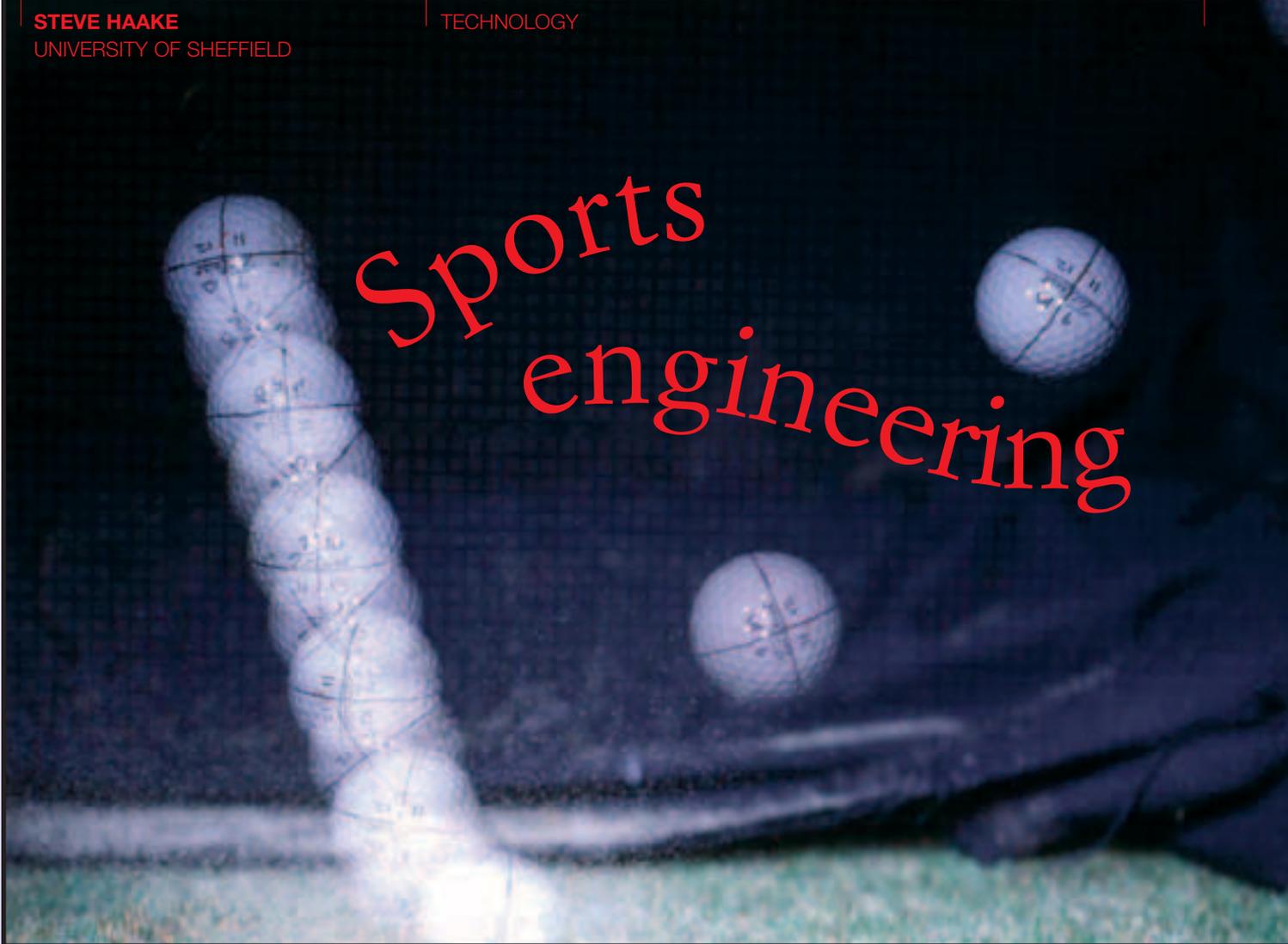


# Sports engineering



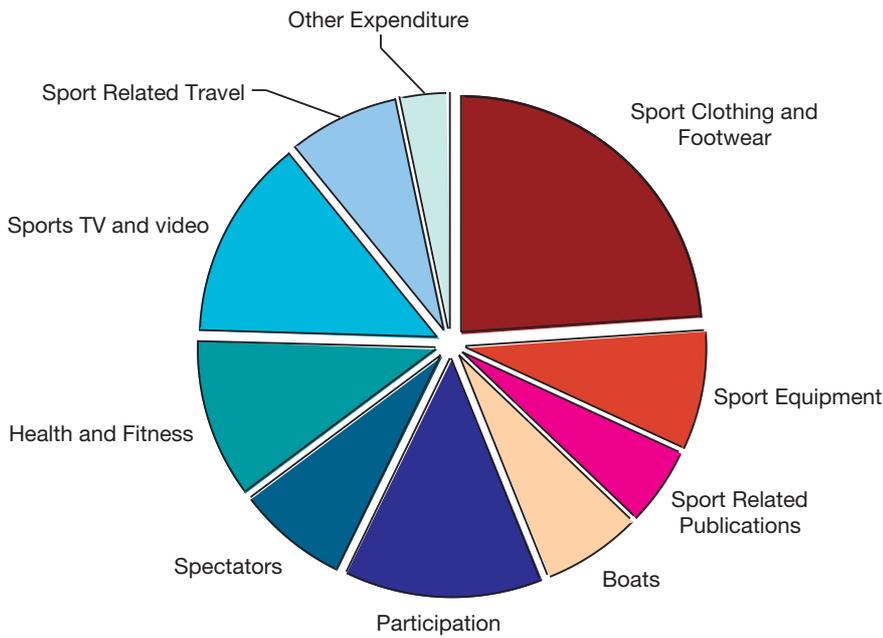
*Sports engineering has emerged in the last two decades as a legitimate area of research. However, some are still not sure what sports engineering is all about and, if it does work, isn't it just cheating? Steve Haake, of the University of Sheffield, has looked at the economics of sport to see why it's so popular and discusses its attraction to students. Some examples from tennis, football and wheelchair racing are described to show how mainstream engineering principles can be used to analyse and redesign sports equipment.*

## Introduction

You may have only just heard of sports engineering but it is not a new topic by any means. Over three hundred years ago, a mechanical line call device was introduced to Real Tennis, whilst in 1672 Newton discussed the way spinning tennis balls deviated in flight. More recently, in 1910, Sir J.J Thompson gave an explanation of the dynamics of golf ball flight in *Nature*, using the analogy of electron beam trajectories. In the last decade or so, sports engineering has become very popular across the world, particularly in the UK. So what is fuelling this interest and is sport 'big business' as many people say? There is a lot of hype surrounding sport, often in the claims of equipment manufacturers. So does sports engineering work and, if it does, isn't the application of engineering to sport simply cheating?

## The economics of sport

I am often told that sport is big business and a few years ago, when grants were scarce, I wondered where the money was spent. The pie chart in Figure 1a shows that consumer expenditure in sport in the UK exceeded £15 billion in 2001. Going clockwise from the top, the first three portions of the chart show that £5.5 billion was spent on products, i.e. clothes and footwear, equipment, boats and publications. Equipment and apparel – usually associated with sports engineering – make up about £4.5 billion per annum of consumer expenditure. These sectors saw significant growth in the 1970s and 1980s due to public sector sports provision and local government investment in sports centres. Since the 1990s, however, public investment has stopped and participation has remained static. Luckily for sports equipment manufacturers, sports participants now



**Figure 1a Breakdown of UK consumer spending on sport**  
 (Source: Sport market forecasts, Sports Industries Research Centre, 2001)

spend more than they did 10 to 15 years ago, possibly because equipment costs almost 30% less in real terms than it used to.

In the UK, interest in sport has been fuelled in the last decade by football and by its television coverage (worth around £1.6 billion over three years). With government spending on sport for this decade approaching £750 million, participation is set to rise, which will in turn boost expenditure on equipment and apparel. This is seen in the chart in Figure 1b, which shows that the sale of sports equipment should grow by more than 30% between 2000 and 2005. This is over twice that predicted for the economy as a whole. Sport is, indeed, very healthy and research in sports engineering should benefit through the growth in sports equipment sales.

**Undergraduates and sports engineering**

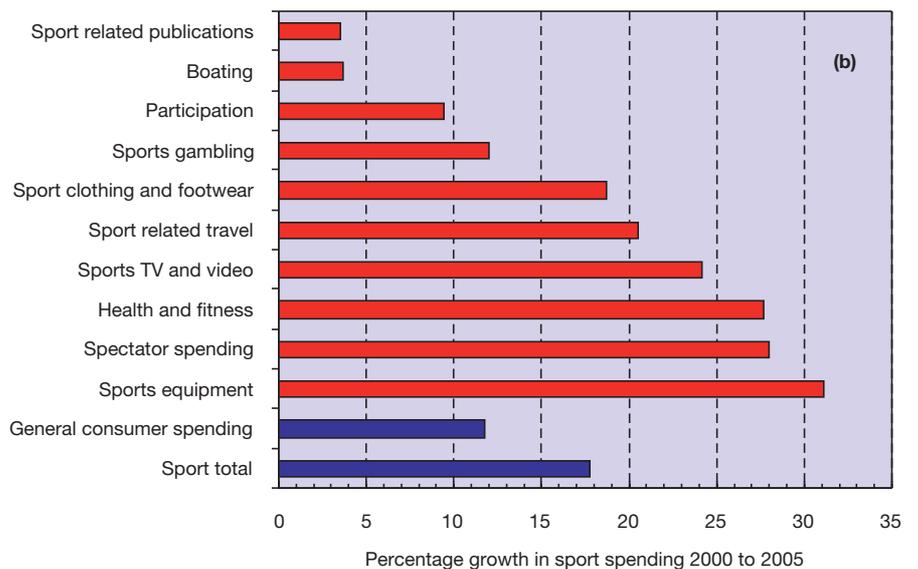
Over the last decade, academia has woken to the realisation that sport can be used to enhance students' interest in mainstream engineering. In the UK there

are currently around 20 undergraduate courses involving the technology or engineering of sport. The University of Bath has recently set up BEng and MEng programmes in sports

engineering. Loughborough and Birmingham have well established courses on sports technology and sports and materials science, respectively. These three institutions alone currently represent yearly intakes of around 100 students and teach courses such as sports equipment design, ergonomics, vibration and dynamics, aerodynamics and sports materials. At the University of Sheffield, the elective on Sports Engineering on the MEng programme in Mechanical Engineering is the most popular final year option, with over 80% of the class choosing to take the subject. Combining sport with engineering is, therefore, an extremely attractive option for students.

**Research in sports engineering**

So what kind of research is there in sports engineering that makes it so interesting? Nearly every university engineering faculty will have produced work relating to sport. At Sheffield, the Department of Mechanical Engineering has carried out research into the dynamics of tennis, the aerodynamics



**Figure 1b Predicted growth in sport compared to the growth in general consumer spending.**  
 (Source: Sport market forecasts, Sports Industries Research Centre, 2001)

of football, the design of ice skates, mountaineering ice axe design and wheelchair athletics. Some of these are outlined below to give a flavour of the sort of work that is being done in the UK.

### Tennis research with the International Tennis Federation

Figure 2 shows some of the work that has been carried out at the University of Sheffield on behalf of the International Tennis Federation. The project's remit was to determine the important design parameters for equipment in relation to its performance.

#### Rackets and balls

Impacts were carried out using different tennis ball designs in a variety of impact positions on different rackets with a variety of string tensions (see Figure 2(a)). One of the problems in this area involves keeping the number of variables to a minimum; this experiment had five (ball type, string tension, racket type, impact position and velocity). Other experiments have included angle, spin, string type, string configuration, mass and moment of inertia. The work has resulted in a mathematical model of impact based upon a viscoelastic model of the ball and a flexible beam model of the racket. The stiffness and damping for the ball are found by measuring contact times and rebound velocities in controlled tests. The stiffness and damping of the ball increase with deformation, which is dominated by the velocity of the impact. The parameters required to model the racket are found through direct measurement of mass and dimension and through vibration measurements to determine its stiffness and the positions of the nodes of vibration. The mathematical model was verified to within a few per cent of experimental results and is able to predict the motion of the racket during a shot, and the velocity, angle and spin of the ball after impact. The main advantage of a flexible beam model

over a simpler rigid body model, is that it can mimic the real-life vibrations of a tennis racket which contribute to both energy loss in the ball and poor feel by the player.

#### Tennis ball aerodynamics

Figure 2 (b) shows an image of streamlines passing over a rotating tennis ball. Research in wind tunnels (at Sheffield, Cambridge and NASA) has shown that the drag coefficient of tennis balls is approximately 0.6, with lift coefficients of up to 0.2, depending upon the amount of spin. Drag coefficients of smooth spheres are generally around 0.5 at low speeds and values can drop to around 0.1 at high speeds, depending upon the surface roughness of the sphere. The transition from high to low drag coefficient is caused by a change from laminar flow at low Reynold's numbers (equivalent to low speed) to turbulent flow at high Reynold's numbers. Interestingly, tennis balls show no such transition and the drag coefficient remains roughly constant for all speeds. This is contrasted with golf balls where the dimples cause transition at quite low Reynold's numbers. The drag coefficient is therefore low for the majority of a golf ball's trajectory which makes it fly a lot further than if it were smooth. This was actually found out by accident early on in the development of golf balls when players found that worn and cut-up golf balls flew a lot further than the newer smooth ones.

Returning to tennis balls, it is clear that the felt is the main parameter to influence their flight. Tennis balls fresh out of the can tend to fluff up after a few shots which can increase the drag coefficient by up to 10%. The felt is soon worn down, however, and balls which are used for a long period can have drag coefficients reduced, which cause them to fly faster. Drag and lift coefficients have been determined for a large range of spins and velocities and has allowed the development of a trajectory model, valid up to serve speeds of 150 mph.

#### Tennis courts

Another set of experiments studied the effect of the surface on ball rebound (see Figure 2(c)). The work showed that all court surfaces can be considered rigid in comparison to tennis balls, even 'soft' surfaces such as grass and clay. This simplifies the modelling of the impact, which allows the surface to be characterised purely by a coefficient of friction measure. The ball's interaction is dominated, therefore, by the dynamic stiffness and damping of the ball, and by the momentum flux of the shell during impact. This flux is the localised mass of the ball, which appears as a wave travelling around the ball and causing the characteristic dimple in the ball during impact seen in Figure 2 (c).

Grass surfaces generally have a low coefficient of friction, which allows a ball to rebound with about 70% of its initial speed at low angles. Clay, on the other hand, has a high coefficient of friction which reduces the ball's rebound to less than 65% of its impact speed and causes the ball to rebound steeply. Manufacturers try to optimise the construction of balls for different surfaces. For instance, dynamically stiff balls have been used on clay courts to try to reduce energy losses during impact and cause the ball to rebound lower and faster, nearer in performance to hard court surfaces.

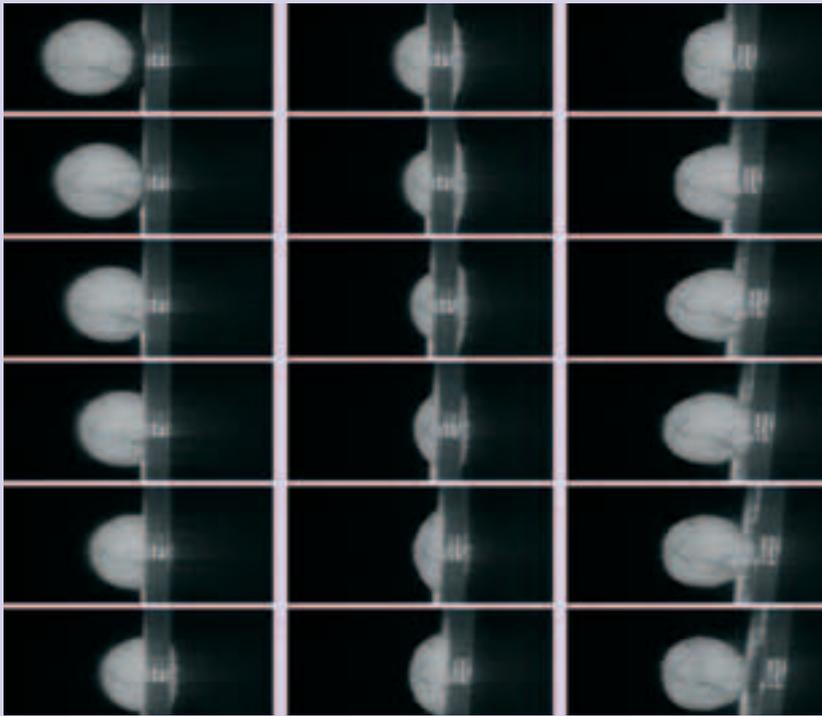
#### A complete model of tennis

Three analytical models were therefore created, one for the ball/racket impact, one for aerodynamics and one for the ball/surface impact. These were combined to create a unified model of tennis dynamics, written in Visual Basic, which can be used to look at the effects of equipment parameters, such as ball construction, racket design, string tension and court construction.

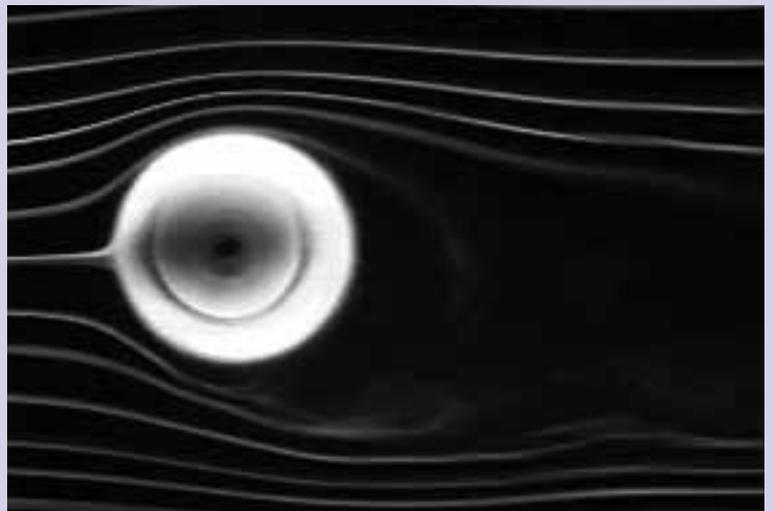
Tennis rackets have changed drastically over the last three decades as the old wooden rackets have been phased out in favour of the newer, lighter polymer and carbon fibre models. One effect of the use of new

Figure 2 Recent work for the International Tennis Federation has looked at all aspects of the dynamics of tennis. An analytical model has been produced to predict the motion of the ball from its impact with the racket, flight through the air and impact with the tennis court to arrival at the receiver. It has been used to assess the affects of racket and ball design on the game.

(a) Image of a tennis ball hitting a freely suspended tennis racket at 45 m/s at 6000 frames per second. The ball and the strings deform about 30 mm. Rigid body dynamics is able to predict the rebound speed of the ball and the recoil of the racket to within 5%. The discrepancy is due to vibrations in the racket. A flexible beam model predicts ball rebound to within 1%.

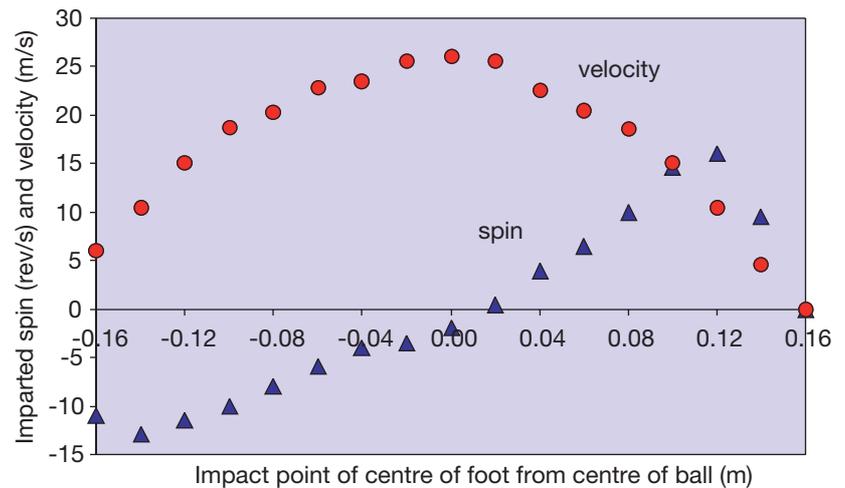


(b) Streamlines across a clockwise rotating tennis ball. The boundary layer separates late on the top surface and early on the bottom one. The subsequent deflection downwards of the airflow indicates an upwards deflection due to the spin.



(c) The vertical impact of a pressurised tennis ball on a rigid surface at 35 m/s. The internal pressure accounts for nearly half of the ball's stiffness compared to an unpressurised ball.





**Figure 3a** A finite element of the lower leg impacting with the ball used to study **(b)** the effect of kicking position and friction on the ball launch characteristics

materials in rackets has been the increase in the polar moment of inertia of the racket, reducing the likelihood that the racket will twist in the player's hand, which in turn reduces mishits. The sweet spot of modern tennis rackets is also larger – this is the area on the strings of the racket that gives the best feel to the player. The sweet spot is, in fact, three spots. The first is the point at which the coefficient of restitution of the racket is greatest and is quite close to the throat of the racket, which is where the centre of mass is located. The second is the centre of percussion or the region on the racket where the translation and rotation during impact with the ball combine to give no reaction at the hand. This tends to be near the centre of the racket. The last 'sweet spot' is the first node of vibration which again is near the centre of the racket. Hitting this point doesn't excite the fundamental vibrations of the racket, which, in turn, feels good to the player.

The mathematical model developed by the University of Sheffield and the International Tennis Federation can be used either to limit the development of tennis equipment or encourage it. Manufacturers can use it to look at the effects of new racket, ball or surface designs on the improvement of performance. Indeed, the research described here, was used directly by

the ITF to introduce a larger ball into the rules of tennis precisely to do the opposite – to slow the game down.

### Football research

#### *Modelling football kicks*

During every FIFA World Cup, talk inevitably touches on the fabulous free kicks that fool defenders and goalkeepers alike by the amount that they deviate during flight. There is still no published work detailing lift and drag characteristics on a spinning football, but Yamagata University, the University of Sheffield and Fluent Europe have combined their results to go part way to explaining the physics behind the kicks. Yamagata University created an experimentally verified finite element model of a lower leg impacting with a football. Figures 3(a) and (b) show the model 4 ms after impact, and the velocity and spin of the launched ball for different offsets of the impact location from the centre of the ball. Clearly, near the centre of the ball, no spin is imparted to the ball and it has a maximum velocity of about 25 m/s (90 km/h, 56 mph). As the player kicks more off centre, the velocity decreases until it approaches zero, when the centre of mass of the foot and leg moves outside the ball (i.e. the foot just skims the outside of the ball). The spin increases as the player hits more to the side of the centre of mass, increasing

to a maximum of about 15 revolutions per second (94 rad/s, 900 rev/min) before decreasing to zero as the foot hits the edge of the ball. What is interesting is that reducing the coefficient of friction to zero does not reduce the spin to zero for off centre hits, as the ball deforms around the foot allowing torque to be applied to it. In practice, this allows the player to impart spin even in extremely wet conditions.

#### *Aerodynamics of footballs*

Wind tunnel tests were carried out at the University of Sheffield on a quarter scale model of a football to determine its drag coefficient. Figure 4(a) shows that the drag coefficient for a football goes through transition from laminar to turbulent flow at a much lower Reynold's number than a smooth sphere, which is due to the seams on the football tripping the boundary layer. For a football, the drag coefficient drops from about 0.5 at low velocities and Reynold's numbers to about 0.2 at higher velocities. Figure 4(b) shows the equivalent drag forces on a standard sized football. The drag force is given by

$$F_D = \frac{1}{2} \rho A C_D v^2$$

where  $\rho$  is the density of air,  $A$  is the cross sectional area of the ball,  $C_D$  is the drag coefficient and  $v$  the velocity. The drag force is dominated by the square of the velocity and this can clearly be

seen in Figure 4(b). However, what can also be seen is that there is a minimum in the drag force at around 8.4 m/s (19 mph, 30 km/h) and a maximum at about 7.5 m/s (17 mph, 27 km/h). Thus, as a football slows down in its flight, it experiences a sudden jump in drag force of about 25% (0.5 N compared to 0.4 N). These higher drag forces occur at the end of the trajectory where the ball is travelling slowest and so act to emphasise any lateral deviations that occur due to spin.

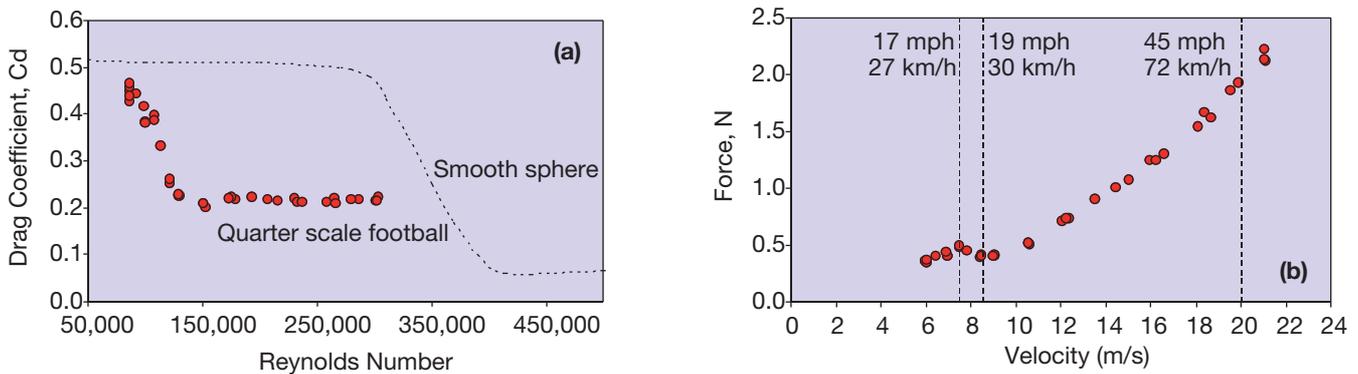
Lift and drag coefficients on spinning footballs are difficult to gain and estimates have been found by looking at controlled trajectories in sports halls

and using a computational fluid dynamics model of a football created by Fluent Europe. It was found that the lift coefficient rises from zero for a non-spinning ball to about 0.2 for a ball with 100 rad/s of spin (950 rad/s). A trajectory model was used to combine all the information gleaned so far to study the effects of free kick strategy using fixed  $C_D$  and  $C_L$  values.

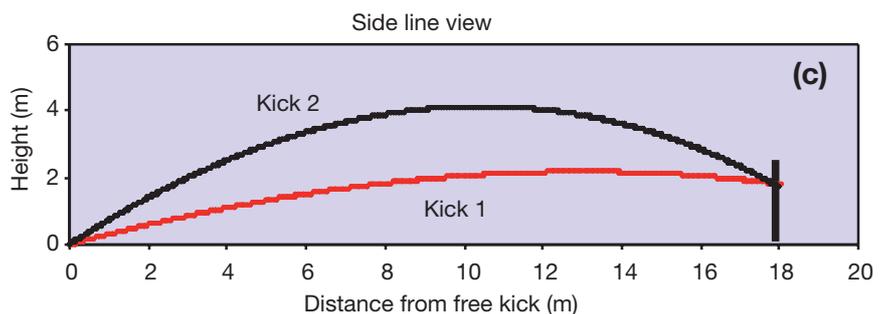
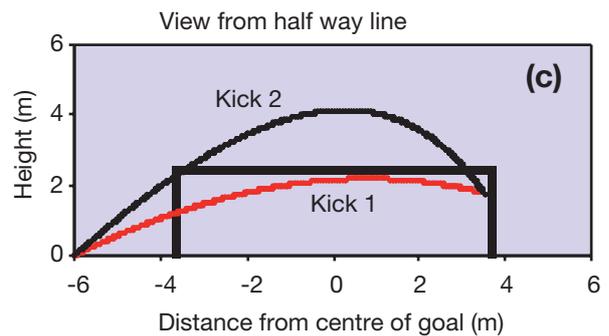
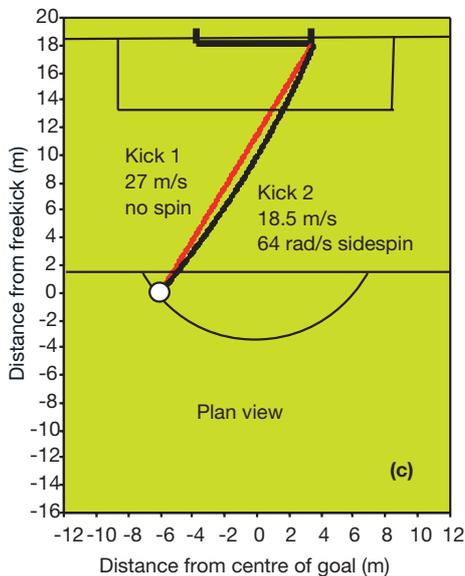
**Simulating free kicks**

Two kicks were studied using information from the model of the leg/ball impact. The first was a fast free kick at 27 m/s with no spin (60 mph, 96 km/h). Figure 4(c) shows that, with

this kick, the ball travels relatively straight into the top corner of the net in about 0.9 s. The non-spinning shot is affected significantly by the seams, since any slight movement makes the separation points alter position, giving an apparently random sideways force and deviation. This is known as the 'knuckle ball' effect in baseball and is difficult for goal keepers to guard against because of the difficulty in predicting where the ball will deviate to. Typical reaction times of athletes are around a quarter of a second so this type of shot only leaves around 0.65 s for the goalkeeper to get to the right place to make a save.



**Figure 4a** Drag coefficient vs Reynold's number **b)** measured drag forces on a quarter scale football vs Reynold's number **c)** trajectories for the flight of two free kicks based upon varying foot impact location to give a fast non-spinning shot and a slower spinning shot.



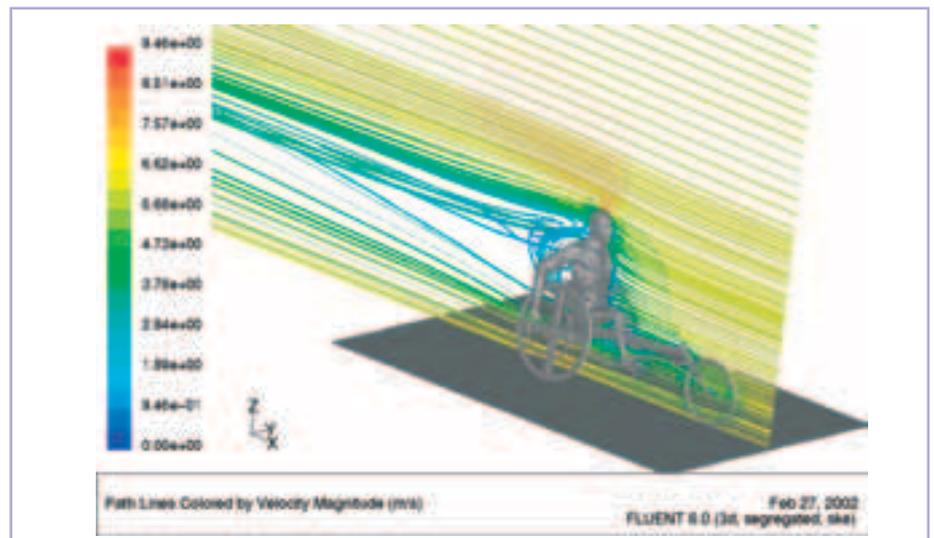
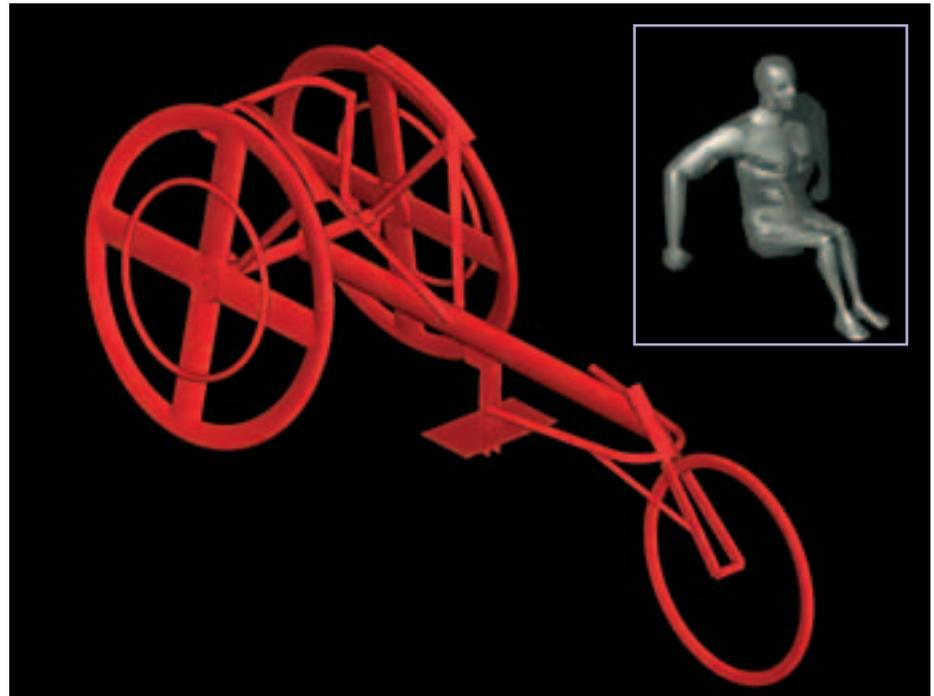
The second simulated free kick had a lower velocity of 18.5 m/s (42 mph, 67 km/h) but with 64 rad/s sidespin (10 rev/s). This shot curves significantly in the air and takes approximately 1.6 s to reach the top corner of the net. So, although the goal keeper has more time to make a save, the deviation is used to disguise the direction of the ball. The shot shown here is likely to bend significantly more than shown due to the higher drag force experienced at the end of the trajectories as the ball goes through transition from turbulent back to laminar flow as shown in Figure 4(a), which has not yet been incorporated into the model.

Football boot manufacturers have understood the significance of the boot/ball interaction on spin for a number of years and have tried to increase the coefficient of friction using geometrical features and new materials on the leather uppers of the boots to increase spin. For football manufacturers, one of the main innovations in recent years has been the use of polymer coatings on the outside of the ball to inhibit water absorption which could increase the mass of the ball significantly during a game.

### Improving elite performance in wheelchair racing

The UK government invests heavily in the UK's elite sportsmen and -women through the various ruling bodies and some of the money is now being earmarked for technological development. One such project looked at the design of racing wheelchairs for the UK wheelchair racing squad via the support of UK Athletics. The optimisation problem was that of improving performance by maximising the athlete's power input while reducing energy losses from aerodynamic drag and from wheel interactions with the surface.

Pro-Engineer CAD software was used to assemble a 3D model of a racing wheelchair, whilst a representative athlete was created by Sammie CAD Ltd with Poser human



**Figure 5** Aerodynamic analysis of wheelchair racing required modelling of both  
**a** Model of a wheelchair drawn using Pro-Engineer  
**b** An athlete modelled using actual dimensions and Poser human modelling software  
**c** Fluid flow lines at 7 m/s around the combined model

modelling software. The wheelchair and athlete were combined and converted to a mesh suitable for CFD analysis (see Figures 5(a) and (b)). CFD analysis of the model was carried out by moving the surface and the fluid over the model at 7 m/s to simulate a moving wheelchair. The flow pattern shown in Figure 5(c) shows recirculation behind the wheelchair and a large wake

caused by separation over the shoulders of the athlete. Modifications were made to the model of the athlete and wheelchair to improve performance. Clearly, the results cannot be shown here due to the confidentiality required prior to the Athens Olympics in 2004. However, the work has shown how to reduce the drag coefficient of the athlete and wheelchair which, when

In cricket, for example, from an engineering point of view, novel materials ... and innovative features could be used ... However, this would change the game to the extent that it simply wouldn't be cricket.

implemented, should benefit the UK's wheelchair athletes, particularly at the next Olympic Games in Athens in 2004.

### Is sports engineering another way of cheating?

Many sports engineers work for 'both sides', these being the equipment manufacturers and athletes on the one hand and the sports governing bodies on the other. Some sports have embraced technology and have allowed changes to be made. For instance, there are no restrictions on the materials that can be used in the polevault and spectacular gains were made in the 1960s and 1970s when glass fibre poles replaced the old wooden poles. In the 1980s, in the javelin, a new rule was introduced which moved its centre of mass forward to stop it flying so far and endangering athletes. Golf, on the other hand, has a number of rules limiting the specifications of equipment that can be used in tournament play, as does tennis.

What is clear, is that the rules of sport are not based around technology, science or engineering, but upon tradition and the need to preserve the sport's identity. In cricket, for example, from an engineering point of view, novel materials could be used in the bat and innovative features could be used on the ball to make it swing more. However, this would change the game to the extent that it simply wouldn't be cricket.

The ruling bodies of sport need to be aware of the technological developments to ensure that nothing too innovative appears. Sports engineers, on the other hand, try to push the envelope of innovations within these rules. As long as all innovations adhere to the rules there is simply no question of 'cheating'. This creates a balance between technology and tradition with the rules as the boundary between them. Both sides need to work together to satisfy the demand for ever improving performance by athletes and the public without compromising the integrity of the sport.

### Conclusions

Sports engineering in the UK has a bright future. The sports industry is forecast to grow faster than the economy, with sports equipment growing more than twice as fast. Research in sports engineering is both exciting and challenging and in the future it could help the UK to be more successful in major international competitions.

Sports engineering is attracting many students to courses around the country and the fact that sport can be used as a mechanism to teach mainstream engineering principles and the excitement of engineering should not be underestimated. ■

### Acknowledgements

Many thanks to the International Tennis Federation for their financial support and use of their wind tunnel; Dr Takeshi Asai at Yamagata University for collaboration on football impacts; Fluent Europe for their help in the aerodynamic analysis of footballs; and UK Athletics for their financial support and permission to discuss results relating to wheelchair racing.

### Further information

[www.sports-engineering.org.uk](http://www.sports-engineering.org.uk)  
*Sports Engineering*, published quarterly by Blackwell Science.  
*Sports market forecasts 2001–2005*, Sports Industry Research Centre, Sheffield, email: [lirc@shu.ac.uk](mailto:lirc@shu.ac.uk)

*Dr Steve Haake is Senior Lecturer in Mechanical Engineering at the University of Sheffield and runs the Sports Engineering Research Group. He is Editor of Sports Engineering and Chairman of the International Sports Engineering Association. One day soon, he will play more sport rather than just write about it!*

