# The curve kick of a football II: flight through the air

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## Abstract

The purpose of this study is to assess the fundamental characteristics that cause a football to spin in a curve ball kick due to impact conditions, and then to examine how the change in spin affects the flight of the ball.

Two experimental trials were carried out to examine the aerodynamic properties of footballs during flight. In the first trial, a football was projected with no spin at varying launch velocities and the trajectory of each flight measured and analysed. A drag coefficient was calculated for each test, based on a trajectory model. The second trial involved a football being fired with the same launch velocity, but varying spin conditions (spin axis horizontal in all cases). Again, the trajectory of each flight was measured and drag and lift coefficients were calculated. This information was used to simulate three typical game situations and the effects of foot impact offset distance and weather conditions were examined.

*Keywords*: aerodynamics, ball trajectory, football, soccer

## Introduction

This part of the study of a curve kick in football focuses on what effect the generation of spin has on the flight of a ball for a typical game situation. The aerodynamics of many sports balls (golf, cricket, tennis, baseball, volleyball) have been studied previously (Bearman & Harvey 1976, Mehta 1985, Haake *et al*. 2000, Watts & Ferrer 1987 and Mehta & Pallis 2001). The results show that the drag and lift coefficients are functions of velocity, spin and surface roughness. It is likely, therefore, that the seams of a football would play a significant part in the flight of a ball through the air. Little work has been published on footballs and therefore, measurements were taken from controlled football trajectories in order to calculate drag and lift coefficients. These could then be used to simulate the flight of a football for a variety of launch conditions.

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## Study of ball flight

### Trial 1: No applied spin over range of velocities

*Test method*

The football used for Trial 1 was a Mitre *Ultimax* (215 mm diameter, 420 g, when inflated to 75.8 kPa). The ball was launched with no spin at approximately 15° to the ground using a specially built ball projection machine. As it was very difficult to keep the orientation of the ball seams constant for all the tests, a random seam orientation was used. Launch velocities varied from 17 m s$^{-1}$ (37 mph) to 31 m s$^{-1}$ (68 mph) and provided a good range of data around the mean value of ball speed of 25.4 m $s^{-1}$, produced by the subjects discussed previously (Asai *et al.* 2002).

A diagram of the experimental setup, as seen from above is shown in Fig. 1. The ball trajectories were filmed using two high speed video cameras (Kodak MotionCorder Analyzer SR-500, San Diego, CA). The first camera (camera 1) was focused close to the exit of the projection machine to measure the launch speed and angle of trajectory. It was set-up to record at a rate of 240 frames $s^{-1}$ with a capture time of 1/1000 s. A typical set of images can be seen in Fig. 2 (they have been superimposed). A pattern was drawn on the ball with indelible ink, to allow any displacements of the ball to be measured from the images.

The second camera (camera 2) filmed the progress of each ball's flight over a horizontal distance of 10 m. The purpose of this camera was to monitor the shape of the trajectory for each ball. The camera was set-up to record at a rate of 120 frames $s^{-1}$ with a capture time of 1/500 s. A typical set of superimposed images from camera 2 can be seen in Fig. 3.

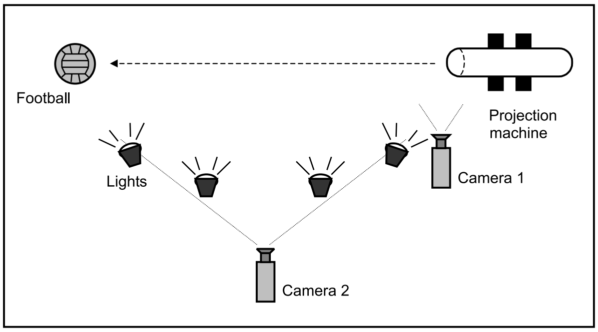


**Figure 1** Diagram of experimental set-up.

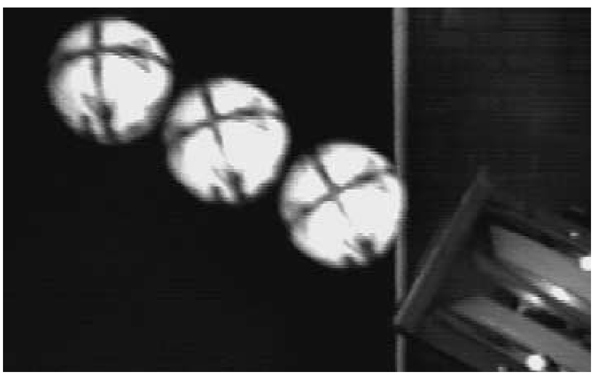

**Figure 2** Typical view from camera 1.

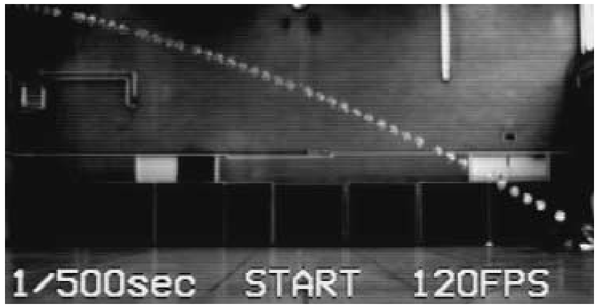


**Figure 3** Typical view from camera 2.

A dedicated image analysis program (Richimas v1.0) was then used to collect co-ordinate data from both cameras, which could be used to calculate the launch conditions and trajectory for each test.

*Data analysis*

Co-ordinate and time data were used to produce trajectory plots as well as the change in the horizontal ($x$) and vertical ($y$) displacements over time. The raw data was then used to produce quadratic fits of the $x$ and $y$ plots over time, using the following equations.

$$x = at + bt^2 \quad (1)$$

$$y = ct + dt^2 \quad (2)$$

An example of this process can be seen in Fig. 4. Once the quadratic coefficients, $a$, $b$, $c$ and $d$ had been found for each test, these fitted trajectories could be compared with a simulation of a ball in flight to determine the lift and drag coefficients for the ball.

*Trajectory simulation*

A step-by-step model, similar to that used by Mehta (1985) was designed for the simulation of a football in flight. The model assumed that the ball is subjected to two forces, $F_d$ and $F_l$, caused by drag and lift as well as $mg$ caused by its weight. A force

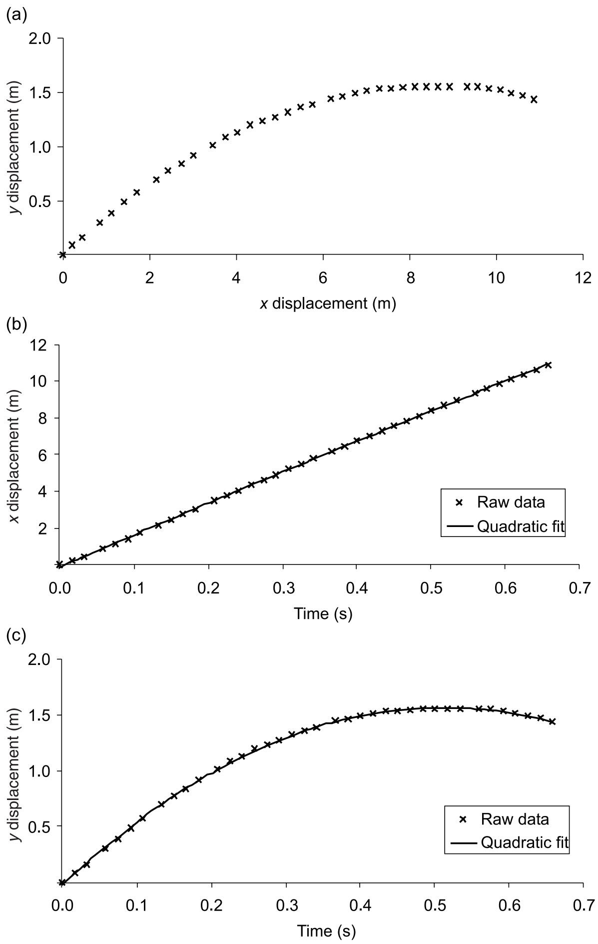


**Figure 4** Typical trajectory (a), $x$ displacement vs. time (b), $y$ displacement vs. time (c).

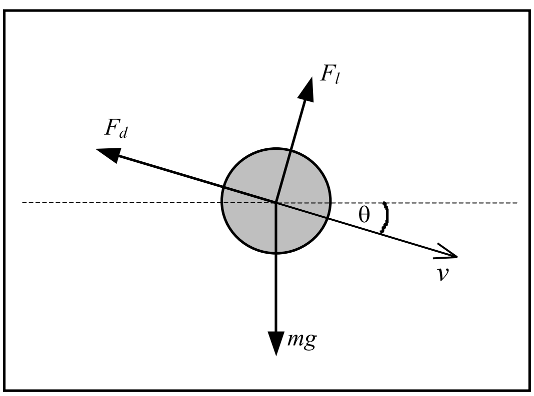


**Figure 5** A schematic diagram of the forces acting on a football.

diagram of a ball travelling with a velocity $v$ at an angle $\theta$ to the ground under these conditions is shown in Fig. 5.

The equations of motion can be derived by resolving the resulting accelerations vertically and horizontally to give

$$m\frac{\mathrm{d}}{\mathrm{d}t}(v\sin\theta) = mg - F_\mathrm{d}\sin\theta - F_\mathrm{l}\cos\theta \quad (3)$$

$$m\frac{\mathrm{d}}{\mathrm{d}t}(v\cos\theta) = -F_\mathrm{d}\cos\theta - F_\mathrm{l}\sin\theta \quad (4)$$

These equations can then be re-written to deal with finite differences using

$$m\delta(v\sin\theta) = \delta t[mg - F_\mathrm{d}\sin\theta - F_\mathrm{l}\cos\theta] \quad (5)$$

$$m\delta(v\cos\theta) = \delta t[-F_\mathrm{d}\sin\theta - F_\mathrm{l}\cos\theta] \quad (6)$$

The forces $F_\mathrm{d}$ and $F_\mathrm{l}$ were assumed to vary with velocity squared according to the following equations

$$F_\mathrm{d} = \tfrac{1}{2}C_\mathrm{d}\rho A v^2 \quad (7)$$

$$F_\mathrm{l} = \tfrac{1}{2}C_\mathrm{l}\rho A v^2 \quad (8)$$

(where, $\rho$ is density of air, $A$ is projected area of ball, $C_\mathrm{d}$ is the drag coefficient and $C_l$ is the lift coefficient.)

For the purposes of this model, it was assumed that the drag and lift coefficients remained constant throughout the trajectory. Given values of $\rho$, $A$, $C_\mathrm{d}$ and $C_\mathrm{l}$ and using initial values of $v$ and $\theta$, the ball trajectory was calculated using a step-by-step process with a small time period, $\delta t$.

For Trial 1 a trajectory simulation was carried out using a time step of 2.5 ms and an initial guess for $C_\mathrm{d}$ being equal to 0.3 and $C_\mathrm{l}$ being equal to 0.0 (as there was no spin on the ball). An iterative solving algorithm was then used to determine $C_\mathrm{d}$ by minimizing the difference between the simulated trajectory and the measured values. The algorithm was Microsoft Excel Solver, which uses a generalized, reduced gradient (GRG2) non-linear optimization code.

*Results*

A typical simulated trajectory is shown in Fig. 6, compared with the measured trajectory for a drag

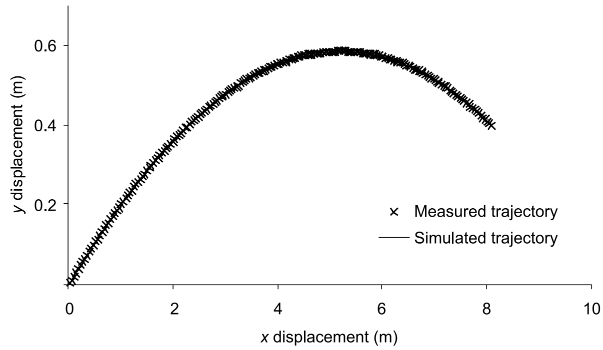


**Figure 6** Measured and simulated football trajectory for a non-spinning football with an initial velocity of 16.9 m $s^{-1}$.

coefficient of 0.11 and for a non-spinning ball with an initial velocity of 16.9 m $s^{-1}$. It can be seen that the correspondence between the theoretical and experimental data is very good. The calculated drag coefficients are plotted with launch velocity as shown in Fig. 7 (a line of best fit has been added). It can be seen that as the launch velocity increased from 15 to 35 m $s^{-1}$, the drag coefficient also increased from around 0.05 to 0.35. In aerodynamic studies that include a transition in the boundary layer from laminar to turbulent behaviour, such large changes in drag coefficient are not uncommon. Not surprisingly, the calculated values of lift coefficient for the non-spinning tests were all found to be close to 0.0 (the average for all the tests was 0.02).

### Trial 2: Varying spin, constant velocity

*Test method*

Testing was repeated using a constant launch velocity of 18 m $s^{-1}$, but with imparted spin varying from 211 rad $s^{-1}$ of top spin to 224 rad $s^{-1}$ of back spin (spin axis remaining horizontal in all cases). The football used for Trial 2 was a Mitre *Max* (218 mm diameter, 430 g, when inflated to 75.8 kPa). Data were collected using the same system as Trial 1 and values of drag and lift coefficient were calculated using the trajectory simulation model, as before.

*Results*

Figure 8 shows the variation in drag and lift coefficient with increasing spin. In order to collate the data, only the moduli have been plotted. In other words, a negative lift coefficient, as found with top spin, has been given the same positive value as a lift coefficient found with back spin.

It can be seen that both the drag and lift coefficients increased non-linearly with spin. The lift coefficient rapidly increased from zero as the spin was increased to 100 rad $s^{-1}$, but then became

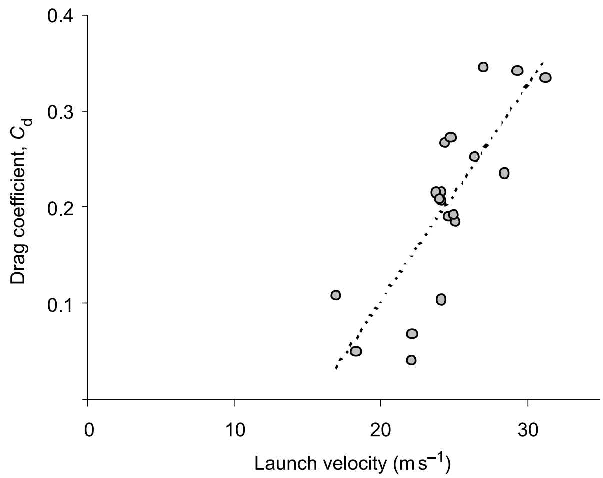


**Figure 7** Drag coefficient varying with launch velocity for non-spinning balls.

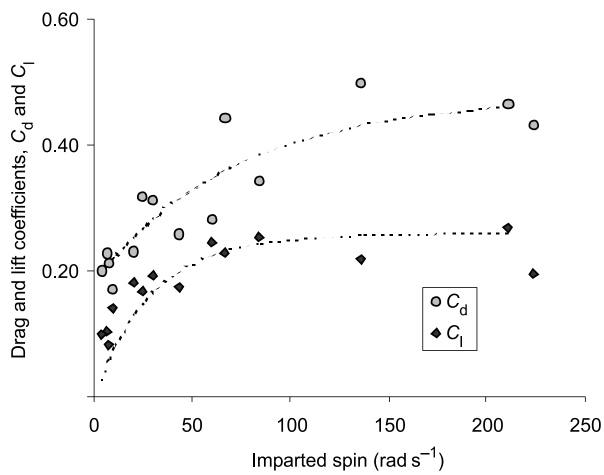


**Figure 8** Drag and lift coefficient vs. imparted spin for balls projected at 18 m $s^{-1}$.

constant at around 0.26. The drag coefficient appeared to increase steadily from 0.2 at 0 rad $s^{-1}$ of spin to 0.5 at 240 rad $s^{-1}$. Curves were fitted to the data (see dotted lines in Fig. 8) which allowed a smoother data set to be used to predict how the trajectory of a ball would be affected by varying the imparted spin. The trajectory model was used to simulate a set of trajectories based on the same launch velocity (18.4 rad $s^{-1}$) and angle (24°). All trajectories were calculated for a flight time of 10.4 s and are shown in Fig. 9. The simulations show that a significant effect on the flight of a football can be achieved by changing the spin alone. For balls fired with no spin, a typical parabolic trajectory is seen. When a large amount of top spin is imparted, excessive dipping in flight is caused by a combination of negative lift and increased drag. When a certain amount of back spin is imparted (up to approximately 100 rad $s^{-1}$), the ball keeps its height because of increased lift. However, when the amount of back spin is increased further this amount of lift is cancelled out by an additional increase in the drag.

## Comparison with previous studies

### *Drag coefficient*

The drag and lift data were compared with previous aerodynamic studies. Figure 10 shows the drag coefficient data for non-spinning balls from Trials 1 and 2, compared with results found from a study

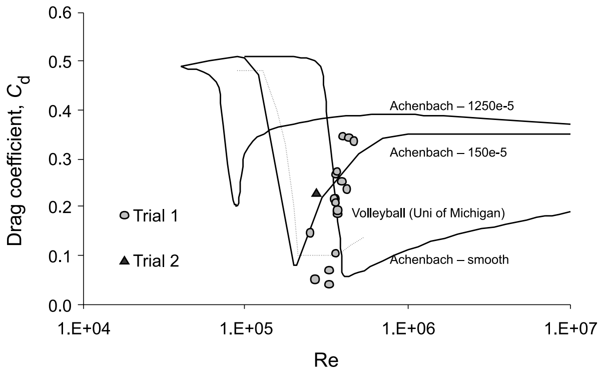


**Figure 10** Drag coefficient vs. Reynolds number for footballs and spheres with varying roughness.

on smooth and rough spheres by Achenbach (1972 & 1974) and an aerodynamic study of volleyballs (Mehta & Pallis 2001). All data are plotted against Reynolds Number, *Re*. The data from Trial 1 and 2 were found to lie between the values found by Achenbach for a smooth sphere and a rough sphere with surface roughness, $k/d$ equal to $150 \times 10^{-5}$ (where $k$ is the roughness height and $d$ is the ball diameter). It is likely that all the tests were carried out at speeds where the boundary layer around the ball was turbulent and consequently, as the speed was increased, this boundary layer thickened, increasing the drag coefficient. Therefore, it might be assumed from this data that a football behaves in the same way as a *slightly* rough sphere, with an increase in drag coefficient at high Reynolds number. Comparing the data with that from the volleyball study, suggests that transition from laminar to turbulent boundary layer behaviour may occur at lower Reynolds number for footballs, compared with volleyballs. This is most likely due to the relative roughness of the two ball types caused by the pattern and depth of the seams. Interestingly, the range of Reynolds numbers that were used in the football tests, $2.5 \times 10^5$ to $4.5 \times 10^5$ (similar to those found typically in a football) is the same range over which a large variation in drag coefficient is found to occur for these spheres. Therefore, if a ball slows down during, say, a free kick, the drag coefficient may change considerably. This effect, along with other aerodynamic phenomena, such as reverse Magnus

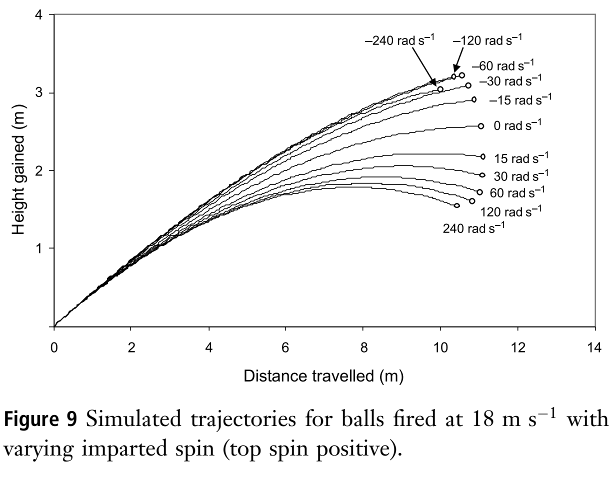


**Figure 9** Simulated trajectories for balls fired at 18 m $s^{-1}$ with varying imparted spin (top spin positive).

effect (Mehta & Pallis 2001), may go some way in explaining some of the more bizarre free kicks that have been seen in the past, such as the successful free kick by Roberto Carlos in France in 1997 (Asai *et al.* 1998).

*Lift coefficient*

Watts & Ferrer (1987) collated lift data from a number of studies of spinning rough spheres in wind tunnels and found that the lift coefficient for rough spheres varies primarily with the dimensionless group $\pi d\omega/V$ (where $d$ is the sphere diameter, $\omega$ is the imparted spin and $V$ is the air speed). This data is shown in Fig. 11, alongside the data from Trial 2 and from the pioneering smooth sphere data of Maccoll (1928). This is clearly in conflict with our data, which shows less dependence on $d\omega/V$. However, Trial 2 showed a similar range of lift coefficients as the smooth sphere study by Maccoll, suggesting that lift coefficients of around 0.3 are the maximum that can be achieved with footballs in a typical game situation.

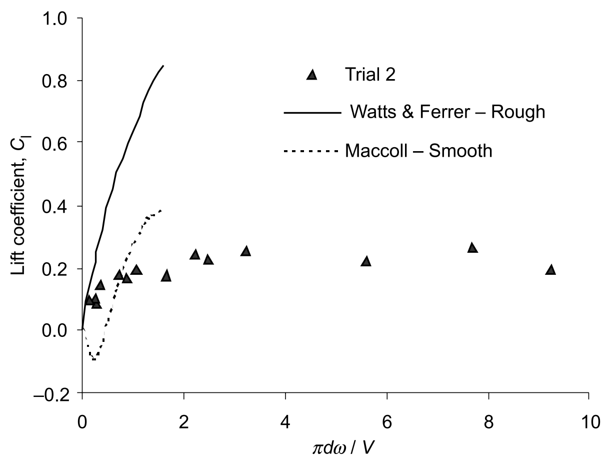


**Figure 11** Lift coefficient vs. $\pi d\omega/V$ for footballs and spheres with varying roughness.

## Effect in a real game situation

*Impact location*

The drag and lift coefficients were used to predict the flight of a football for various match situations. The effects of impact location and weather conditions could then be examined. As discussed in the paper that accompanies this study (Asai *et al.* 2002), if a ball is struck at its centre, with a foot velocity of 25 m $s^{-1}$ and a coefficient of friction of 0.4, it will have an effective launch velocity of 26 m $s^{-1}$ and no spin. According to Trial 1 this would lead to a drag coefficient of 0.24 and a lift coefficient of zero. A three-dimensional trajectory model using these coefficients was then used to simulate a goal being scored in the top right-hand corner (just inside the right post) from a free kick taken just outside the penalty area. This is referred to as 'Kick a' and can be seen in Fig. 12.

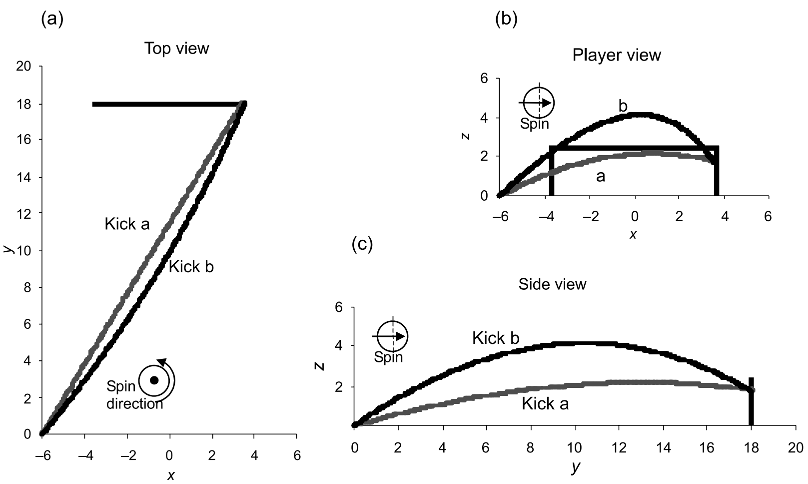


**Figure 12** Prediction for flight of two free kicks in three dimensions, based on varying foot impact location.

If the impact location of the foot striking the ball was offset by 0.08 m to the right, this would cause the ball velocity to drop to 18.5 m $s^{-1}$ and a spin of 10.2 rev $s^{-1}$ (64 rad $s^{-1}$) to be imparted to the ball, with a vertical spin axis (i.e. in an anti-clockwise direction when viewed from above, Asai *et al.* 2002). For spin in this direction, a sideways 'Magnus' force is applied to the ball, rather than 'lift' (Mehta 1985). It was assumed that the lift coefficients found from Trial 2, where spin was applied about a horizontal axis, could be used as 'Magnus' coefficients for a situation where spin is applied about a vertical axis, in order to calculate the sideways force acting on the ball. The drag and Magnus coefficients were found from Trial 2 to be 0.34 and 0.25, respectively. Note that the drag coefficient is higher than Kick a, although the velocity has decreased, because of the imparted spin. Another trajectory, 'Kick b', was then simulated to score a goal in the top right-hand corner, taken from the same position as Kick a. For the purposes of this simulation the spin axis was assumed to remain vertical throughout the flight and to be in an anti-clockwise direction when viewed from above. 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. Both kicks can be seen in Fig. 12. The trajectory plots show how Kick b curves to a much greater extent than Kick a, because of the sideways Magnus force, caused by the ball spinning. 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. This effect, combined with the variation in drag means that the total time required to score is 0.9 s for Kick a, whereas it is 1.6 s for Kick b. This comparison demonstrates the choice of strategy available to a player when taking such a kick. He can either strike the ball centrally to gain as much velocity as possible and therefore give the goal keeper less time to react, or he can strike it off-set from the centre to put spin on the ball, which may allow him to bend it 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.

*Weather conditions*

Another hypothetical situation was then examined based on weather conditions. It was assumed that if Kick b was carried out in wet conditions, the coefficient of friction would drop and so would the amount of spin imparted on the ball. Asai *et al.* (2002) found that the greatest reduction in spin due to a drop in coefficient of friction was approximately equal to 2 rev $s^{-1}$ (13 rad $s^{-1}$). If the ball was launched at the same velocity (18.5 m $s^{-1}$), but now with 13 rad $s^{-1}$ less spin than Kick b (51 rad $s^{-1}$), the corresponding drag and Magnus coefficients found from Trial 2 would be 0.32 and 0.23, respectively. This trajectory, 'Kick c', was simulated with the same launch angle as Kick b. The objective here was to try and simulate a player kicking a ball in wet conditions, but assuming that the ball would follow the same path as found through experience in dry conditions. Both kicks are shown in Fig. 13. It can be seen that although Kick b is successful (with the ball arriving at a ball radius to the left of the right post), Kick c arrives at a position just outside the right goal post (a ball radius to the right), due to the ball not bending as much as in Kick b. This demonstrates the need for players, in wet conditions, to either take care in wiping the ball and boot before taking a kick, or aim more to the left to ensure such a kick is successful.

## Conclusions

The objective of this study was to assess what effect the generation of spin has on the flight of a football in a curve kick. Measurements taken from controlled football trajectories have shown that for non-spinning balls, the amount of drag increases with launch velocity, over the range of velocities measured. For spinning balls, the amount of drag and lift increases with imparted spin, for tests carried out with the same launch velocity.

Trajectory simulations have demonstrated how a player can choose a particular strategy when taking a free kick, based on the impact location of the foot

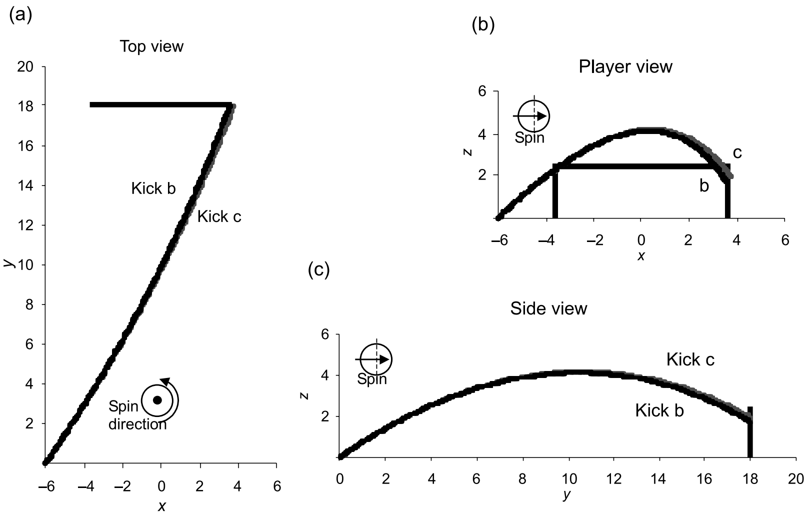


**Figure 13** Prediction for flight of two free kicks in three dimensions, based on varying launch spin.

striking the ball. A ball that is struck at the centre will follow a near straight trajectory, dipping slightly before reaching the goal. A ball that is struck off centre will bend before reaching the goal, but as velocity is lost for such a kick, it will need to be launched at a steeper angle and will result in a significantly longer flight time.

These simulations also demonstrate the effect of reduced friction at impact. If friction between the boot and ball is reduced, possibly caused by wet conditions, the imparted spin will be less and the ball will not bend as much in flight. This research has demonstrated that the change in drag coefficient due to transition is an effect that happens at velocities that occur during play in football. Further work is required to examine this effect in more detail.

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