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Understanding the effect of seams on the aerodynamics of an association football

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ABSTRACT

The aerodynamic properties of an association football were measured using a wind tunnel arrangement. A third scale model of a generic football (with seams) was used as well as a 'mini-football'. As the wind speed was increased, the drag coefficient decreased from 0.5 to 0.2, suggesting a transition from laminar to turbulent behaviour in the boundary layer. For spinning footballs, the Magnus effect was observed and it was found that reverse Magnus effects were possible at low Reynolds numbers. Measurements on spinning smooth spheres found that laminar behaviour led to a high drag coefficient for a large range of Reynolds numbers and Magnus effects were inconsistent, but generally showed reverse Magnus behaviour at high Reynolds number and spin parameter. Trajectory simulations of free kicks demonstrated that a football that is struck in the centre will follow a near straight trajectory, dipping slightly before reaching the goal, whereas a football that is struck off centre will bend before reaching the goal, but will have a significantly longer flight time. The curving kick simulation was repeated for a smooth ball, which resulted in a longer flight time, due to increased drag, and the ball curving in the opposite direction, due to reverse Magnus effects. The presence of seams was found to encourage turbulent behaviour, resulting in reduced drag and more predictable Magnus behaviour for a conventional football, compared to a smooth ball.

Keywords: football, soccer, free kick, aerodynamics, transition, drag, lift, Magnus effect, smooth sphere

NOTATION

a, b, c and d	Magnus curve fit coefficients
A	projected area of sphere
C_d	drag coefficient
C_m	Magnus coefficient
F_d	drag force
F_m	force due to Magnus effects
Re	Reynolds number
S_p	spin parameter
v	relative velocity of the air
v_{eq}	equatorial velocity of the ball surface, relative to its centre
ρ	density of the air
ω	ball spin

1. INTRODUCTION

The aim of this study was to gain a full understanding of the aerodynamics of an association football during its flight after a controlled kicking situation (e.g. a free kick). The behaviour of a spinning ball in flight is largely determined by the transition of the boundary layer from laminar to turbulent and boundary layer separation, both of which have led to considerable research activity and are well-understood phenomena [1, 2]. Previous studies on ball aerodynamics include that by Bearman and Harvey [3] who found that dimples on a golf ball serve to reduce the critical Reynolds number indicating that surface geometry can have a significant effect on ball flight. Studies related to other sports including cricket [1], tennis [4], baseball [5], volleyball [6] have measured the drag and Magnus forces experienced by a ball during flight for varying velocity and spin conditions and examined the effect on transition and boundary layer separation. This work built on ground-breaking research by Achenbach [7, 8] on the aerodynamics of smooth and rough spheres, which showed that increased surface roughness encourages transition to occur at low values of Reynolds number. These issues are well described in a comprehensive review of sports ball aerodynamics by Mehta [1]. However, little work has been published on footballs, which differ from other sports balls due the presence and orientation of seams. Therefore, wind tunnel measurements were taken from stationary and spinning scale models of footballs, in order to calculate drag and Magnus coefficients. A previous study on the interaction between the foot and ball by Asai *et al.* [9] provided a range of launch conditions (speed and spin) for a free kick situation, based on a foot impact velocity of 25 m/s. Aerodynamic data can then be used to simulate the flight of a football for various

launch conditions and compare the behaviour with that of a smooth ball. A summary of the launch condition data is shown in Table 1 and indicates a trade-off between speed and spin, depending on the impact location of the foot. If the ball is struck centrally, it will be launched with high velocity and relatively little spin, but if the impact location is moved towards the edge of the ball, spin is now applied, but the launch velocity is reduced. This effect is non-symmetrical due to the geometry of the foot.

2. STUDY OF THE AERODYNAMICS

There are two main approaches to measuring forces on sports balls during flight. The first approach is to take measurements from controlled football trajectories using high speed video footage [10]. Although this is a well-recognised method that undoubtedly examines what actually happens as a ball travels through the air, it is susceptible to errors. The trajectory must be measured very accurately, as the effect of drag and Magnus force is determined by analyzing the subtle changes in the shape of the trajectory. Monitoring the change in drag due to velocity is further complicated by the fact that the velocity changes during flight. Other effects such as turbulence, camera misalignment and inaccurate velocity measurement can all lead to further inaccuracies, although these errors can be reduced by employing more cameras.

The second approach is to use a wind tunnel, with the sports ball being held in place whilst air is blown around it. This method has the advantage that the speed of the air can be accurately controlled and kept constant and the forces acting on the ball can be measured by attaching the ball to a force balance arrangement.

3. THE EFFECT OF VELOCITY ON DRAG

All experiments were carried out using an open circuit wind tunnel (provided by the International Tennis Federation, Roehampton, UK and supplied by Aerotech ATE Ltd.). A slotted wall test section had been fitted to reduce blockage effects normally associated with closed wall test sections. The test section (305 mm x 355 mm) was fitted with 30% open area ratio walls, based upon the technology developed for automotive wind tunnels (Waudby-Smith and Rainbird [11], Macha *et al.* [12]). A honeycomb section

settling chamber with a contraction ratio of 10:1 and two screens were also included in the tunnel to produce a high quality flow.

The velocity variation along the entire test section was $\pm 0.25\%$, across the entire test section was $\pm 0.3\%$ and the turbulence intensity in the test section was 0.3%.

Due to the limiting size of the working section, a scale plastic model of a football was created using rapid prototyping (66 mm in diameter compared to 218 mm for a full size football). The model had a generic seam pattern, commonly used by many football manufacturers, which consisted of 20 hexagonal and 12 pentagonal patches (see Figure 1). After the rapid prototyping process the ball model was sanded and polished to create a smooth surface, as would be found for a real ball. This resulted in a test section blockage of only about 4 % (based on cross-sectional area) which is negligible for a 30 % open area slotted working section (Macha *et al.* [12]), and therefore blockage corrections were not applied.

The effect of velocity on the drag of a non-spinning ball was first measured by mounting the ball on an 'L'-shaped sting that was attached to a three-component balance manufactured by TEM Engineering Ltd. The force balance had a resolution of 0.018 N and was capable of measuring up to 10 N. A shroud was mounted in front of the sting in an attempt to reduce the drag force due to the sting itself (see Figure 1).

The air speed in the working section of the wind tunnel was varied from 20 m/s (the minimum consistent speed achievable) up to 70 m/s and back down again. The drag and lift forces experienced by the ball-sting arrangement were measured using the force balance at regular intervals and three runs of tests were carried out, with the ball model mounted in three different orientations (the ball being rotated 90° about the sting between each run of tests).

When this testing was complete, the drag acting solely on the sting, the 'tare' drag, was measured. This was done by mounting a 66 mm diameter sphere with a hole larger than the diameter of the sting, in the same place as the football model had been, using supports from the side. It was mounted so that no contact was made between the sphere and the sting and the tests were run again to measure the tare drag experienced by the sting alone. The tare drag was found to be quite high, accounting for almost half the total drag measured on the ball-sting arrangement and although this amount of tare drag was unexpected, it was thought to be due to the relatively large cross-section of the sting, which had been designed to be

sturdy and prevent any unwanted vibrations in the ball-sting arrangement. Work on tennis ball aerodynamics, since this research was carried out, reduced the tare drag slightly by redesigning the shrouding of the sting [13].

The measured drag forces were adjusted for tare drag and can be seen in Figure 2. Generally, the drag force increases with air flow speed, as one would expect. However, there is a small fluctuation in the drag force at low speeds due to transition. The data were based on mean values from around 300 force measurements sampled over 10 s for each test, which led to an average standard error of 1.3 %. There was found to be no major effect on the drag due to ball orientation as each run of tests gave very similar results. A mini-football was also mounted in the wind tunnel and tests repeated in three orientations. The football used was a smaller version of the Adidas Fernova design with the same generic seam pattern as the rapid prototyped ball and was 140 mm in diameter (compared to 218 mm for a full size ball). The data were again adjusted for tare drag and the resulting drag force on the ball was found to vary with the square of the air flow speed. No major effect was observed due to the orientation of the ball.

To predict the drag forces that a full size football would experience during flight, the drag data from the scale model and the mini football were converted to drag coefficient data using equation 1 and plotted against Reynolds number (see Figure 3).

$$F_d = \frac{1}{2} C_d \rho A v^2 \quad (1)$$

(where, F_d is the drag force, ρ is density of the air, A is projected area of the ball, C_d is the drag coefficient, v is the velocity of the air).

In a real match situation a football has a velocity range of around 5 m/s (11 mph) to 32 m/s (70 mph), which in normal atmospheric conditions equates to a range in Reynolds number of approximately 70,000 to 500,000. The data in Figure 3 show a sharp drop in drag coefficient from about 0.5 to 0.2 over a range in Reynolds number from about 90,000 to 130,000 and then a slight increase over the rest of the range. This sharp drop is due to a transition in the behaviour of the air in the boundary layer, surrounding the ball. At low Reynolds number (and therefore, low speeds) the boundary layer is laminar. An example of this situation can be seen in Figure 4a, which shows a jet of smoke travelling around the ball model when the Reynolds number is 90,000 (equivalent to 6.1 m/s for a full size football). The boundary layer

separates quite early and there is a large wake behind the ball and consequently, a large drag coefficient. As the speed of the air is increased, the flow in the boundary layer becomes turbulent and mixing occurs with the surrounding air. This gives the boundary layer sufficient energy to travel further round the ball and separate later. This effect can be seen in Figure 4b, which shows a jet of smoke travelling around the ball model for a Reynolds number of 130,000 (equivalent to 9.1 m/s for a full size football). There is less wake behind the ball and the drag coefficient is reduced.

Also shown on Figure 3 are the results of other aerodynamic studies on spheres; dimpled ball data from Bearman and Harvey [3] and smooth sphere data from Achenbach [7]. Achenbach [8] found that an increase in surface roughness had the effect of moving the transition from laminar to turbulent behaviour to a lower Reynolds number. A similar effect has been found for sports balls that have surface roughness [6]. It is well known that dimples on golf balls help to reduce drag by moving the transition point to lower Reynolds number so that the flow around a golf ball is turbulent for more of its flight. Judging by Figure 3, the seam pattern on a football, seems to have a similar effect, but not to such a great extent. If a football were completely smooth, according to Achenbach's data, it would have a higher drag coefficient for most of the range of Reynolds numbers, seen in play.

4. MAGNUS FORCE MEASUREMENTS

In order to measure Magnus forces for footballs, the third scale football model was mounted in the wind tunnel, by horizontal stings from both sides, as shown in Figure 5, in order to allow spin to be applied. The stings had a stepped profile to reduce the interference around the ball whilst maximising the strength of the sting and minimising the vibration of the ball. Each sting had a diameter of 3.5 mm and extended up to 35 mm away from each side of the ball. Preliminary testing showed that this is the critical area in which the interference of the air flow over the ball must be minimised. A further 85 mm of the sting was shrouded by an elliptical shroud with a height and width of 20 mm and 35 mm respectively, to reduce the load acting on the stings. This resulted in a test section blockage of only about 6 % and as for the non-spinning tests, blockage corrections were not applied.

The horizontal supports allowed the ball to be spun at up to 3,000 rpm in both directions (top spin and back spin), the axles being driven by an electric motor some way out of the airflow. Force balances in the

supports were used to measure the drag force acting on the ball-axle arrangement and the lift force generated by the Magnus effect. Each balance was mounted on vertical struts which were located outside the slotted wall test section and were bespoke units supplied by Aerotech ATE Ltd. Each channel of the two-component force balance was sampled and routed into dedicated sensor units which provided digital, high-resolution output data. The force balance had been previously calibrated by Aerotech and was checked prior to the commencement of each test. The magnitude of the uncertainty in the measurement of load was of the order of 10^{-4} N. Tests were carried out at a range of wind speeds from 20 m/s to 60 m/s and a range of spins $\pm 2,800$ rpm (150 rad/s). The Magnus force data, F_m were based on averages from 50 measurements sampled over 10 s and were found to have an average standard error of 0.007 N (2.1 %). The force data were converted to Magnus coefficients, C_m , in a similar way to that used previously for the drag coefficients (see equation 1). Hence, the following equation was used with a sign convention of positive lift (and Magnus coefficient) for positive back spin.

$$F_m = \frac{1}{2} C_m \rho A v^2 \quad (2)$$

Past studies of the Magnus effect of sports balls have found it convenient to plot Magnus coefficient against a spin parameter, v_{eq}/v , where v_{eq} is the equatorial velocity of the ball surface, relative to its centre (equal to $r\omega$, the radius multiplied by the spin) and v is the ball velocity relative to the air [5]. These data are shown in Figure 6, together with standard errors that varied with Reynolds number (on average, around 10 %). It can be seen that for high values of Reynolds number ($Re = 210,000$, $Re = 170,000$), the Magnus coefficient generally increased with the spin parameter. This was a similar relationship to that found by Watts and Ferrer [5] for baseballs (see Figure 6) and can be generally explained by the conventional Magnus effect. Here the separation of the boundary layer is enhanced on the advancing side of the ball, but delayed on the retreating side of the ball causing an asymmetric pressure distribution and a resultant force acting in the direction of the advancing side [1]. The faster the ball spins (relative to its speed), the greater the force and the Magnus coefficient increases. This effect happens at post-critical Reynolds numbers when the boundary layer on both sides of the ball is turbulent.

However, a phenomenon known as *Reverse Magnus* effect can also be seen in Figure 6 for the football tests at lower Reynolds number ($Re = 90,000$). For low values of spin parameter, a negative Magnus coefficient was measured suggesting that a football travelling at low speed with a small amount of top spin would actually experience a slight upwards force. Reverse Magnus occurs when there is a difference in the type of boundary layer on either side of the ball. On the advancing side, the effective Reynolds number (relative to the ball surface) is high enough for turbulent behaviour and separation occurs relatively late. However, on the retreating side, the effective Reynolds number is somewhat lower allowing stable, laminar behaviour in the boundary layer. This separates early and the asymmetric pressure distribution now causes a resultant force to act in the direction of the retreating side [5]. The minimum value of Magnus coefficient was measured to be around -0.3 . This effect is also found with smooth spheres, as shown by the Maccoll [14] data in Figure 5. Differences between the Magnus coefficient data for footballs and that for baseballs from Watts and Ferrer [5], at relatively low Reynolds numbers, can be explained by the difference in ball geometry (which may encourage transition more readily for baseballs, so that no reverse Magnus effects were measured).

Mathematical fits were applied to the data to allow a Magnus coefficient for a generic football to be predicted for any Reynolds number and spin parameter. The equation used for this purpose was

$$C_m = a(1 - e^{-bS_p}) - cS_p(1 - e^{-dS_p}) \quad (3)$$

(where S_p is the spin parameter v_{eq}/v).

The coefficients a , b , c and d all vary with Reynolds number as shown in Table 2 and the calculated fits for these data are shown using dotted lines in Figure 5. **Note:** some care should be taken if extrapolating these fits into regions far away from the values of Reynolds number and spin parameter tested (i.e., outside the ranges of $90,000 < Re < 290,000$ and $0.0 < Sp < 0.5$).

5. EFFECT OF SPIN ON DRAG

The drag forces measured during the spinning ball tests were used to examine the effect of spin on drag. The drag force data were based on averages from 50 measurements and gave an average standard error of

0.01 N (0.5 %). The measurements of drag force with zero spin were compared with data from the experiments that used a rear mounted sting (see earlier section) to calculate the effect of the tare drag, due to the side supports. All the data were adjusted for tare, and drag coefficients then calculated which can be seen in Figure 7, together with standard errors that varied with Reynolds number (on average, around 1.7 %). The data suggests that for footballs, the main effect on drag is that due to Reynolds number, not spin parameter. The slight variation due to spin parameter was found to be of a similar order to that found for dimpled balls by Davies [15] and Bearman and Harvey [3], but of a different form, due to the differing geometry.

6. AERODYNAMICS OF A SMOOTH SPHERE

To examine the effects of seams being present on a football, the aerodynamics of a smooth sphere were considered, for comparison. The non-spinning and spinning ball experiments were repeated for a 66 mm diameter smooth sphere and drag and Magnus coefficients were calculated for a range of velocities and spin rates.

The drag coefficient data for a non-spinning smooth sphere, according to our experiments using the rear mounted sting, were slightly higher than those of Achenbach [6] (see Figure 3) and for most of the Reynolds numbers typically found in play for football ($Re = 70,000$ to $500,000$), they remained constant at around $0.53 (\pm 0.02)$. The high drag coefficient suggests that the flow regime here is sub-critical, which is in accordance with the Achenbach data. For the spinning smooth sphere tests (using side supports) the drag coefficient data was found to be, on average about $0.54 (\pm 0.04)$ for all test conditions (see example data in Figure 7). For tests using the side-support arrangement, but with zero spin, drag coefficients were found to be constant at around $0.53 (\pm 0.02)$ for all Reynolds numbers tested ($Re = 90,000$ to $260,000$). The consistency in drag coefficient for a non-spinning ball, using both experimental arrangements, lends confidence to the methodology used, especially considering that previous studies have found that the support arrangement used can have an effect on the measured drag coefficient [13].

When the Magnus forces were measured for the spinning smooth spheres, great variation was found at low values of spin parameter v_{eq}/v . The data suggested that the forces experienced on the sphere for the

same spin parameter were either positive or negative, depending on the history of spin applied (i.e. what would be expected due to conventional Magnus or reverse Magnus effects). Applying increasing spin was found to lead to transition and for a particular spin, the force experienced by the sphere was observed to ‘flip’ and act in the opposite direction. However, when the spin was decreased again the force ‘flipped back’ at a different value of spin. It is thought that this lack of repeatability was due to inconsistency in the boundary layer separation of smooth spheres, which is well-recognised and was commented on by Achenbach [8]. This phenomenon will be investigated further in future studies, but what was clear was that at higher values of spin parameter (0.3 and above) and higher Reynolds number (170,000 and above), the behaviour became more consistent and reverse Magnus behaviour was always observed. At these higher values of Reynolds number, a Magnus coefficient of around $-0.31 (\pm 0.02)$ was found to be relatively constant for different values of spin parameter, with any variation mainly due to Reynolds number (see Figure 6).

7. KICK SIMULATIONS

Now that a complete set of relationships had been found for the effect of velocity and spin on drag and Magnus force experienced by a football, a number of kicking situations could be simulated. This was achieved by using a three-dimensional trajectory simulation model that calculated the forces experienced by the ball at discrete time intervals during its flight using the equations 1 and 2 (a time step of 2.5 ms was used). The coefficients C_d and C_m were calculated at each time interval based on the mathematical fits of the wind tunnel data, as the velocity of the ball changed and consequently so did the Reynolds number and the spin parameter. The spin was assumed to remain in the horizontal plane throughout the flight with no significant degradation.

According to the Asai *et al.* [9] data in Table 1 a football struck in its centre would have a launch velocity of 26 m/s and a spin of 1.9 rev/s (12 rad/s), clockwise from above. According to the aerodynamic study of footballs, this would lead to an initial drag coefficient of 0.22 (for a Reynolds number of 390,000). For simplicity, the Magnus coefficient here was taken as 0.0 due to the relatively low value of spin which, combined with the relatively high launch velocity, led to a spin parameter of only 0.05. The three-

dimensional trajectory model was used to simulate this kick if it was taken 18 m away from the goal, 6 m off-set to the right of the centre of the goal, with a goal being scored in the top left-hand corner (“Kick a”, Figure 8). The simulation showed that the flow around the ball was turbulent throughout so the drag coefficient remained relatively constant.

If the foot impact location was off-set by 80 mm to the right (see Table 1), this would give a launch velocity of 18.5 m/s and a spin of 10.2 rev/s (64 rad/s), anti-clockwise from above. The initial drag and Magnus coefficients for this type of kick were calculated to be 0.22 and 0.32 respectively for a Reynolds number of 270,000 and a spin parameter of 0.43. This kick, “Kick b”, was simulated to score a goal in the top left-hand corner, from the same position as Kick a. The drag coefficient was again found to remain the same throughout and the Magnus coefficient also remained fairly constant due to the combined effect of reducing Reynolds number and increasing spin parameter. For this simulation, the value of spin was assumed to stay constant throughout. Spin degradation has not been examined in detail for footballs, but using data from a previous study relating to golf balls [16], a worst-case scenario calculation led to a decrease in spin of only 1 % during Kick b.

In order for both free kicks to be successful, the launch angle had to be altered in the same way that a player would do instinctively for a choice of kick. The trajectory plots in Figure 8 show how Kick b curves to a much greater extent than Kick a, due to the sideways Magnus force. However, because the ball is travelling more slowly for Kick b (by approximately 30%), it must be launched higher into the air to reach the same point as Kick a. The total time required to score is 0.9 s for Kick a and 1.4 s for Kick b. This demonstrates the choice of strategy available to a player when taking such a kick. The ball can be struck centrally to gain as much velocity as possible or it can be struck off-set from the centre to put spin on the ball, thus allowing the ball to be bent round a defensive wall of players. It is thought that in an actual game situation, an experienced player would be able to strike the ball with sufficient force to gain high velocity *and* spin.

To examine the effect of the seams, the curving kick, Kick b was simulated again using the aerodynamic coefficients found for a smooth sphere. It was assumed that as the Reynolds number at launch for this kick was 270,000 and the spin parameter was 0.43, the drag and Magnus coefficients would remain

constant throughout flight at values of 0.53 and -0.33 , respectively (based on the wind tunnel measurements). This kick, “Kick c”, is shown in Figure 9 and it is clear that a perfectly smooth football with no seams would behave in a completely different way to one that contains seams. Kick c experiences a reverse Magnus effect, which means that even though spin is applied in an anti-clockwise direction (when viewed from above), the ball curves to the right. Increased drag force due to laminar behaviour in the boundary layer throughout its flight, means that the smooth ball has not reached the goal, by the time the football has scored, (1.4 s after being launched with the same conditions).

This demonstrates that the presence of seams on a football mean that for most dynamic conditions, the flow regime is super-critical and turbulent boundary layer behaviour reduces the drag on the ball. The increased roughness due to the seams also means that the Magnus forces experienced are generally consistent and a conventional Magnus effect is found for the majority of the dynamic conditions seen in play. A very smooth football would undoubtedly perform in a very strange way, often curving in the opposite direction to that expected by players. Further research is now required to investigate what effect the depth, number and pattern of seams has on the drag and Magnus forces experienced by spinning footballs, under various atmospheric conditions. This will aid the future design of balls for optimum playing performance.

8. CONCLUSIONS

Wind tunnel measurements of football shaped spheres showed the effect of a transition from laminar to turbulent behaviour in the boundary layer, causing a low drag coefficient at high Reynolds number. For spinning footballs, the Magnus effect was observed and it was found that reverse Magnus effects were possible at low Reynolds numbers. Measurements on spinning smooth spheres found that laminar behaviour lead to a high drag coefficient for a large range of Reynolds numbers and Magnus effects were inconsistent, but generally showed reverse Magnus behaviour at high Reynolds number and spin parameter. Some of these phenomena have been demonstrated successfully using Computational Fluid Dynamics [17] but further work in this area could be carried out to simulate the effects of the sting and axle arrangements in the wind tunnel experiments.

Trajectory simulations demonstrated that a football that is struck in the centre will follow a near straight trajectory, dipping slightly before reaching the goal. A football that is struck off centre will bend before reaching the goal, but will have a significantly longer flight time. A smooth ball that is struck off centre will have a longer flight time still, due to increased drag and it will curve in the opposite direction, due to reverse Magnus effects. The presence of seams was found to encourage transition, resulting in reduced drag and a more predictable Magnus behaviour for a conventional football, compared to a smooth sphere. It is hoped that this understanding and methodology can be used to predict the behaviour of new designs of football, with different seam depths and patterns.

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REFERENCES

- [1] **Mehta, R.D.** Aerodynamics of sports balls. *Ann. Rev. Fluid Mech.*, 1985, **17**, 151-189.
- [2] **Massey, B. S.** *Mechanics of Fluids*, 6th edition, 1989 (Chapman & Hall, London).
- [3] **Bearman, P.W. and Harvey, J.K.** Golf ball aerodynamics. *Aeronautical Quarterly*, 1976, **27**, 112-122.
- [4] **Haake, S.J., Chadwick, S.G., Dignall, R.J., Goodwill, S., and Rose, P.** Engineering tennis – slowing the game down. *Sports Engineering*, 2000, **3**, 131-144.
- [5] **Watts, R.G. and Ferrer, R.** The lateral force on a spinning sphere: Aerodynamics of a curveball. *Amer. J. Physics*, 1987, **55**, 40-44.
- [6] **Mehta, R.D. and Pallis, J.M.** Sports ball aerodynamics: Effects of velocity, spin and surface roughness. In *Materials and Science in Sports*, Proceedings of Symposium sponsored by TMS (The Minerals, Metals and Minerals Society), San Diego, 2001, pp. 185-197 (TMS press).
- [7] **Achenbach, E.** Experiments on the flow past spheres at very high Reynolds numbers. *J. Fluid Mech.*, 1972, **54**, 565-575.

- [8] **Achenbach, E.** The effects of surface roughness and tunnel blockage on the flow past spheres. *J. Fluid Mech.*, 1974, **65**, 113-125.
- [9] **Asai, T., Carré, M. J., Akatsuka, T. and Haake, S. J.** The Curve Kick of a Football I: Impact with the Foot. *Sports Engineering*, 2002, **5**, 183-192.
- [10] **Carré, M. J., Asai, T., Akatsuka, T. and Haake, S. J.** The Curve Kick of a Football II: Flight Through the Air. *Sports Engineering*, 2002, **5**, 193-200.
- [11] **Waudby-Smith, P.M. and Rainbird, W.J.** Some principles of automotive aerodynamic testing in wind tunnels with examples from slotted wall test section, 1985, SAE paper no. 850284.
- [12] **Macha, M., Buffington, R. and Henfling, J.** Slotted-wall blockage corrections for disks and parachutes, *Journal of Aircraft*, 1991, **28(9)**, 592-597.
- [13] **Goodwill, S.R., Chin, S.B. and Haake, S.J.** Wind tunnel testing of spinning and non-spinning tennis balls, *J. Wind Engineering & Industrial Aerodynamics*, 2004, **92(11)**, 935-958.
- [14] **Maccoll, J.** Aerodynamics of a spinning sphere, *J. Royal Aeronautical Society*, 1928, **32**, 777-791.
- [15] **Davies, J. M.** The aerodynamics of golf balls. *J. Applied Physics*, 1949, **20**, 821-828.
- [16] **Smits, A. J. and Smith, D. R.** A new aerodynamical model of a golf ball in flight. In *Science and Golf II*, Proceedings of the World Scientific Congress of Golf, 1994, pp. 340-346 (E & FN Spon, London).
- [17] **Carré, M. J., Goodwill, S.R. and Haake, S. J.** Understanding the aerodynamics of a spinning soccer ball. In *The Engineering of Sport 5*, Proceedings of the 5th International Conference on the Engineering of Sport, Davis CA, 2004, Vol 1, pp. 70-76 (ISEA, Sheffield, UK).

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List of Captions

Table 1. Launch condition data adapted from Asai *et al.* [9].

Figure 1. Ball-sting arrangement used for the non-spinning tests, using scale model of a football (reproduced from *Biomedical Engineering Principles in Sports*, Chapter 13, Fig. 13.18 with kind permission of Springer Science and Business Media).

Figure 2. Drag force plotted against air flow speed for non-spinning scale model of a football.

Figure 3. Wind tunnel drag coefficient data plotted against Reynolds number, compared with data for other spheres.

Figure 4. Smoke flow around the scale football model showing: (a) laminar flow at $Re = 90,000$; and (b) turbulent flow at $Re = 130,000$ (reproduced with the kind permission of the International Sports Engineering Association).

Figure 5. Magnus coefficient data for spinning balls over a range of velocities (standard errors shown as error bars).

Figure 6. Drag coefficient data for spinning balls over a range of velocities (standard errors shown as error bars).

Table 2. Equations for the coefficients used to predict Magnus coefficient.

Figure 7. Predictions for the flight of two free kicks based on varying foot impact location.

Figure 8. Predictions for the flight of two curving free kicks based on type of ball.

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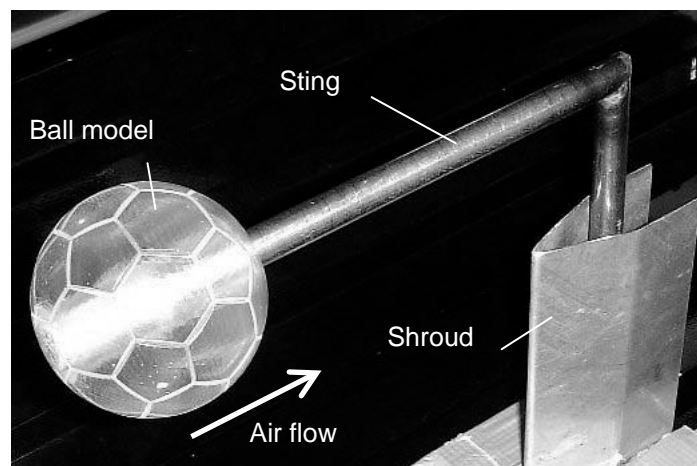
Table 1. Launch condition data adapted from Asai *et al.* [9].

Impact location	Ball launch speed (m/s)	Launch spin (rev/s), anti-clockwise, from above
160 mm left of centre	6.2	-10.6
120 mm left of centre	15.2	-11.0
80 mm left of centre	20.5	-8.2
40 mm left of centre	23.5	-3.5
central	26.0	-1.9
40 mm right of centre	23.1	4.0
80 mm right of centre	18.5	10.5
120 mm right of centre	11.2	16.2
160 mm right of centre	0.0	0.0

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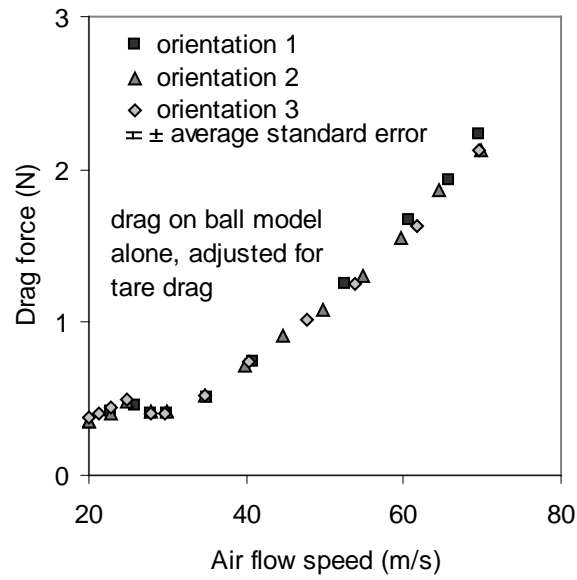
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Figure 1. Ball-sting arrangement used for the non-spinning tests, using scale model of a football (reproduced from *Biomedical Engineering Principles in Sports*, Chapter 13, Fig. 13.18 with kind permission of Springer Science and Business Media).



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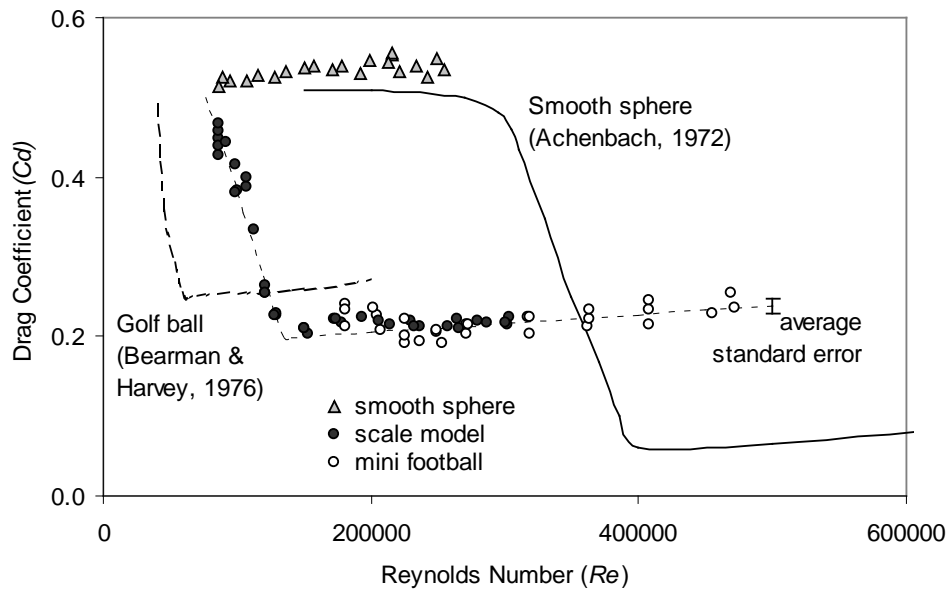
Figure 2. Drag force plotted against air flow speed for non-spinning scale model of a football.



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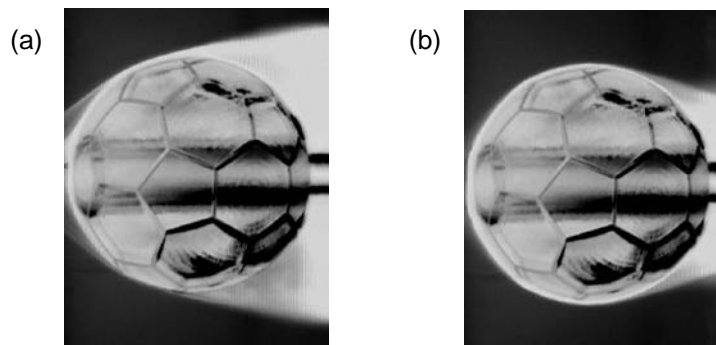
Figure 3. Wind tunnel drag coefficient data plotted against Reynolds number, compared with data for other spheres.



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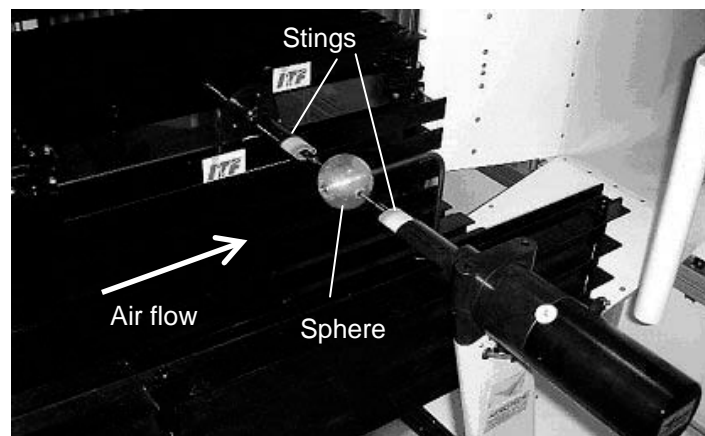
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Figure 4. Smoke flow around the scale football model showing: (a) laminar flow at $Re = 90,000$; and (b) turbulent flow at $Re = 130,000$ (reproduced with the kind permission of the International Sports Engineering Association).



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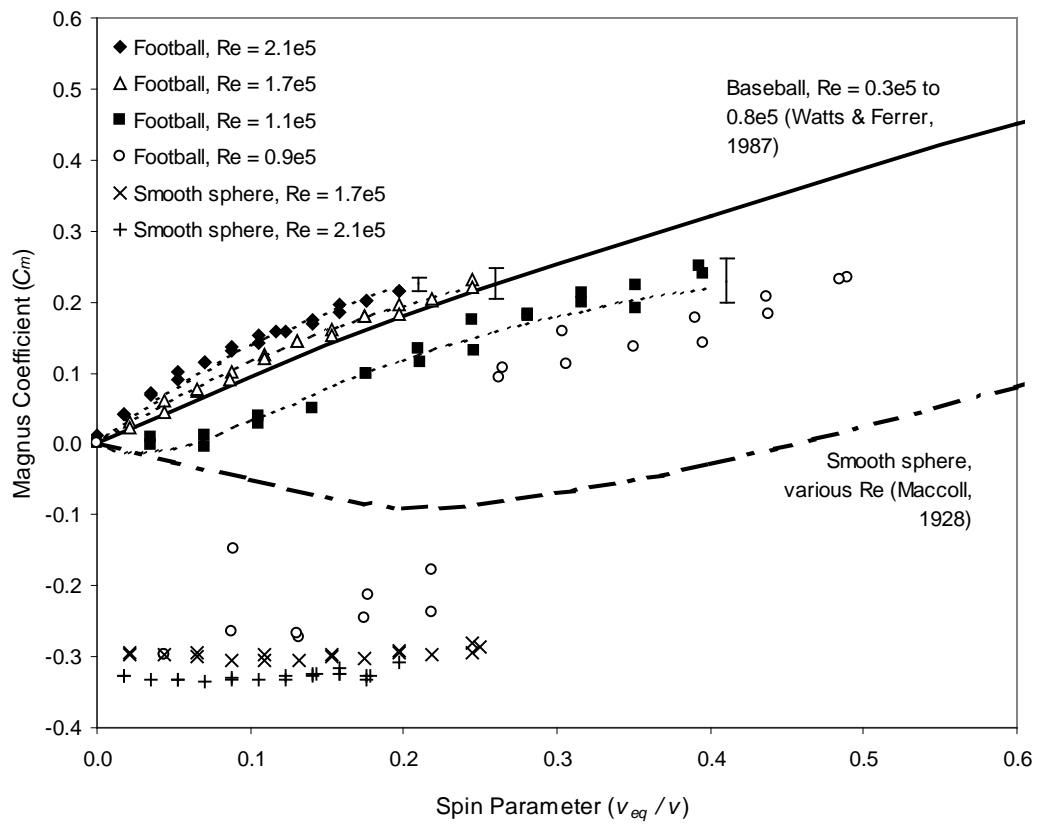
Figure 5. Ball-sting arrangement used for the spinning tests (shown with smooth sphere).



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Figure 6. Magnus coefficient data for spinning balls over a range of velocities (standard errors shown as error bars).



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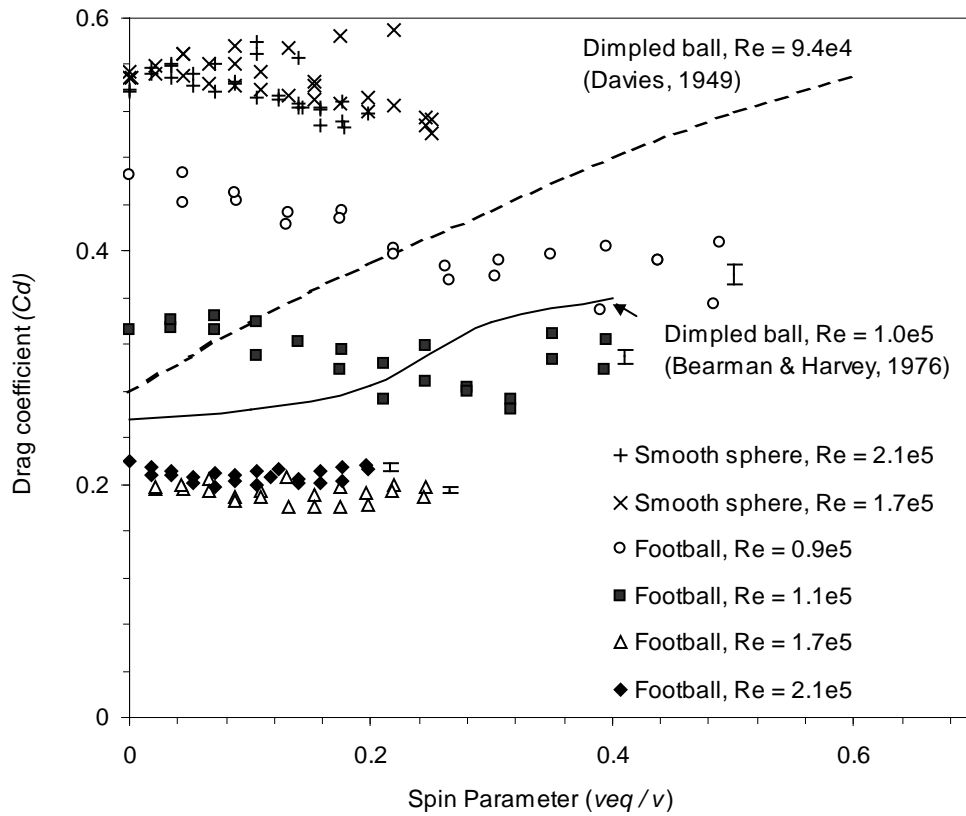
Table 2. Equations for the coefficients used to predict Magnus coefficient.

Coefficient	Equation
<i>a</i>	0.35
<i>b</i>	$Re * 0.0000239$
<i>c</i>	$12150 * e^{(-0.0000822 * Re)}$
<i>d</i>	$Re * 0.000142$

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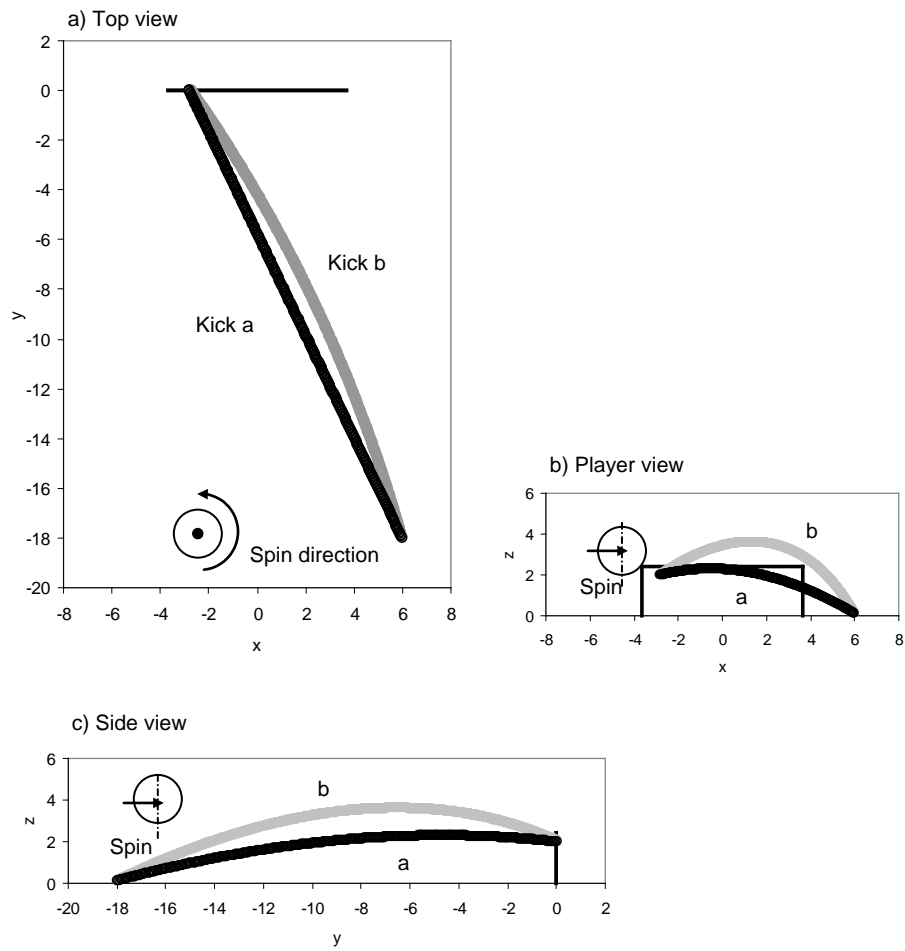
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Figure 7. Drag coefficient data for spinning balls over a range of velocities (standard errors shown as error bars).



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Figure 8. Predictions for the flight of two free kicks based on varying foot impact location.



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Figure 9. Predictions for the flight of two curving free kicks based on type of ball.

