Giving physics a sporting chance

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Can the perceived difficulties of physics, especially in the 14–19 curriculum, be addressed by the use of sport as a medium? This article attempts to present contexts for this age group to be introduced to a variety of mechanics concepts.

The author's discussions with undergraduate and PGCE (see endnote) physics students lead to the conclusion that even these students, who can be considered successful, sometimes find physics to be a 3D subject: Dull, Dry and Difficult! Two factors appear to impact on this view: the mathematical content and the physics context. One approach that sets the physics in a more accessible context, from which the mathematics can then be developed, is via the medium of sport. Below are two examples of such contexts: football and tennis, which allow students to access a range of physics topics. While, in parts, the mathematics developed may be more applicable to the 16–19 curriculum, the opportunities for modelling and practical exercises have been included with the full 14–19 age range in mind.

Physics and football

When the likes of Real Madrid's David Beckham and Roberto Carlos 'bend' a football around and/or over a defensive wall they make instinctive use of the Magnus effect.

The Magnus effect takes its name from the German physicist Thomas Magnus who, in 1852, explained the theorem proposed by Bernouilli in 1740, which stated that '*the pressure in a fast moving fluid is lower than that in similar slow moving fluid*'. Bernouilli's theorem is used to explain such diverse phenomena as the lift in aircraft wings, where the shape ensures that the air above the wing is moving faster than the air below the wing, and the use of the collar on a Bunsen burner where the jet of gas in the chimney is moving faster than the air outside and hence air is drawn into the open collar (Figure 1).

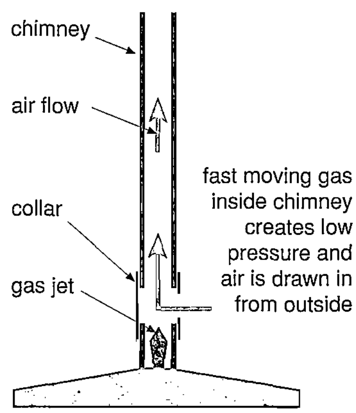

Figure 1 Air flow in a Bunsen burner.

An interesting teaching point is the fact that the Magnus force was even applied, as a means of propulsion, to a 'sailing' ship. In February 1925 a ship designed by the German naval architect Anton Flettner

ABSTRACT
Pupils in school often see little relevance to the science, particularly physics, that they study. This paper sets out a rationale for developing an understanding of physics through the medium of sport. Pupils in the 14–16 age range can follow the tennis racket example either as an investigation or simply as part of their study of energy, especially gravitational potential and kinetic energy, whilst the more able or post-16 students can extend this to coefficient of restitution. Post-16 students can also study the Magnus effect, from the Bunsen burner to the free kick via ships' rotors.

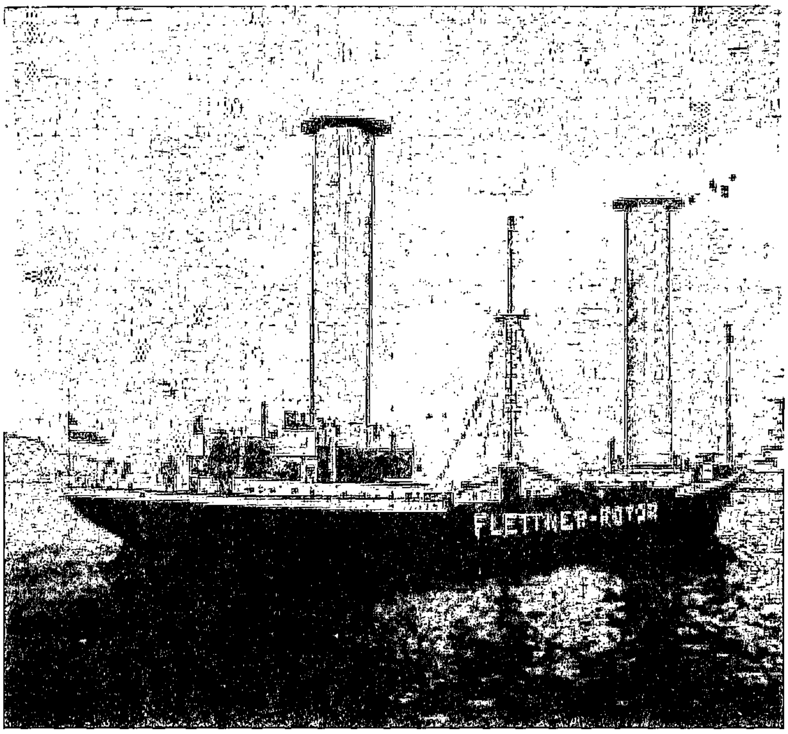

Figure 2 The *Bruckua* showing the two rotors.

had its masts replaced with two vertical rotating cylinders driven by electric motors. The ship, *Bruckua*, made a voyage from Danzig to Scotland, reaching a speed of up to 14 km h^{-1} (Figure 2).

The Magnus or lift force F_L acting on a ball is related to both its linear velocity and its rate of rotation by:

$$F_L = C_L \rho d^3 f v$$

where

C_L is the 'lift coefficient'
ρ is the density of the air
d is the diameter of the ball
f is the frequency of rotation or 'spin' of the ball
v is the velocity of the ball.

The direction of the Magnus force on a football is shown in Figure 3.

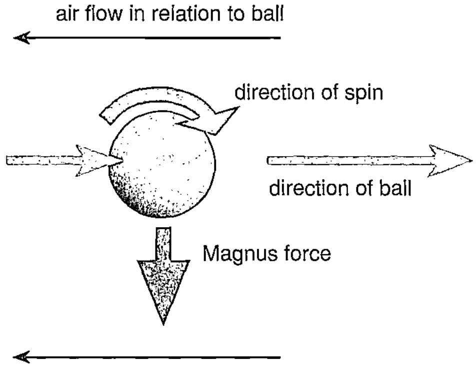

Figure 3 The Magnus effect on a spinning ball.

If we assume that the magnitude of the Magnus force is constant during the flight of the ball then, by reference to Figure 4, we have:

$y = vt$ $\quad y \propto t$ (where t is time)

$x = \frac{1}{2}at^2$ $\quad x \propto t^2$

hence, $x \propto y^2$ which is the equation of a parabola and therefore justifies the path drawn in Figure 4. As a teaching activity students can model $x \propto y^2$ or $x = ky^2$ (where k is a constant) with a range of values for k, using a spreadsheet and/or graph package.

Wesson (2002) suggests that the total displacement sideways, D, is related to the distance from the goal, L, by:

$$\frac{D}{L} = kn \quad \text{or} \quad D = knL$$

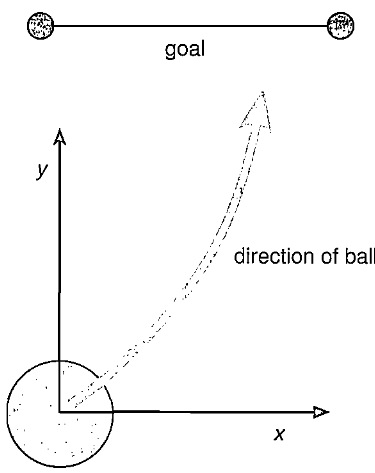

Figure 4 Parabolic flight of the football.

where n is the number of rotations during the flight of the ball. Whilst data from footballs are unavailable, evidence from other smooth balls suggests that k is of the order of 0.01. Once again students can investigate variation in k, n and L as a simple modelling exercise.

Consider now a ball kicked with an initial velocity of 25 m s^{-1} towards the goal from a distance of 25 m. Assuming a spin rate of 10 revolutions per second and a time of flight of 1 second:

Solving $D = knL$ gives:

$$D = 0.01 \times 10 \times 25 = 2.5 \text{ m}$$

However, using the same data calculations by Ireson (2001), $s = ut + \frac{1}{2}at^2$ (where s is displacement and u is initial velocity) with the value of a determined from $F_L = C_L \rho d^3 f v$ using the FIFA regulation values for mass and diameter of the ball, gives:

$$s = 0 \times 1 + 0.5 \times 9.14 = 4.57 \text{ m}$$

Since neither solution can be verified or refuted using an actual situation, they provide a good discussion point for students looking at ideas and evidence in science. Students should also be alerted to the fact, if not shown, that video evidence shows that, at times, a player can make a ball 'bend' with very little spin.

If the assumption that the Magnus force remains constant during the flight of the ball is considered to be invalid, a fuller understanding may be achieved. As the ball travels through the air it experiences drag that reduces its velocity. However, the drag force is itself dependent on the velocity of the ball, and the variation of the drag force, F_d, with velocity is as shown in Figure 5 which is taken from Ireson (2001).

This analysis can be modelled as a 7th order polynomial, for those with suitable mathematics background, but it is based on a treatment of a soccer ball as a 'smooth sphere'. Wesson (2002) challenges this assumption and suggests that a simpler square relationship may be closer – see Figure 6.

Obviously this can be an area for student research, at AS/A2 level (16–19 years), and the development of modelling skills. Such student research, with tutorial support, may lead to the solving of dr/dt where r is the position vector, $r = (x, y, z)$, taking x, y, z as the normal spatial coordinates.

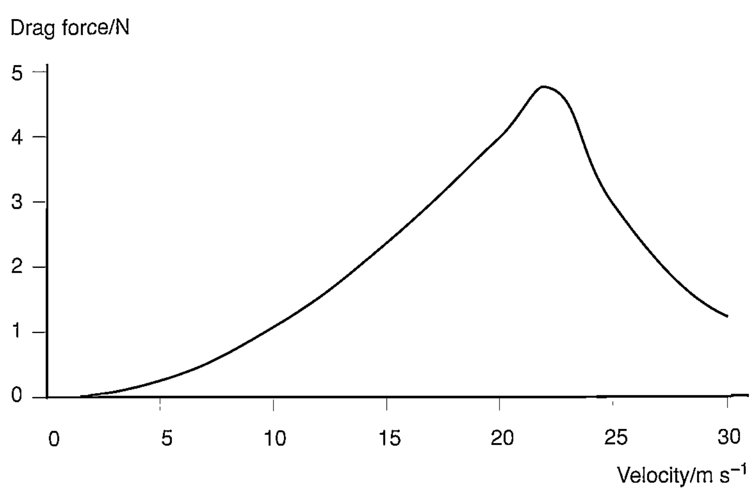

Figure 5 Variation of drag force with velocity.

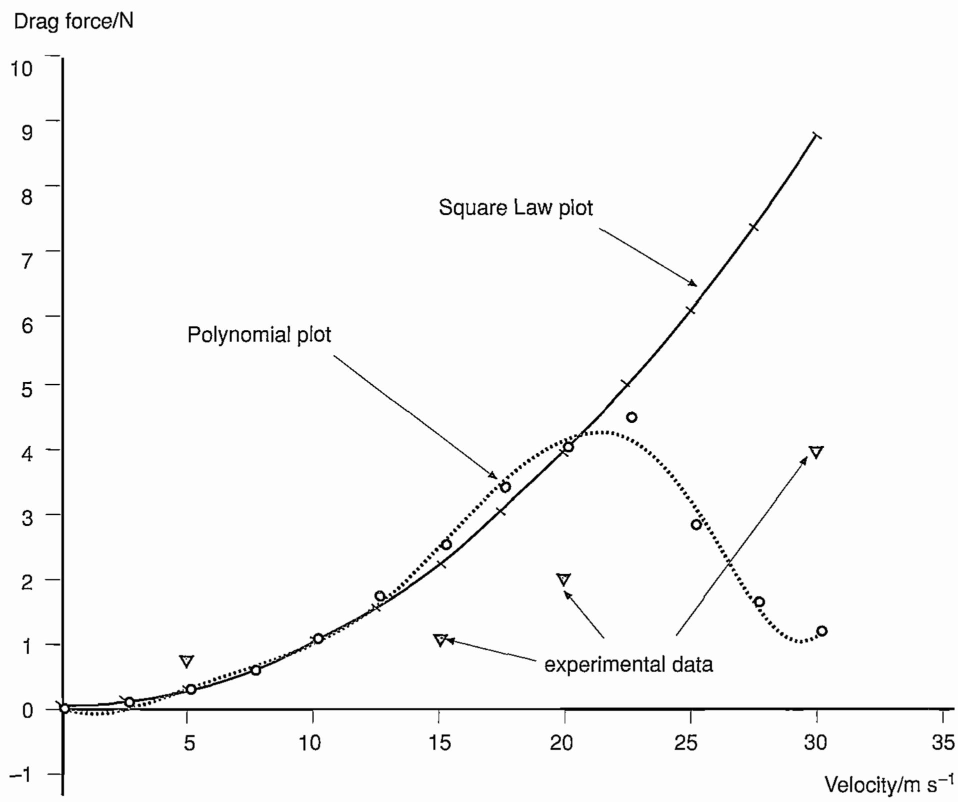

Figure 6 Drag force versus velocity using polynomial, square and experimental data.

Physics and tennis

Anyone who has ever hit a ball with a tennis racket will, at some time, have felt the effect of hitting it in the 'wrong place'. The 'right place' causes no vibration to be felt in the hand and racket manufacturers refer to this as the 'sweet spot'. However, the physics of why this should be so is not obvious and further investigation reveals that it may be more useful to talk of not one, but four sweet spots, as shown in Figure 7.

Imagine now a tennis racket balanced on the end of its handle (Figure 8). If a ball impacts on the racket at its centre of mass then the motion of the racket would be purely translational. If the ball strikes a point other than the centre of mass then a translation will be needed to conserve linear momentum and a rotation will be needed to conserve angular momentum. A point on the racket face exists where the distance the tip of the handle moves to the right/left under translation is equal to the distance moved to the left/

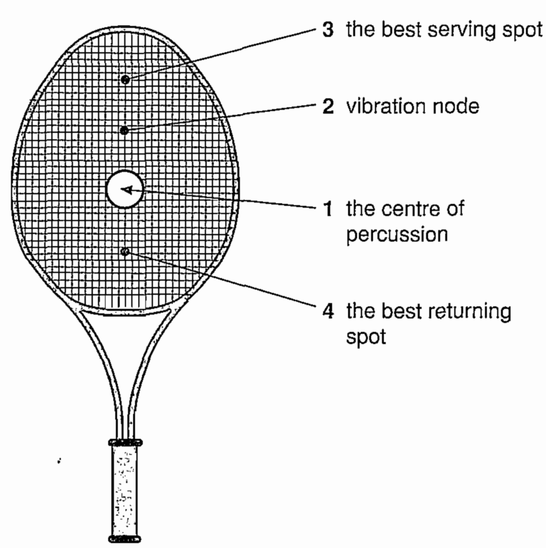

Figure 7 The four sweet spots on the tennis racket.

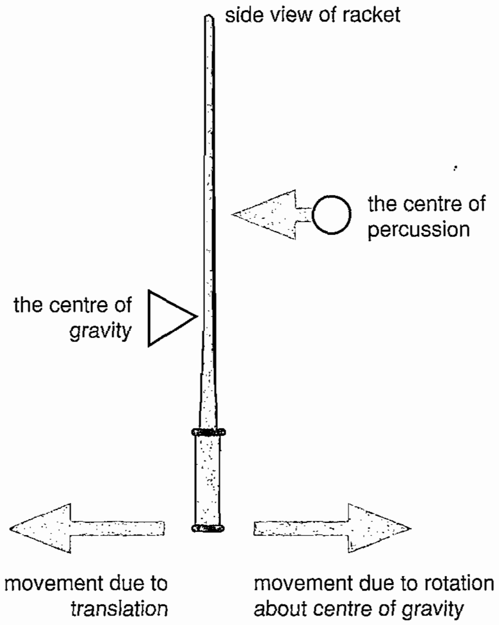

Figure 8 Rotation and translation of the racket when struck at the centre of percussion, sweet spot 1.

right under rotation – this is 'sweet spot 1' and is known as the centre of percussion. Striking the ball here causes minimum force on the forearm of the player. On a typical racket the centre of percussion will be of the order of 5.0 cm above the centre of the strings. A student investigation could be set which enables this position to be found.

Unfortunately, limiting the force on the forearm by striking the ball at the centre of percussion leads to a different problem: the racket vibrates! The fundamental mode for a typical racket lies in the range 100 Hz to 150 Hz, with one node being close to the centre of the strings and the other in the handle. Striking the ball at a node, 'sweet spot 2', will result in no vibration (students may have noticed this phenomenon in cricket bats and hockey sticks if not in a tennis racket). The lack of vibration affords greater racket control that can, in turn, result in lower levels of muscle fatigue in the forearm, which could be of great importance in a long match.

Imagine a racket clamped by the handle and balls then being dropped on to the strings along a line from the handle to the tip. If the rebound height is recorded the coefficient of restitution can be found (Figure 9).

The coefficient of restitution is defined as the ratio of the rebound speed, v_r, to the incident speed, v_i.

Using $\Delta mgh = \Delta \frac{1}{2}mv^2$

(where m is mass, g acceleration due to gravity and h height),

dropping a ball from a height h_i implies that

$mgh_i = \frac{1}{2}mv_i^2$

which leads to $v_i^2 = 2gh_i$ (where h_i is the initial height, as h_r is the rebound height.)

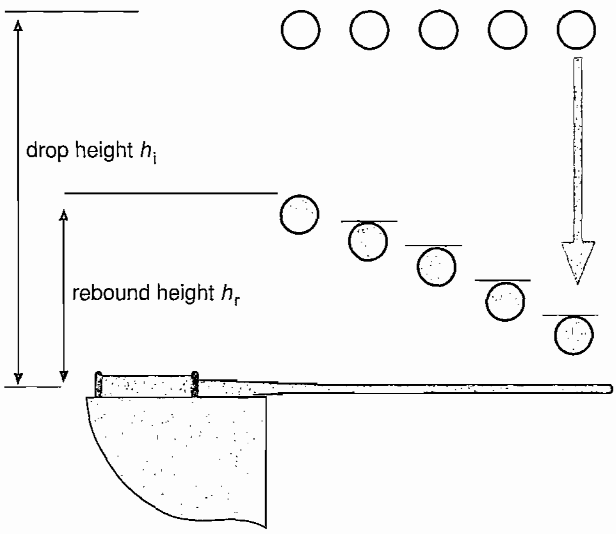

Figure 9 *Finding the sweet spots by measuring the coefficient of restitution.*

If the ball rebounds to a height h_r then this implies $mgh_r = \frac{1}{2}mv_i^2$ which leads to $v_r^2 = 2gh_r$.

The coefficient of restitution, e, is therefore given by:

$$e = \frac{h_r}{h_i}$$

This allows 'sweet spot 3', the dead spot, where the coefficient of restitution is a minimum and 'sweet spot 4', the lively spot, where the coefficient of restitution is maximum to be found. At the dead spot minimum energy is returned to the ball from the stationary racket. Similarly, if a stationary ball is hit by a moving, for example rotating, racket then all of the rotational energy will be given to the ball. This makes this spot the best place to strike the ball when serving.

When returning a ball, if pace is required, the best place to strike the ball will be the lively spot since this will return maximum energy to the ball.

Finding sweet spots 3 and 4 makes for an investigation that is suitable for both GCSE (under 16s) and AS/A2 students.

References

Ireson, G. (2001) Beckham as physicist. *Physics Education*, **36**, 10–14.

Wesson, J. (2002) Football physics. *Physics World*, **15**, 41–44.

Endnote

PGCE: Post Graduate Certificate of Education is the more common route into secondary school science teaching in England. Students following such a course to become physics teachers, which is most often one year full time, will have at least a first degree in which fifty per cent is recognised as physics.

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