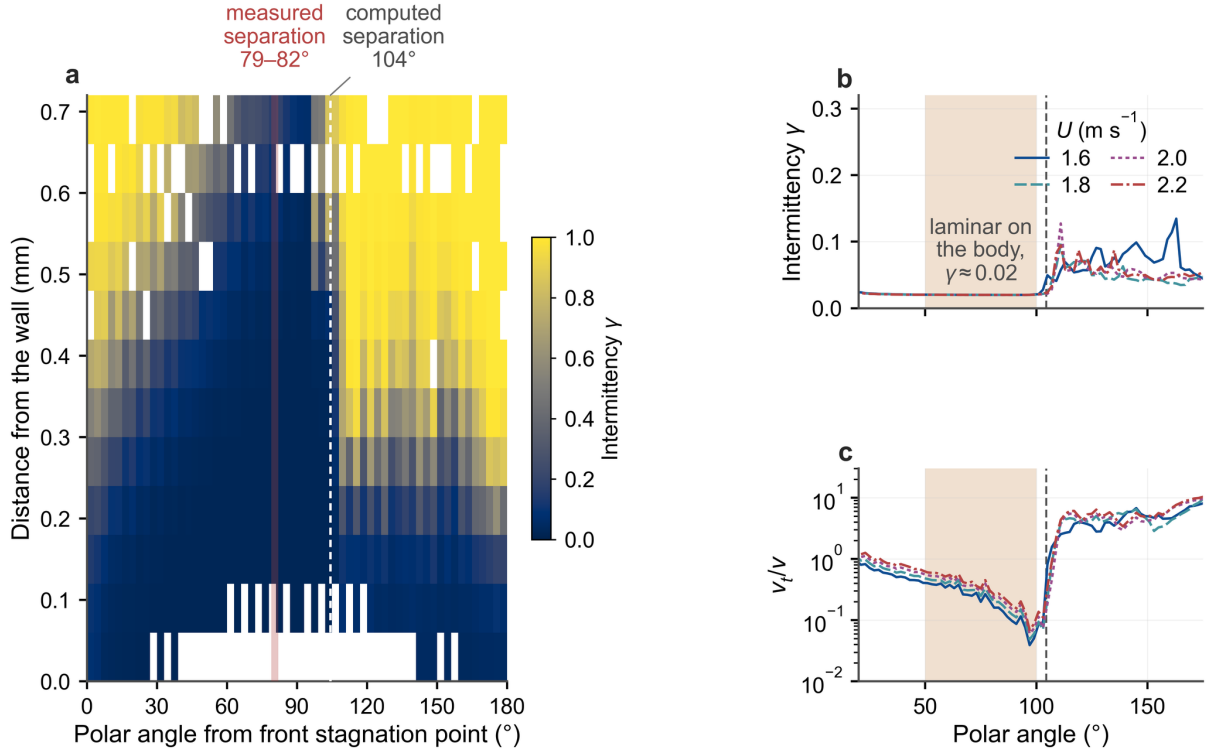


Fig. 5 Transition diagnostics for the sphere at $t = 80$ s. (a) Intermittency against polar angle and distance from the wall on the mid-plane at $U = 1.8$ m/s; blank cells contain fewer than four samples. (b) Near-wall intermittency, averaged over the three points nearest the wall, and (c) eddy-viscosity ratio, averaged within 1 mm of the wall, at the four velocities. Shading marks 50–100°; dashed lines mark the computed separation angle

The separation angle alone was a misleading diagnostic in this case. The computed 104° coincided with the $100\text{--}110^\circ$ that Achenbach [1] reported above the crisis, and with the 102° computed by Li et al. [7]. The intermittency field distinguished turbulent separation from the excessively delayed laminar separation obtained here. The distributions of intermittency and eddy-viscosity ratio should therefore be reported alongside drag whenever a transition-sensitive closure is assessed.

3.3. Effect of the crown texture

The cap was simulated with the same mesh settings, discretization schemes, boundary conditions, and time step as the sphere. Table 2 and Fig. 6 compare the two bodies at the four velocities. At 1.6, 1.8, and 2.0 m/s, the differences in drag coefficient, cap relative to sphere, were +0.5 %, -1.1 %, and +1.1 %, and none exceeded its expanded uncertainty ($k = 2$). At 2.2 m/s, the drag coefficient of the cap was 30.6 ± 20.9 % higher than that of the sphere, a difference of 2.9 standard uncertainties.

Table 2 Drag coefficients of the sphere and the cap at the same time step, averaged over $t = 30\text{--}80$ s. SE_1 and SE_2 are the standard errors of the time average for the sphere and the cap; ΔC_d is the difference, cap relative to sphere, with its expanded uncertainty ($k = 2$)

U (m/s)	Re	C_d sphere	C_d cap	SE_1	SE_2	$\Delta C_d (k = 2)$
1.6	3.2×10^5	0.1531	0.1539	5.08 %	7.62 %	$+0.51 \pm 18.41 \%$
1.8	3.6×10^5	0.1341	0.1327	0.53 %	0.38 %	$-1.05 \pm 1.29 \%$
2.0	4.0×10^5	0.1276	0.1290	0.60 %	0.33 %	$+1.12 \pm 1.38 \%$
2.2	4.4×10^5	0.1245	0.1626	0.60 %	7.98 %	$+30.55 \pm 20.88 \%$

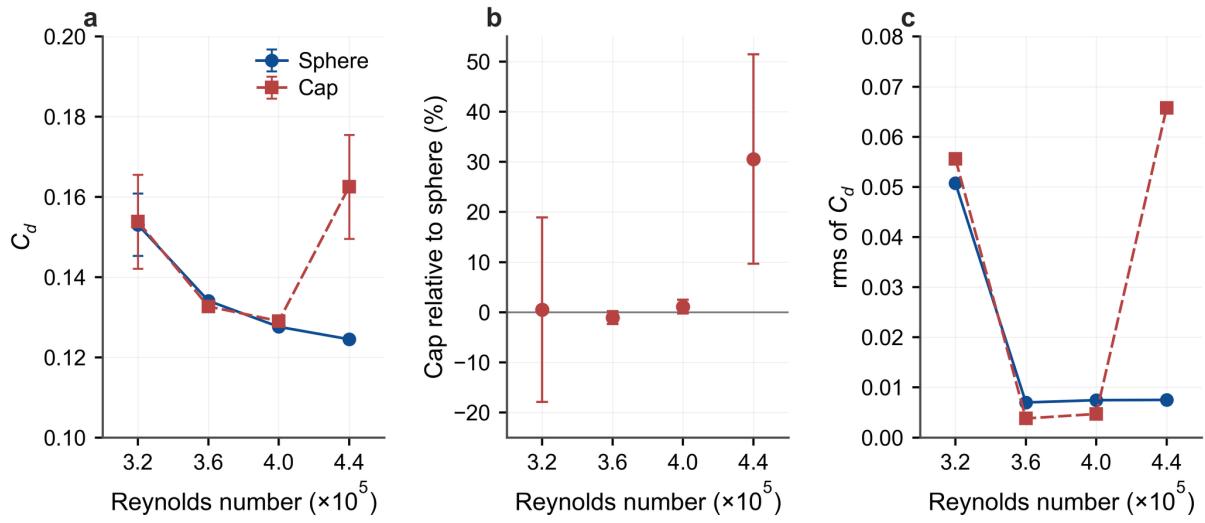


Fig. 6 Comparison of the two geometries at the same time step, averaged over $t = 30\text{--}80$ s. (a) Drag coefficient against Reynolds number, with standard errors. (b) Difference in drag coefficient, cap relative to sphere, with expanded uncertainties ($k = 2$). (c) Root-mean-square fluctuation of the drag coefficient

The resolution of the comparison depended on the flow's steadiness. At 1.8 and 2.0 m/s, both runs were steady in the mean with standard errors below 0.6 %, and the 95 % intervals excluded changes larger than 2.5 %. At 1.6 m/s, both bodies showed large intermittent fluctuations of drag, and differences smaller than approximately 18 % could not be resolved.

The difference at 2.2 m/s arose from intermittent high-drag episodes on the cap (Fig. 7). Over the averaging window, the drag coefficient of the cap exceeded 0.15 for 44 % of the time and peaked at 0.38, whereas that of the sphere remained between 0.11 and 0.13. Each episode coincided with a large lateral force, which indicated a strongly deflected wake. The resultant of the lift and side-force coefficients reached 0.31 on the cap, compared with at most 0.14 on the sphere (Fig. 7e). The increase was carried by the pressure drag: the viscous contribution was 0.0089 on the cap and 0.0091 on the sphere. Moving the start of the averaging window from 30 to 40 s gave differences of +29.5 to +35.2 %.

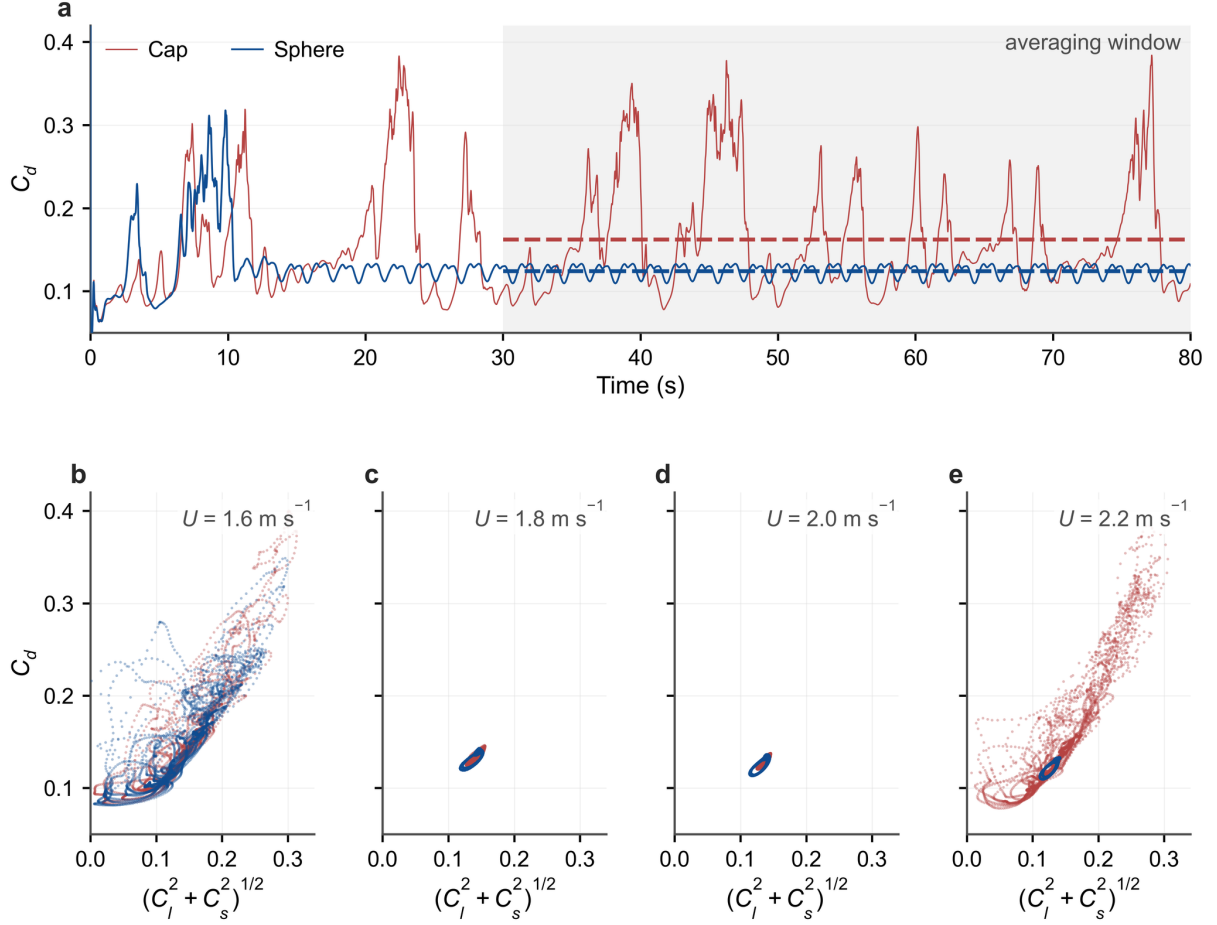


Fig. 7 Drag episodes and lateral force. (a) Drag coefficient of both bodies at $U = 2.2$ m/s; shading marks the averaging window, and dashed lines mark the window means. (b–e) Drag coefficient against the resultant lateral force coefficient, $(C_l^2 + C_s^2)^{1/2}$, over $t = 30$ – 80 s at $U = 1.6, 1.8, 2.0$, and 2.2 m/s. Each point is one sample; samples are 0.015 s apart

The same episodes occurred on both bodies at 1.6 m/s and on neither body at 1.8 or 2.0 m/s (Fig. 7b–d). The root-mean-square drag fluctuation followed the same pattern (Fig. 6c): 0.051 – 0.056 at 1.6 m/s and below 0.008 at 1.8 and 2.0 m/s on both bodies, and 0.066 on the cap against 0.0075 on the sphere at 2.2 m/s. The wake of the sphere therefore settled into a steady state above 1.6 m/s, whereas that of the cap settled at 1.8 and 2.0 m/s but not at 2.2 m/s.

The cap separated slightly earlier than the sphere, at 102.2° compared with 104.3 to 104.6° , by a similar amount at all four velocities. Each value was taken from the surface sample at $t = 80$ s. Because the wall shear stress on the cap oscillated about zero up to 119° , the close agreement of its four values overstates their precision. Both bodies separated more than 20° downstream of the expected 79 – 82° , and the shift of approximately 2° was small relative to this common error.

The wall resolution differed between the bodies due to prism-layer truncation (Section 2.1). The mean wall-normal distance of the first cell center in wall units, y^+ , was 0.45 to 0.57 on the sphere and 0.66 to 0.82 on the cap. On the cap, the maximum reached 24 to 41 , but all faces with $y^+ > 5$ lay upstream of 38.4° , inside the textured band, and covered 1.2 to 2.0% of the sampled surface. Friction contributed

approximately 7 % of the total drag; therefore, these faces are unlikely to account for the change in pressure drag that arose from the state of the wake.

3.4. Verification

Three single-variable studies on the sphere, detailed in Online Resource 1, quantified the sensitivity to grid resolution, free-stream turbulence, and time step (Fig. 8). The grid and turbulence studies were performed at 1.8 m/s with a maximum time step of 0.003 s. Three meshes of 2 262 454, 4 847 403, and 10 127 983 cells gave $C_d = 0.0898$, 0.1296, and 0.1319. The change from the production mesh to the fine mesh was +1.75 %, with a combined standard error of 0.76 %. This change was resolved at 2.3σ and was taken as the discretization error of the production mesh. No grid-convergence index was computed because Richardson extrapolation gave an observed order of 11.6 against a theoretical order of 2. The separation angle behaved differently: it increased from 102.2° to 104.3° and then to 118.9° with refinement, moving away from the expected $79\text{--}82^\circ$ without converging.

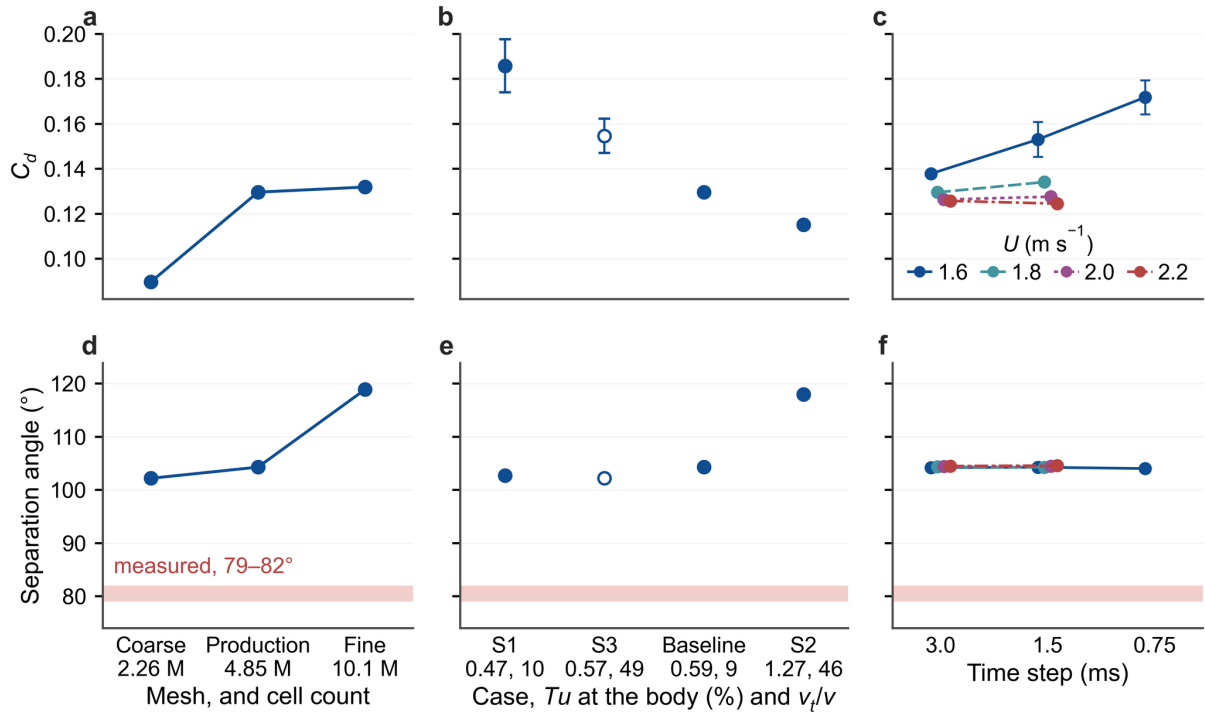


Fig. 8 Verification studies on the sphere: drag coefficient (a–c) and separation angle (d–f) against (a, d) mesh, (b, e) free-stream turbulence, and (c, f) time step. Grid and turbulence cases are at $U = 1.8$ m/s with a maximum time step of 0.003 s; grid cases are averaged over $t = 20\text{--}50.41$ s. Tick labels in (b, e) give the turbulence intensity at the body and the eddy-viscosity ratio, and the open symbol marks the case that did not meet the convergence criteria. Time-step cases are averaged over $t = 30\text{--}80$ s. Error bars are standard errors; shading marks the expected laminar separation angle, $79\text{--}82^\circ$

The second study varied the free-stream turbulence. The prescribed inlet intensity of 1.00 % decayed to 0.593 % at the body, above the 0.45 % of Achenbach’s experiment. Lowering the intensity at the body toward the experimental value, to 0.470 %, raised the drag coefficient from 0.1296 to 0.173–0.186,

while separation moved only from 104.3° to 102.7° . Increasing the eddy-viscosity ratio from 9 to 49 at approximately the same intensity at the body raised the drag coefficient by 19.3 % relative to the production case.

The third study compared the time steps of 0.003, 0.0015, and 0.00075 s (Fig. 8c, f; Online Resource 1: Section S2). Halving the step from 0.003 to 0.0015 s changed the drag coefficient by +3.5, +1.0, and -1.0 % at 1.8, 2.0, and 2.2 m/s; only the first change was resolved. At 1.6 m/s, the drag coefficient rose with each refinement, from 0.138 to 0.153 and 0.172, but neither increase was resolved ($+11 \pm 11$ % and $+12 \pm 15$ %, $k = 2$). The two finer steps sustained the high-drag episodes of Section 3.3, which the coarsest step damped. The separation angle, the wall resolution, and the viscous drag did not change with the step; therefore, the time step affected only the wake.

4. Discussion

4.1. Persistence of the laminar boundary layer

Five mechanisms could explain why the boundary layer remained laminar well beyond the expected separation point; three were tested directly. First, varying the turbulence intensity at the body between values that bracketed and exceeded Achenbach's 0.45 % kept the separation between 102.7° and 118.0° (Section 3.4). This ruled out the inflow turbulence level, but not an error in the transition-onset correlation or in the transition model itself. Second, mesh refinement moved the separation away from the expected value. Third, changing the discretization of the transition equations from upwind to limited-linear differencing left the boundary layer laminar, which excluded numerical dissipation. Mesh-surface irregularity is also unlikely to act as a distributed trip. Its root-mean-square deviation of $45.6 \mu\text{m}$ gave a roughness Reynolds number $Re_k = u_k k / \nu$ of 19 to 22, where u_k is the undisturbed velocity at the roughness height k , an order of magnitude below the critical values of approximately 250 to 600 reported by Braslow and Knox [12]; only the maximum deviation of $240 \mu\text{m}$, with $Re_k \approx 570$, fell within that range. The same calculation, with the laminar boundary-layer thickness from Thwaites' method [13], placed the band in which a trip would be effective at 55 to 65° .

The two remaining mechanisms are an overprediction of laminar boundary-layer stability by the transition model and a self-sustaining solution, in which a near-potential pressure field weakens the adverse pressure gradient and keeps the wake narrow.

4.2. Implications for cap design

Two results bear on cap design. The first, corroborated by independent studies, is that pressure drag dominates. Zaïdi et al. [14] found that form drag accounted for 88 % of the total drag in a two-dimensional simulation of underwater swimming. Barbosa et al. [15] attributed 85.9 ± 9.3 % of passive drag

to pressure in 60 young swimmers, and the share computed here was 92.6 to 94.5 %. An effective cap must therefore alter separation; reducing skin friction alone offers little, regardless of the transition behavior in Section 3.2.

The second result is that a texture confined to the forebody can change drag through the wake. The relief lay approximately 60° upstream of separation, in the favorable-pressure-gradient region, and moved the separation by only approximately 2° . It was nevertheless associated with a different wake state at 2.2 m/s, in which the cap's wake returned to the intermittent state exhibited by both bodies at 1.6 m/s. This behavior may have reflected a sensitivity of the wake to small changes in the separating shear layer rather than a change in transition. Over the simulated range, the texture either left the drag unchanged or increased it, rather than reducing it as the tripping premise predicts. Relief placed in the 55 to 65° band (Section 4.1) remains the natural test of that premise.

The absence of a resolved difference at 1.6–2.0 m/s agrees with Gatta et al. [5], who found no significant difference between smooth and dimpled caps when towing swimmers at 1.5–1.9 m/s. Mean race velocities for men's long-course freestyle world records give $Re = 3.45 \times 10^5$ over 1500 m and 4.31×10^5 over 100 m (Online Resource 1: Table S3); therefore, the increase at 2.2 m/s lies near sprint race pace. Its effect on race time depends on the head's share of whole-body drag and on how active drag scales with velocity [16].

4.3. Limitations

Because the drag crisis was not reproduced, the absolute drag coefficients are model-specific; the conclusions concern differences between the two bodies under identical numerical conditions. The head was idealized as an isolated sphere carrying one commercial texture; a head–body geometry and other relief patterns are the logical extensions.

5. Conclusions

This study provided the first controlled computational comparison of a smooth sphere and an idealized crown-textured swim cap at swimming Reynolds numbers, with both bodies meshed with identical parameters and advanced with an identical fixed time step. No difference in drag was resolved at 1.6, 1.8, and 2.0 m/s, and at 1.8 and 2.0 m/s changes larger than 2.5 % were excluded. At 2.2 m/s, the drag coefficient of the cap was $31 \pm 21\%$ ($k = 2$) higher than that of the sphere, because its wake remained in an intermittent, strongly deflected state from which the wake of the sphere had settled. The drag difference, therefore, arose in the wake rather than through forebody transition. No statistically resolved drag reduction was observed at any simulated velocity. Two methodological findings emerged from the first assessment of the Langtry–Menter model against the sphere drag crisis. First, on a mesh of

4.85×10^6 cells, the boundary layer separated while laminar at approximately 104° , an angle that coincides with turbulent separation above the crisis; hence, the separation angle alone was misleading without the intermittency field. Second, a coarse time step damped the low-frequency unsteadiness of the wake at the lowest velocity; consequently, comparisons between geometries require a matched, fixed step. Finally, because pressure drag accounted for more than 92 % of the total, an effective cap would need to alter separation or the wake rather than skin friction. Relief placed at $55\text{--}65^\circ$, where a trip is expected to be effective, is the natural next test.

Acknowledgements

This work used OpenFOAM v2512, developed and released by OpenCFD Ltd (Keysight Technologies, Bracknell, UK).

Author contributions

Y.J. is the sole author and is responsible for all CRediT roles: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing of the original draft, review and editing, and visualization.

Funding

No funding was received for this work.

Data availability

The dataset “Swim-cap surface texture and the sphere drag crisis: force histories, flow fields, surface samples, and meshes from fixed-time-step URANS simulations” (version 2.0.0) is openly available in the Zenodo repository at <https://doi.org/10.5281/zenodo.23030402> [17]. It contains the force time series, meridional pressure and wall-shear profiles, sampled surfaces, geometries, meshes, and volume fields for every case reported here, together with the case-generation, analysis, and figure scripts. Online Resource 1 contains the run matrix and convergence statistics, the time-step, grid, and free-stream turbulence studies in full, the mesh generation and numerical settings, seven supplementary figures, and three supplementary tables.

Declarations

Conflict of interest

The author declares no competing interests. Geometry 2 is an idealized representation of a commercially available competition cap. The author has no financial or personal relationship with its manufacturer, received no materials, funding, or consultancy from that manufacturer, and the manufacturer had no role in the design, execution, analysis, or reporting of this study.

Ethical approval

Not applicable. This study involved no human participants, their data, or biological material, and no animals.

Use of generative AI

During the preparation of this work, the author used Claude Opus 5.5 (Anthropic, San Francisco, CA, USA) for language editing and clarity improvement of the manuscript. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Supplementary Information (Online Resource 1)

S1. Run matrix and convergence statistics

Table S1 lists the 13 runs of this study and their convergence statistics. Eight runs form the matched sweep of the main text: both bodies at four velocities with a time step of 1.5×10^{-3} s. The other five form the time-step study on the sphere: four runs with a step of 3.0×10^{-3} s and one run at 1.6 m/s with a step of 7.5×10^{-4} s. Every run was started from a uniform field and averaged over $t = 30\text{--}80$ s.

Table S1 Run matrix and convergence statistics, averaged over $t = 30\text{--}80$ s. SE is the standard error of the time average. Drift, split, lateral force, and start sensitivity correspond to criteria (ii) to (v) of Section 2.3 of the main text; the last column gives the tolerance applied (Section S1)

Body	U (m/s)	Time step (ms)	C_d	SE (%)	Drift (%)	Split (%)	Lateral	Start (%)	Tolerance
Sphere	1.6	1.5	0.1531	5.08	3.35	1.80	0.0138	2.11	2 SE
Sphere	1.8	1.5	0.1341	0.53	0.02	0.00	0.0005	0.09	Fixed
Sphere	2.0	1.5	0.1276	0.60	0.01	0.35	0.0041	0.11	Fixed
Sphere	2.2	1.5	0.1245	0.60	0.01	0.00	0.0021	0.08	Fixed
Cap	1.6	1.5	0.1539	7.62	6.18	12.38	0.0190	3.11	2 SE
Cap	1.8	1.5	0.1327	0.38	0.14	0.51	0.0041	0.14	Fixed
Cap	2.0	1.5	0.1290	0.33	0.01	0.07	0.0031	0.05	Fixed
Cap	2.2	1.5	0.1626	7.98	1.16	6.17	0.0243	3.60	2 SE
Sphere	1.6	3.0	0.1378	0.52	0.01	0.13	0.0041	0.02	Fixed
Sphere	1.8	3.0	0.1295	0.48	0.00	0.04	0.0016	0.08	Fixed
Sphere	2.0	3.0	0.1263	0.55	0.01	0.01	0.0015	0.06	Fixed
Sphere	2.2	3.0	0.1257	0.59	0.02	0.28	0.0036	0.12	Fixed
Sphere	1.6	0.75	0.1718	4.43	1.35	4.62	0.0336	1.03	2 SE

The four runs with the coarsest step were first computed using adaptive time stepping capped at 0.003 s, to $t = 50$ s at 1.6 and 1.8 m/s, to $t = 41$ s at 2.0 m/s, and to $t = 80$ s at 2.2 m/s. After the first 0.5 s, the step remained at its cap, realized as 2.994×10^{-3} s. The first three runs were continued from their saved states to $t = 80$ s with the step fixed at this value, so that the continuation changed no effective setting. On the same time grid, the continued runs reproduced the original drag histories to within 1×10^{-4} in drag coefficient. Each force history is archived as one continuous record from $t = 0$ to 80 s.

The statistics in Table S1 follow the criteria of Section 2.3 of the main text. Cycles were counted from the mean interval between upward crossings of the mean drag; every run spanned 13 to 41 cycles and met criterion (i). Drift is the change in the running mean over the last five cycles, and split is the split-half difference. The lateral column gives the larger magnitude of the mean lift and side-force coefficients,

$|C_l|$ and $|C_s|$. Start sensitivity is the largest change in the mean when the start of the window is moved from 30 to 40 s in steps of 2.5 s. For the four runs with intermittent high-drag episodes, the tolerances of criteria (ii) to (v) were set to twice the standard error of the tested quantity; the last column identifies these runs.

S2. Time-step study

Fig. S1 shows the drag history of the sphere at 1.6 m/s for the three time steps. With the step of 3.0×10^{-3} s, the start-up episodes decayed within the first 20 s, and the drag then oscillated regularly with a root-mean-square of 0.0067. With the two finer steps, episodes of high drag recurred throughout the run, and the root-mean-square rose to 0.051 and 0.057. The mean drag coefficient over $t = 30\text{--}80$ s was 0.138, 0.153, and 0.172. The two increments, $+11 \pm 11\%$ and $+12 \pm 15\%$ ($k = 2$), were not resolved against the sampling uncertainty, although both were positive.

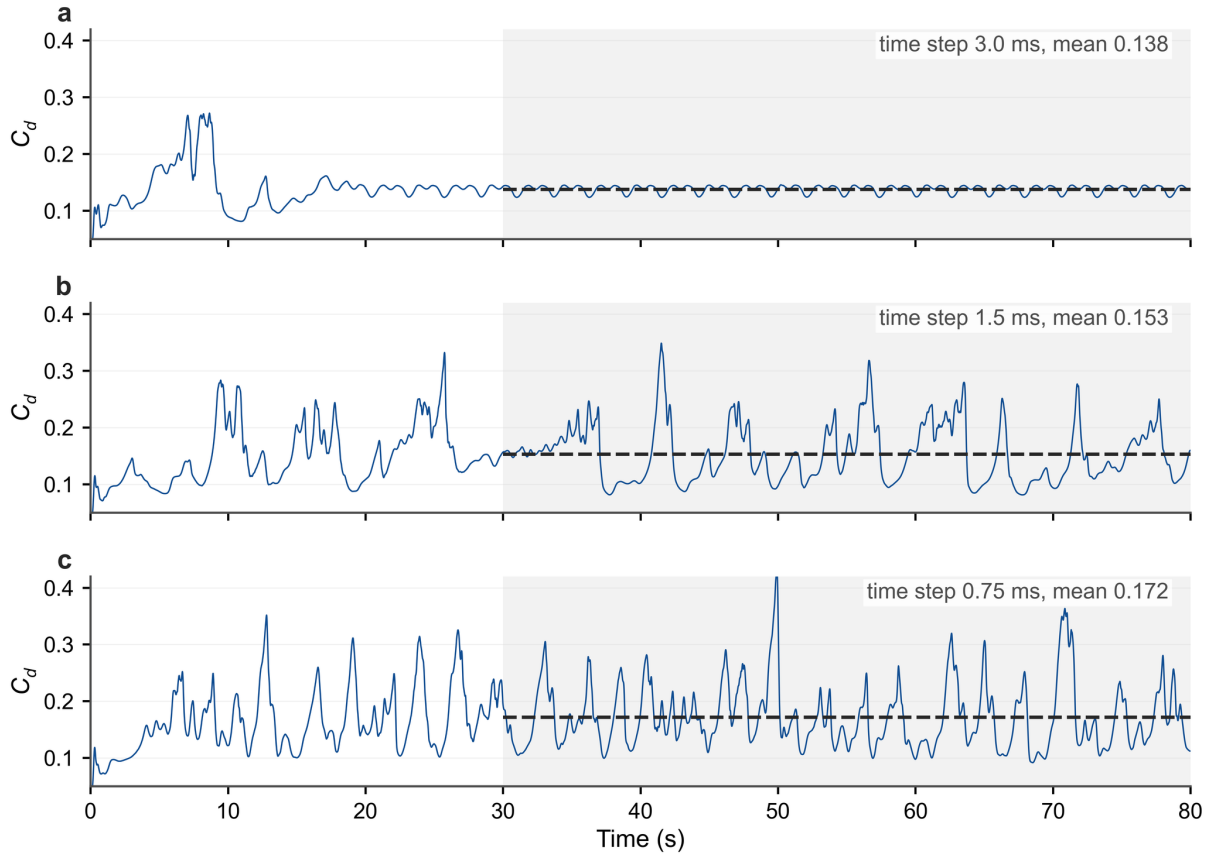


Fig. S1 Drag coefficient of the sphere at $U = 1.6$ m/s with time steps of (a) 3.0 ms, (b) 1.5 ms, and (c) 0.75 ms. Shading marks the averaging window, and dashed lines mark the window means

At 1.8, 2.0, and 2.2 m/s, the flow was steady in the mean at both steps, and halving the step from 3.0×10^{-3} to 1.5×10^{-3} s changed the drag coefficient by $+3.5 \pm 1.5\%$, $+1.0 \pm 1.6\%$, and

$-1.0 \pm 1.7\%$ ($k = 2$). The separation angle ($104.0\text{--}104.6^\circ$), the mean and maximum y^+ , and the viscous drag did not change with the step at any velocity (Table S1). The time step therefore affected the unsteadiness of the wake, and it mattered most at the lowest velocity, where the flow lay close to the boundary between the intermittent and steady states. The comparison of the two geometries in the main text accordingly uses the same step for both bodies.

S3. Grid and free-stream turbulence studies

Both studies were performed on the sphere at $U = 1.8$ m/s, with one variable changed at a time and every case started from a uniform field. Both used a maximum time step of 3.0×10^{-3} s, the coarse level of Section S2, at which the drag at this velocity was 3.5 % lower than with the production step (Section S2). The comparisons within each study were therefore made at a common step.

The grid study used three geometrically similar meshes of 2 262 454, 4 847 403, and 10 127 983 cells, a refinement ratio of $r \approx 1.28$. Only the background resolution was varied; therefore, the surface refinement, the wake refinement, the prism-layer stack, and y^+ were refined in proportion; the layer stack was kept at 0.518 of the local surface cell on all three meshes. Over the common window $t = 20\text{--}50.41$ s, the coarse mesh gave $C_d = 0.0898 \pm 0.77\%$, the production mesh $0.1296 \pm 0.62\%$, and the fine mesh $0.1319 \pm 0.41\%$ (Fig. 8a, d of the main text). The coarse-to-production change of 44.4 % placed the coarse mesh well outside the asymptotic range. The production-to-fine change was +1.75 % against a combined standard error of 0.76 %, a difference of 2.3σ , and was taken as the discretization error of the production mesh relative to a mesh with 2.1 times as many cells. No grid-convergence index was computed. Richardson extrapolation of the triplet gave an observed order of 11.6, against a theoretical order of 2, which showed that the sequence was not in the asymptotic range; the pairwise difference and its uncertainty are the meaningful quantities.

The separation angle responded to refinement differently from the drag. On the three meshes it moved from 102.2° to 104.3° and 118.9° , increasing monotonically and moving away from the expected $79\text{--}82^\circ$, a shift of 16.7° across a 4.5-fold increase in cell count over which the drag coefficient changed by 1.75 % (Fig. S2). The profiles also differed in form. On the coarse and production meshes, the wall shear stress crossed zero and then oscillated about zero up to approximately 118° ; therefore, the quoted separation angle marks the start of a marginally attached band. On the fine mesh, there was no such band: the wall shear stress remained negative up to 118.9° and then became clearly positive. Refinement thus removed an ambiguity present on the two coarser meshes rather than moving a well-defined separation point downstream.

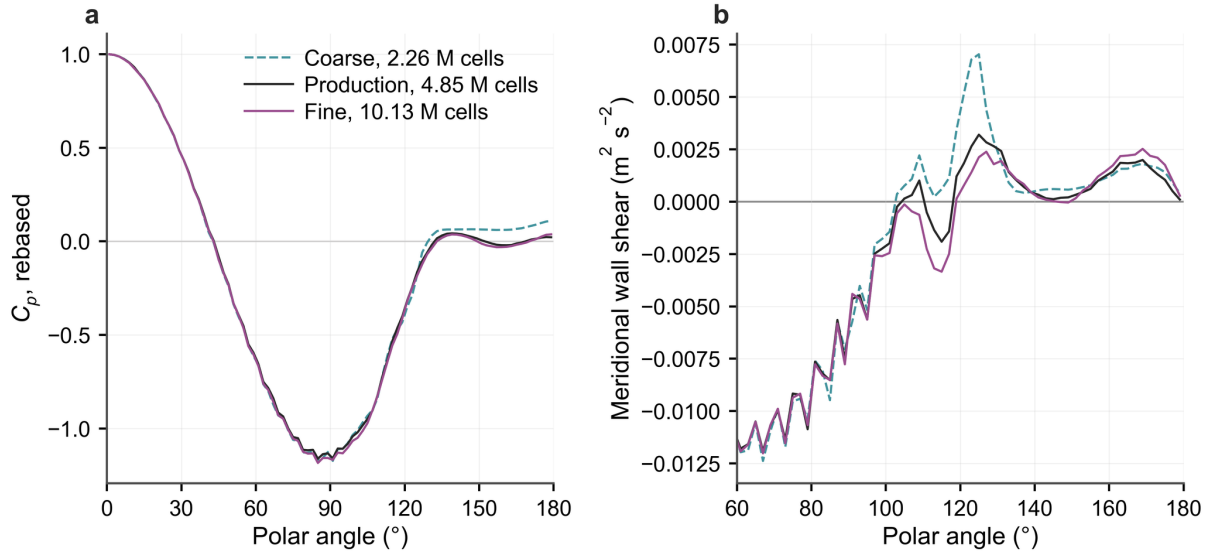


Fig. S2 Surface profiles of the sphere on the three meshes at $U = 1.8 \text{ m/s}$. (a) Pressure coefficient, rebased to 1 at the stagnation point. (b) Meridional wall shear stress; the first zero crossing is the separation point

The free-stream turbulence decayed between the inlet and the body. Measured on the stagnation streamline, the intensity was 1.00 % at the inlet and 0.593 % at the body, compared with 0.581 % from the standard decay law and 0.45 % in Achenbach’s tunnel. Reducing the intensity at the body to 0.470 % raised the drag coefficient from 0.1296 to 0.173–0.186, an increase of 33–43 %, while separation moved only from 104.3° to 102.7° (Fig. 8b, e of the main text). The range reflected the sensitivity of this case to the start of the averaging window, approximately 7 %; therefore, the effect is quoted as approximately 40 %. Raising the intensity to 1.274 % at an eddy-viscosity ratio of 46 lowered the drag coefficient to 0.1151 and moved separation to 118.0° . This case changed two variables, and a further case isolated the second: at an intensity of 0.570 %, close to the baseline 0.593 %, raising the eddy-viscosity ratio from 9 to 49 increased the drag coefficient by 19.3 %. The -11.2 % change of the high-intensity case was thus the sum of two effects of opposite sign. The case at the higher eddy-viscosity ratio did not meet the convergence criteria, because its drag had a root-mean-square of 33 % of the mean; every 10 s block of that run nevertheless exceeded the baseline, which establishes the sign of the effect. All four intensities were measured from the archived fields; the decay law underestimated them by 2–8 %.

Two conclusions follow. First, the late separation was not caused by the inflow turbulence: at intensities that bracketed the experimental value, separation remained more than 20° downstream of the expected angle. Second, the absolute drag depended strongly on the specified free-stream turbulence, including the eddy-viscosity ratio; consequently, absolute drag coefficients from transition-sensitive simulations should be reported together with the turbulence boundary condition.

S4. Mesh generation and near-wall resolution

Both meshes were generated using snappyHexMesh with the settings in Section S9. The refinement recipe was identical for the two bodies: surface refinement at level 5, approximately 1.25 mm; 15 prism layers with an expansion ratio of 1.15, a first-layer thickness of 1.36×10^{-5} m, a stack thickness of 6.47×10^{-4} m, and a near-wall aspect ratio of approximately 88; and nested wake refinement boxes at levels 4, 3, and 2. The layer-addition controls were also identical: a feature angle of 180° , a slip feature angle of 75° , and no layer cancellation. The far-field and boundary-layer resolutions therefore matched, and the 0.7 % difference in cell count, 4 847 403 against 4 812 263, arose only from the surface shape.

One difference in the realized mesh followed from the geometry and could not be removed by a meshing setting. On the sphere, the layer specification was realized in full: all 55 616 surface faces and 100 % of the ideal layer cells were extruded. On the cap, 99.95 % of the faces were extruded but only 94.28 % of the ideal layer cells were added, because the layers were truncated over the ridges, whose flanks reached 23.9° to the local radial direction, compared with at most 0.6° on the sphere. Fig. S3 compares the two stacks; the consequences for the wall resolution are reported in Section S6.

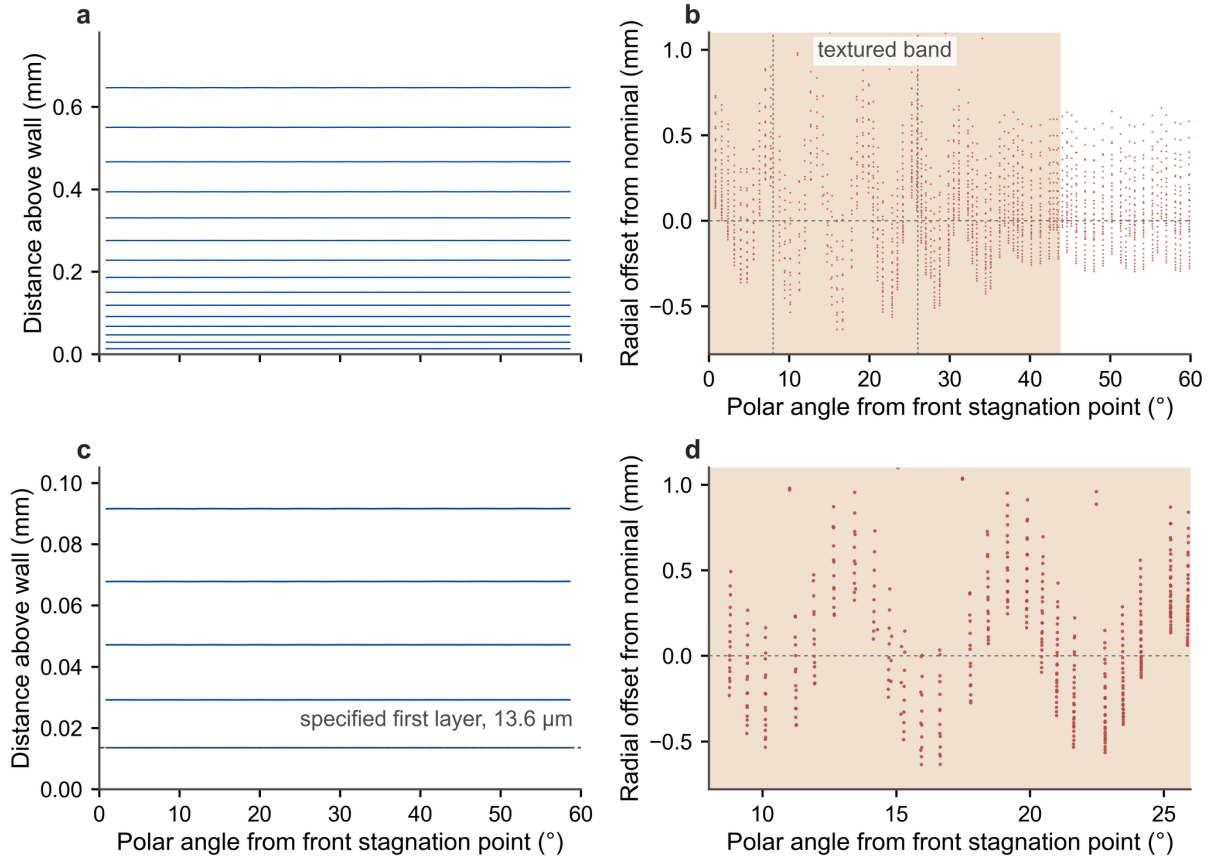


Fig. S3 Near-wall mesh of both bodies, generated from the same layer specification. (a) Mesh levels above the wall on the sphere, each line tracing one level along the surface. (b) Near-wall mesh points on the cap, plotted as radial offset from the nominal sphere; shading marks the textured band, and dashed lines mark the window shown in (d). (c) The first six layers of (a); the lowest level lies at the specified first-layer thickness of $13.6\ \mu\text{m}$. (d) Detail of (b) over three ridges, plotted as points because no level can be traced as a single curve on the cap

S5. Wake precession and the averaging requirement

The lateral force coefficients of both bodies were dominated by a single low-frequency peak at $St = 0.018\text{--}0.028$ at all four velocities (Fig. S4), an order of magnitude below the classical shedding value of approximately 0.2; this corresponds to periods of approximately 4 to 7 s, or 36 to 56 convective times D/U . With 20 s spectral segments, the frequency resolution was approximately 0.005 in Strouhal number; therefore, no trend with velocity is claimed. The instantaneous lift and side-force coefficients had root-mean-square values of 0.09–0.11, comparable to the drag coefficient, whereas their means over the averaging window satisfied criterion (iv).

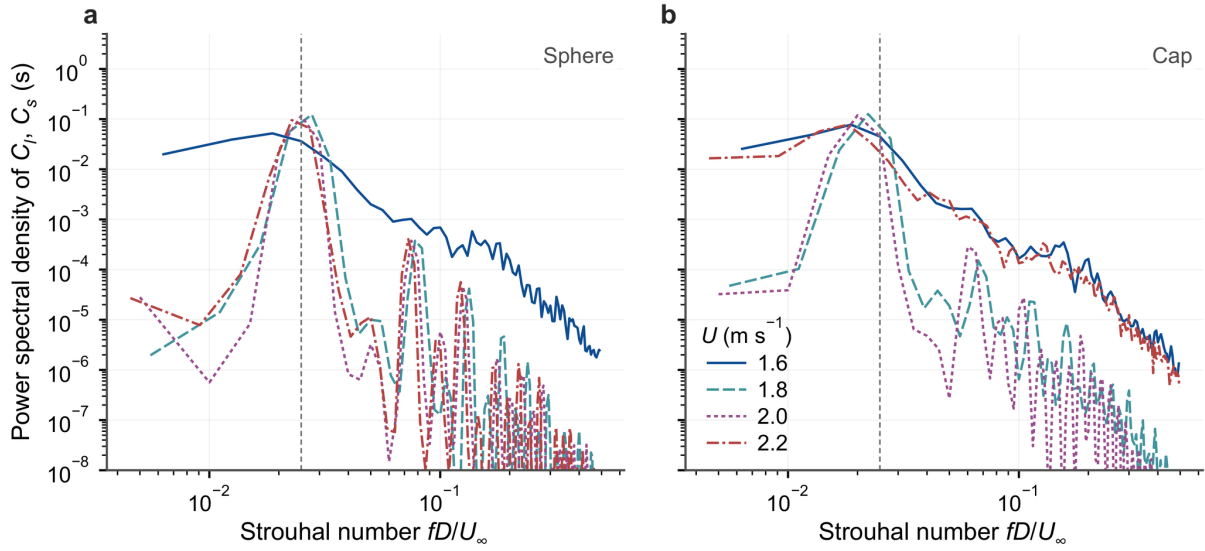


Fig. S4 Power spectral density of the lift and side-force coefficients, averaged over the two components, for (a) the sphere and (b) the cap at the four velocities, over $t = 30\text{--}80$ s. The dashed line marks $St = 0.025$

This behavior was a property of the flow rather than of the mesh. The mesh was symmetric about $x = 0$ to machine precision, with zero mirror mismatch and equal face counts in the two half-spaces. The global stability analysis of Szabó and Mahesh (reference [10] of the main text) predicted a stationary asymmetric mode for axisymmetric bodies and noted that the asymmetry observed in experiments was robust to changes in pitch, yaw, trip-wire geometry, free-stream turbulence, and surface roughness. Li and Zhou (reference [11] of the main text) observed the corresponding force signature at $Re = 300$. Both studies were conducted at far lower Reynolds numbers; the present runs extend the observation to the drag-crisis range. Because the azimuthal orientation of such a mode is neutrally stable on a body of revolution, the mode precesses, which is what the force spectra show. In the runs with high-drag episodes, each episode coincided with a large excursion of the lateral force (Fig. 7 of the main text), which suggests that the episodes were large-amplitude departures of the same asymmetric wake. Two consequences follow for comparable studies. First, the statistics became stationary only after $t \approx 15\text{--}30$ s; therefore, a criterion expressed in shedding cycles would be approximately an order of magnitude too short. Second, body symmetry should be assessed over at least one precession period.

S6. Surface profiles, drag breakdown, and wall resolution of the two bodies

The cap separated at 102.2° at all four velocities, compared with 104.3° , 104.3° , 104.5° , and 104.6° on the sphere, each from the surface sample at $t = 80$ s. Both bodies separated more than 20° downstream of the expected $79\text{--}82^\circ$; therefore, the shift of approximately 2° was small relative to their common error. On the cap, the meridional wall shear stress oscillated about zero from the first crossing to approximately 119° ; consequently, the agreement of the four cap values to a tenth of a degree does not indicate that precision. Fig. S5 compares the surface profiles of the two bodies at 1.8 m/s: the pressure distributions

coincided outside the textured band, and the wall shear stress differed mainly within it, where the ridges modulated the attached boundary layer.

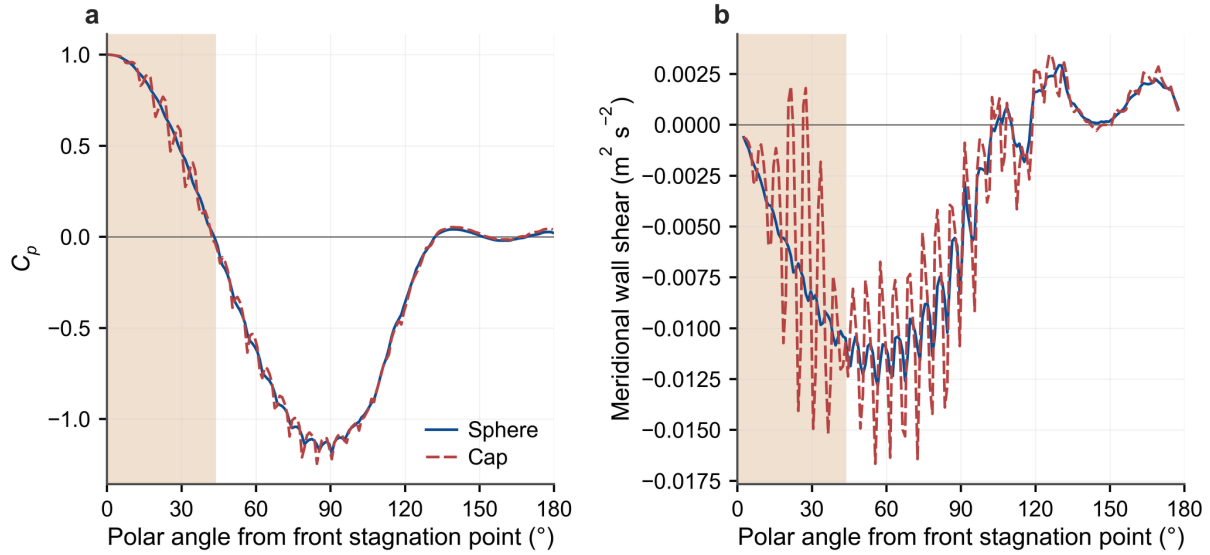


Fig. S5 Surface profiles of the two bodies at $U = 1.8$ m/s. (a) Pressure coefficient, time-averaged over $t = 5\text{--}80$ s and rebased to 1 at the stagnation point. (b) Meridional wall shear stress at $t = 80$ s. Shading marks the textured band, $0\text{--}43.8^\circ$

Pressure drag accounted for 92.6–93.2 % of the total on the sphere and 92.8–94.5 % on the cap (Fig. S6). The largest share, on the cap at 2.2 m/s, accompanied the higher drag of that case, whose viscous contribution was slightly lower than that of the sphere. The wall resolution differed between the bodies because of the prism-layer truncation (Section S4). The mean y^+ was 0.45–0.57 on the sphere and 0.66–0.82 on the cap, and the maximum was 0.88–1.14 on the sphere and 24–41 on the cap. On the cap, the 99th percentile was 5.7–7.3, and 7.7–12.5 % of the faces had $y^+ > 1$. At 1.6 to 2.0 m/s, 96–98 % of these faces lay in the textured band, and at 2.2 m/s 73 % did. All faces with $y^+ > 5$, 1.2–2.0 % of the surface, lay upstream of 38.4° . Outside the textured band, the two bodies were resolved alike (Fig. S6b).

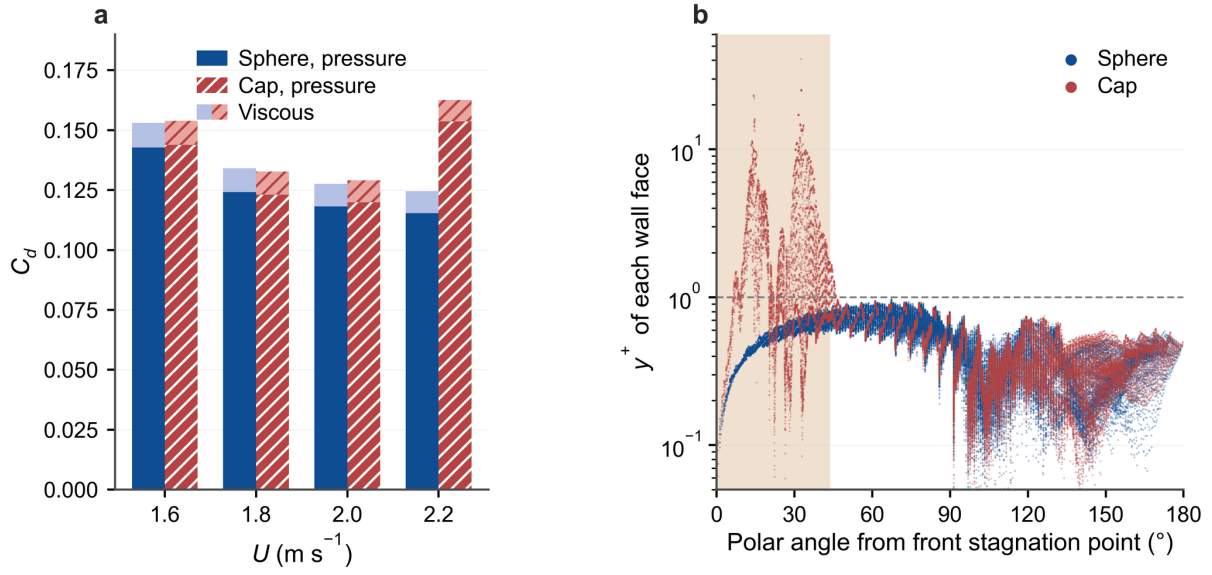


Fig. S6 Drag breakdown and wall resolution. (a) Pressure and viscous contributions to the drag coefficient of both bodies, averaged over $t = 30\text{--}80$ s. (b) y^+ of each wall face against polar angle at $U = 1.8$ m/s and $t = 80$ s; shading marks the textured band, and the dashed line marks $y^+ = 1$

S7. Digitization of Achenbach's drag curve

Fig. 3 of the main text compares the computed drag coefficients with Achenbach's measurement rather than with a band summarizing it. His figure 4 was digitized for that purpose. The page carries a 1-bit scan; therefore, there are no vector data, and the markers had to be recovered from the image. The printed grid gave the calibration: horizontal rules at $C_d = 0$ to 0.7 and vertical rules at the decades 10^4 to 10^7 , fitted by least squares with residuals of 0.5 and 1.1 pixels, where one pixel is 0.001 in C_d and 0.5 % in Reynolds number. The markers are open circles that overlap into continuous chains; consequently, connected-component labeling recovered only the few that stand alone. A signed annulus matched filter, whose positive ring rewards the printed stroke and whose negative core rejects solid ink, recovered 110 of them. The count was unchanged between thresholds of 0.75 and 0.85 of a perfect match.

Three values that Achenbach stated in his own text, none of which was used in the calibration, checked the result across the full width of the panel. They are the subcritical plateau, digitized at $C_d = 0.505$ against a stated value of approximately 0.5; the transcritical value at $Re = 6 \times 10^6$, digitized at 0.191 against a stated 0.19; and the Reynolds number of the minimum, digitized at 3.85×10^5 against a stated critical Reynolds number of approximately 3.7×10^5 . The digitized minimum drag coefficient was approximately 0.06.

S8. Free-stream conditions and race-pace mapping

Table S2 provides the inlet turbulence quantities maintained across the velocity sweep, calculated from the intensity and eddy-viscosity ratio of Section 2.2 of the main text.

Table S2 Free-stream conditions. The inlet turbulence quantities hold a turbulence intensity of 1 % and an eddy-viscosity ratio of 10 constant across the sweep. The transition-model inlet values are identical for all cases

U (m/s)	Re	k (m ² /s ²)	ω (s ⁻¹)
1.6	3.2×10^5	3.84×10^{-4}	38.4
1.8	3.6×10^5	4.86×10^{-4}	48.6
2.0	4.0×10^5	6.00×10^{-4}	60.0
2.2	4.4×10^5	7.26×10^{-4}	72.6

Table S3 maps the simulated Reynolds number range onto competitive race pace, as used in Section 4.2 of the main text.

Table S3 Mean race velocity and corresponding head Reynolds number by event, from men's long-course freestyle world-record times. Mean velocity includes starts and turns and therefore exceeds free-swimming velocity

Event	Time (s)	Mean velocity (m/s)	Re at $D = 0.2$ m	Within simulated range
1500 m	870.67	1.723	3.45×10^5	Yes
800 m	452.12	1.769	3.54×10^5	Yes
400 m	219.96	1.819	3.64×10^5	Yes
200 m	102.00	1.961	3.92×10^5	Yes
100 m	46.40	2.155	4.31×10^5	Yes
50 m	20.88	2.395	4.79×10^5	Marginally above

S9. Mesh generation and preparation

The meshes were created using snappyHexMesh. The bounding box of the domain was divided into $50 \times 100 \times 50$ cells in the x , y , and z directions, which gives a uniform base cell of 40 mm, and surface refinement level 5 is equivalent to 1.25 mm. All settings below are the same for both geometries except where specified, and their names reflect the interface used to create the dictionaries.

Castellation settings. Maximum local cells 4×10^7 ; maximum global cells 1×10^8 ; minimum refinement cells 1; maximum load unbalance 0.2; three cells between levels; feature angle for resolution 30° ; disable free-standing zone faces.

Snapping settings. Five mesh-to-surface conforming iterations; tolerance 2; 150 iterations of solver; 8 relaxation iterations; 10 iterations of maximum conformation; disable implicit feature snapping; enable explicit feature snapping; disable multi-surface feature detection.

Addition of layers. Fifteen layers were added with an expansion ratio of 1.15, a minimum thickness of 1×10^{-6} m, and a first-layer thickness of 1.36×10^{-5} m on the production and cap meshes, resulting in a stack of 6.47×10^{-4} m. For the grid-study family, the thickness of the first layer depended on the bounding-box resolution and was 1.79×10^{-5} , 1.36×10^{-5} , and 1.05×10^{-5} m for the coarse, production, and fine meshes, respectively; the thickness of the whole layer stack remained 0.518 of the local surface cell. Mesh settings common to both geometries: 8 relaxation iterations; 2 surface-normal smoothing iterations; 5 internal-mesh smoothing iterations; 10 layer-thickness smoothing iterations; maximum face-thickness ratio 0.5; maximum thickness-to-medial ratio 0.5; minimum median-axis angle 90° ; zero buffer cells between refinement levels; 50 layer-addition iterations; 20 iterations of strict quality control. A feature angle of 180° , a slip feature angle of 75° , and no allowed canceled layers around sharp features are robustness settings. Because the smooth sphere has no feature edges, these settings do not affect geometry 1, but on geometry 2 they prevent the mesher from canceling layers over the crown ridges.

Mesh quality controls. Maximum non-orthogonality 70° (75° relaxed); maximum boundary skewness 20° ; maximum internal skewness 4° ; maximum concaveness 80° ; minimum cell volume 1×10^{-13} m³; minimum tetrahedral quality -1×10^{30} ; minimum face area -1 m²; minimum face twist 0.01; minimum determinant 0.001; minimum face weight 0.02; minimum volume ratio 0.01; minimum triangle twist -1; four iterations of error distribution; error reduction 0.75; merge tolerance 1×10^{-6} ; maximum meshing time 1.8×10^4 s.

Refinement regions. Surface refinement was applied at minimum and maximum level 5 over the whole surface of the body, without a cell zone. Next come three Cartesian boxes corresponding to the wake regions. Their bounding boxes were found from the exported mesh, not from the meshing job, by classifying all cells by their volumes into refinement levels and computing the bounding box for each of them: near wake, level 4, from (- 0.159, - 0.110, - 0.159) to (0.159, 0.450, 0.159); mid wake, level 3, from (- 0.220, - 0.122, - 0.220) to (0.220, 1.000, 0.220) ; far wake, level 2 , from (- 0.351, - 0.145, - 0.351) to (0.351, 1.792, 0.351). Every bound corresponds to an extreme cell-center position offset by half of the cell size, and is therefore accurate to half of the local cell size. Coordinates are in meters, the body is centered at the origin, and the flow is in the +y direction.

The raw export was not directly runnable. Its preparation included copying the points, faces, owner, neighbour, boundary, and zone files to the mesh directory of the case, except the face map file, which is not part of the standard set; mesh check; renaming of the patches to generate body, inlet, outlet, and far-

field patches; and renumbering. Renaming of the patches must be performed before decomposition; otherwise, the force function objects refer to a nonexistent patch, and the case runs to completion without any force output. The mesh must never be passed through `reconstructParMesh`, because it collapses the thin prism layers. Success of the layer extrusion is indicated by a minimum cell volume of approximately $1.3 \times 10^{-11} \text{ m}^3$; approximately $4.6 \times 10^{-10} \text{ m}^3$ means failed layers.

S10. Surface mesh quality

Two discretization artifacts appear in the surface and wall-shear profiles. First, the surface faces were distributed in discrete rings: from 0 to 824 faces per degree of the polar angle, with a mean of 309, because cutting the hexahedral mesh with the sphere produces rings of faces rather than evenly spaced faces. The pressure coefficient is stored per face; therefore, every ring generates a band of nearly constant value. Both artifacts are illustrated in Fig. S7.

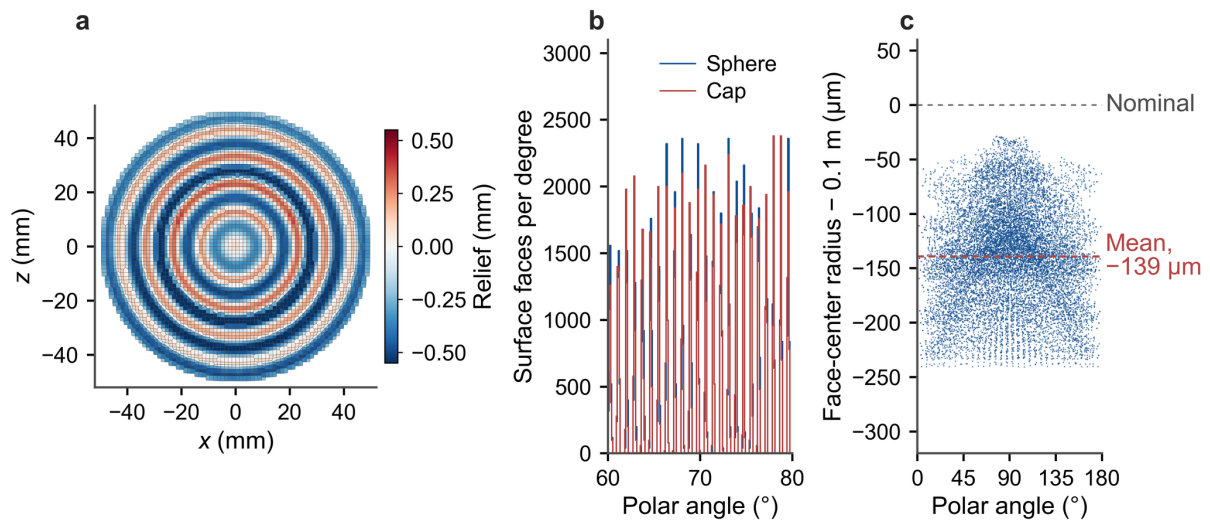


Fig. S7 Surface mesh and the two discretization artifacts described in this section. (a) Cap surface mesh out to a polar angle of 30° , viewed from upstream along the flow axis and colored by relief about the nominal sphere. (b) Number of surface faces per degree of polar angle for both bodies; faces are distributed in discrete rings, not smoothly. (c) Face-center radius of the meshed sphere relative to the nominal 0.1 m; the surface lies a mean of $139 \mu\text{m}$ inside the nominal sphere, with a root-mean-square scatter of $45.6 \mu\text{m}$

Second, the surface mesh did not conform to the nominal sphere. Face-center radii varied from 0.099760 to 0.099971 m relative to the nominal 0.1 m, yielding a mean offset of $139 \mu\text{m}$ inside the nominal sphere, a root-mean-square scatter of $45.6 \mu\text{m}$, a maximum deviation of $240 \mu\text{m}$, and an effective diameter of 0.199722 m. The mean offset was uniform in polar angle, $139 \mu\text{m}$ at 50° and $127 \mu\text{m}$ at 100° , and therefore represented a slightly smaller sphere, not roughness. As a result, the drag coefficient carries a systematic positive bias of 0.28 %, and the wall-normal spacing scatter was 3.4 times the $13.6 \mu\text{m}$ first-cell height. As discussed in Section 4.1 of the main text, the scatter is unlikely to trip the boundary layer.

Discretization into rings of faces was 3.0 times more prominent on the textured cap than on the smooth sphere when compared over the bands where the surfaces are perfectly spherical, and it caused the oscillations in the wall shear downstream of separation described in Section 3.3 of the main text. The discretization is a property of the mesh, not of the surface, because the two bodies are geometrically identical beyond 43.8° .

S11. Numerical settings

All cases were generated by a single shell script, `make_case.sh`, included in the replication package. This script takes the free-stream velocity, the mesh directory, and, optionally, the turbulence intensity and eddy-viscosity ratio as inputs, and it calculates the turbulence kinetic energy, the specific dissipation rate, and the transition-onset momentum-thickness Reynolds number according to the Langtry–Menter correlation. The script was verified against the cases run in this paper by regenerating a case and comparing it with the archived case directory: `fvSchemes`, `fvSolution`, and all seven initial and boundary condition files were byte-identical, and every substantive `controlDict` entry was identical as well. The only differences were the extra white space created by OpenFOAM’s recreation of the file, and the settings changed for the fixed-time-step runs: the end time, the maximum time step, and the maximum Courant number, given in the next paragraph.

Time stepping used adjustable steps with a maximum Courant number of 20 and a maximum step of 0.0015 s, or 0.00075 s for the finer run of the time-step study. Because fields were written every 0.5 s of simulated time, the solver rounded the step so that each output interval contained a whole number of steps, which gave realized steps of 1.5015×10^{-3} and 7.496×10^{-4} s. The Courant limit was never reached in these runs. The coarse set used a maximum Courant number of 15 and a maximum step of 0.003 s, realized as 2.994×10^{-3} s, and was continued with this step held fixed (Section S1). Field averaging started at $t = 5$ s.

The convection schemes were Gauss linearUpwindV with the cell-limited linear gradient for momentum, Gauss upwind for the turbulence kinetic energy and specific dissipation rate, Gauss limitedLinear01 for intermittency, and Gauss limitedLinear for transition-onset momentum thickness Reynolds number; the Laplacian schemes were Gauss linear corrected. The pressure equation was solved using GAMG with a Gauss–Seidel smoother to a tolerance of 1×10^{-6} , with a relative tolerance of 0.05 on the intermediate correctors and 0 on the final one; the remaining equations were solved using smoothSolver with a symmetric Gauss–Seidel smoother to a tolerance of 1×10^{-8} . The relaxation factors were 0.9 for velocity and 0.8 for the turbulence and transition variables.

Nine function objects were used during the execution of every case: `residuals`, `forces1`, `forceCoeffs1`, `fieldAverage1`, `yPlus1`, `wallShearStress1`, `pressureCoeff`, `areaAverage_sphere`, and `areaAverage_outlet`.

The force coefficients were calculated using a reference area of 0.0314159 m^2 , a reference length of 0.2 m , a density of 998 kg/m^3 , and a drag direction of $(0, 1, 0)$.

The surface pressure, wall shear stress, and y^+ were sampled on the body at $t = 80 \text{ s}$ using the `sampleSurf` function. The time-averaged surface pressure and the mid-plane fields used in Figs. 4 and 5 of the main text were sampled from the same time using the `sampleMeanSurf` and `sampleMeanPlane` functions, which are included in the replication package.