The Science of Soccer

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For Olive
My favourite football fan

Preface

Football is by far the world's most popular game. Millions play the game and hundreds of millions are entertained by it, either at football grounds or through television. Despite this the scientific aspects of the game have hardly been recognised, let alone discussed and analysed. This is in contrast to some other games which have received much more attention, particularly so in the case of golf.

What is meant by 'science' in the context of football? This book deals basically with two types of subject. The first is the 'hard science', which mainly involves using physics to uncover basic facts about the game. This ranges from understanding the comparatively simple mechanics of the kick to the remarkably complex fluid dynamics associated with the flight of the ball. The second group of subjects is diverse. There is the role of chance in deciding results and, more significantly, in influencing which team wins the Championship or the Cup. Is the winning team the best team? We look at the players and ask how their success varies with age. We also ask, what is the best height for footballers and, with almost incredible results, what is the best time of year for them to be born? Further subjects include analysis of the laws, various theoretical aspects of the play, and the economics of the professional game.

In the first nine chapters of the book these subjects are described without the use of mathematics. The mathematical analysis which underlies this description is saved for the tenth and final chapter. Most of the material in the book is original and in many areas the author has made progress only with the assistance of others. I must thank David Goodall for the help he gave in experiments on the bounce and flight of the ball, and both him and Chris Lowry for the experiments which produced the drag curve for a football. The on-field experiments were carried out with the help of Mickey Lewis and the Oxford United Youth team. My understanding of the development of the ball was much improved in discussions with Duncan Anderson of Mitre, and I have taken the information on club finances from the *Annual Review of Football Finance* produced by Deloitte and Touche.

I am grateful to John Navas, the Commissioning Editor at Institute of Physics Publishing. Without his interest and encouragement this book would not have seen the light of day. Thanks are also due to Jack Connor and John Hardwick who read the manuscript and made many helpful suggestions. The book uses, and depends upon, a large number of figures. These were all produced by Stuart Morris. I am very grateful to him for his skill and unfailing helpfulness. Finally, I must thank Lynda Lee for her care and dedication in typing the manuscript and dealing with the many corrections and rewrites this involved

John Wesson
January 2002

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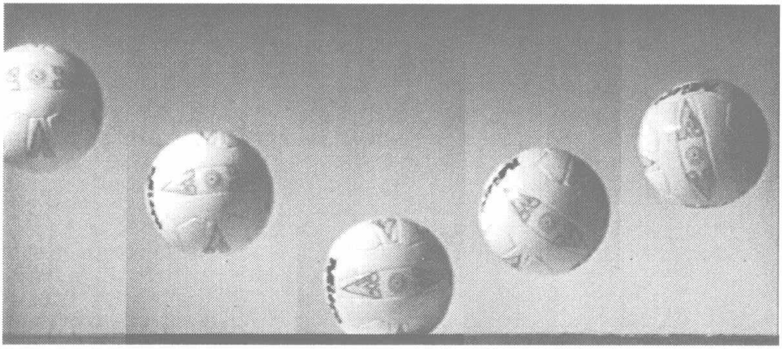

1

The ball and the bounce

The ball

Ball-like objects must have been kicked competitively for thousands of years. It doesn't require much imagination to picture a boy kicking a stone and being challenged for possession by his friends. However the success of 'soccer' was dependent on the introduction of the modern ball with its well-chosen size, weight and bounce characteristics.

When soccer was invented in the nineteenth century the ball consisted of an ox or pig bladder encased in leather. The bladder was pumped through a gap in the leather casing, and when the ball was fully pumped this gap was closed with lacing. While this structure was a great advance, a good shape was dependent on careful manufacture and was often lost with use. The animal bladder was soon replaced by a rubber 'bladder' but the use of leather persisted until the 1960s.

The principal deficiency of leather as a casing material was that it absorbed water. When this was combined with its tendency to collect mud the weight of the ball could be doubled. Many of us can recollect the sight of such a ball with its exposed lacing hurtling toward us and expecting to be headed.

The period up to the late 1980s saw the introduction of multi-layer casing and the development of a totally synthetic ball. Synthetic fibre layers are covered with a smooth polymer surface material and the ball is inflated with a latex bladder. This ball resists the retention of water and reliably maintains its shape.

The casing of high quality balls is made up of panels. These panels, which can have a variety of shapes, are stitched together through pre-punched stitch holes using threads which are waxed for improved water resistance. This can require up to 2000 stitches. The lacing is long gone, the ball now being pumped through a tiny hole in the casing. Such balls are close to ideal.

The general requirements for the ball are fairly obvious. The ball mustn't be too heavy to kick, or so light that it is blown about, or will not carry. It shouldn't be too large to manoeuvre or too small to control, and the best diameter, fixed in 1872, turned out to be about the size of the foot. The optimisation took place by trial and error and the present ball is defined quite closely by the laws of the game.

The laws state that 'The circumference shall not be more than 28 inches and not less than 27 inches. The weight of the ball shall be not more than 16 ounces and not less than 14 ounces. The pressure shall be equal to 0.6 to 1.1 atmosphere.' Since 1 atmosphere is 14.7 pounds per square inch this pressure range corresponds to 8.8 to 16.2 pounds per square inch. (The usually quoted 8.5 to 15.6 pounds per square inch results from the use of an inaccurate conversion factor.)

From a scientific point of view the requirement that the pressure should be so low is amusing. Any attempt to reduce the pressure in the ball below one atmosphere would make it collapse. Even at a pressure of 1.1 atmosphere the ball would be a rather floppy object. What the rule really calls for, of course, is a pressure *difference* between the inside and the outside of the ball, the pressure inside being equal to 1.6 to 2.1 atmosphere.

Calculation of the ball's behaviour involves the mass of the ball. For our purposes mass is simply related to weight. The weight of an object of given mass is just the force exerted on that mass by gravity. The names used for the two quantities are rather confusing, a mass of one pound being said to have a weight of one pound. However, this need not trouble us; suffice it to say that the football has a mass of between 0.875 and 1.0 pound or 0.40 and 0.45 kilogram.

Although it will not enter our analysis of the behaviour of the ball, it is of interest to know how the pressure operates. The air in the atmosphere consists of very small particles called molecules. A hundred thousand air molecules placed sided by side would measure the same as the diameter of a human hair. In reality the molecules are randomly distributed in space. The number of molecules is enormous, there being 400 million million million (4×10^{20}) molecules in each inch cube. Nevertheless most of the space is empty, the molecules occupying about a thousandth of the volume.

The molecules are not stationary. They move with a speed greater than that of a jumbo jet. The individual molecules move in random directions with speeds around a thousand miles per hour. As a result of this motion the molecules are continually colliding with each other. The molecules which are adjacent to the casing of the ball also collide with the casing and it is this bombardment of the casing which provides the pressure on its surface and gives the ball its stiffness.

The air molecules inside the ball have the same speed as those outside, and the extra pressure inside the ball arises because there are more molecules in a given volume. This was the purpose of pumping the ball – to introduce the extra molecules. Thus the outward pressure on the casing of the ball comes from the larger number of molecules impinging on the inner surface as compared with the number on the outer surface.

The bounce

The bounce seems so natural that the need for an explanation might not be apparent. When solid balls bounce it is the

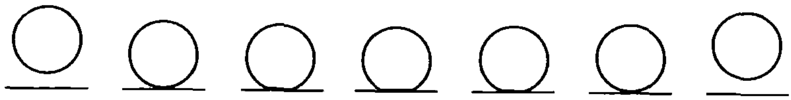

Figure 1.1. Sequence of states of the ball during the bounce.

elasticity of the material of the ball which allows the bounce. This applies for example to golf and squash balls. But the casing of a football provides practically no elasticity. If an unpumped ball is dropped it stays dead on the ground.

It is the higher pressure air in the ball which gives it its elasticity and produces the bounce. It also makes the ball responsive to the kick. The ball actually bounces from the foot, and this allows a well-struck ball to travel at a speed of over 80 miles per hour. Furthermore, a headed ball obviously depends upon a bounce from the forehead. We shall examine these subjects later, but first let us look at a simpler matter, the bounce itself.

We shall analyse the mechanics of the bounce to see what forces are involved and will find that the duration of the bounce is determined simply by the three rules specifying the size, weight and pressure. The basic geometry of the bounce is illustrated in figure 1.1. The individual drawings show the state of the ball during a vertical bounce. After the ball makes contact with the ground an increasing area of the casing is flattened against the ground until the ball is brought to rest. The velocity of the ball is then reversed. As the ball rises the contact area reduces and finally the ball leaves the ground.

It might be expected that the pressure changes arising from the deformation of the ball are important for the bounce but this is not so. To clarify this we will first examine the pressure changes which do occur.

Pressure changes

It is obvious that before contact with the ground the air pressure is uniform throughout the ball. When contact occurs and the bottom of the ball is flattened, the deformation increases the pressure around the flattened region. However, this pressure increase is rapidly redistributed over the whole of the ball. The speed with which this redistribution occurs is the speed of sound, around 770 miles per hour. This means that sound travels across the ball in about a thousandth of a second and this is fast enough to maintain an almost equal pressure throughout the ball during the bounce.

Although the pressure remains essentially uniform inside the ball the pressure itself will actually increase. This is because the flattening at the bottom of the ball reduces the volume occupied by the air, in other words the air is compressed. The resulting pressure increase depends on the speed of the ball before the bounce. A ball reaching the ground at 20 miles per hour is deformed by about an inch and this gives a pressure increase of only 5%. Such small pressure changes inside the ball can be neglected in understanding the mechanism of the bounce. So what does cause the bounce and what is the timescale?

Mechanism of the bounce

While the ball is undeformed the pressure on any part of the inner surface is balanced by an equal pressure on the opposite facing part of the surface as illustrated in figure 1.2. Consequently, as expected, there is no resultant force on the ball. However, when the ball is in contact with the ground additional forces comes into play. The casing exerts a pressure

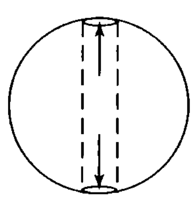

Figure 1.2. Pressure forces on opposing surfaces cancel.

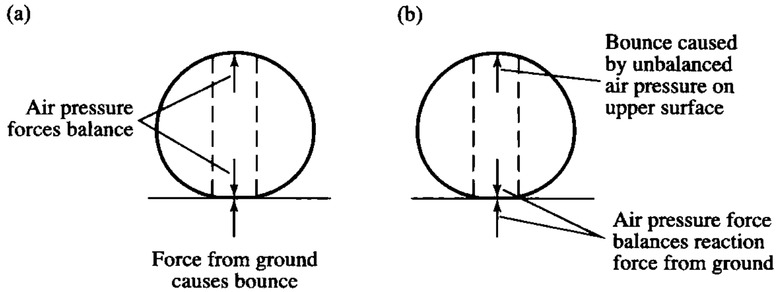

Figure 1.3. Two descriptions of the force balance during the bounce.

on the ground and, from Newton's third law, the ground exerts an equal and opposite pressure on the casing. There are two ways of viewing the resultant forces.

In the first, and more intuitive, we say that it is the upward force from the ground which first slows the ball and then accelerates it upwards, producing the bounce. In this description the air pressure force on the deformed casing is still balanced by the pressure on the opposite surface, as shown in figure 1.3(a). In the second description we say that there is no resultant force acting on the casing in contact with the ground, the excess air pressure inside the ball balancing the reaction force from the ground. The force which now causes the bounce is that of the unbalanced air pressure on that part of the casing opposite to the contact area, as illustrated in figure 1.3(b). These two descriptions are equally valid.

Because the force on the ball is proportional to the area of contact with the ground and the area of contact is itself determined by the distance of the centre of the ball from the ground, it is possible to calculate the motion of the ball. The result is illustrated in the graph of figure 1.4 which plots the height of the centre of the ball against time.

As we would expect, the calculation involves the mass and radius of the ball and the excess pressure inside it. These are precisely the quantities specified by the rules governing the ball. It is perhaps surprising that these are the only

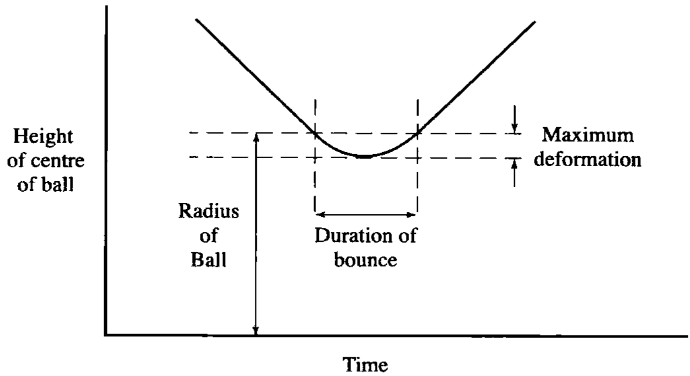

Figure 1.4. Motion of ball during bounce.

quantities involved, and that the rules determine the duration of the bounce. This turns out to be just under a hundredth of a second. The bounce time is somewhat shorter than the framing time of television pictures and in television transmissions the brief contact with the ground is often missed. Fortunately our brain fills in the gap for us.

Apart from small corrections the duration of the bounce is independent of the speed of the ball. A faster ball is more deformed but the resulting larger force means that the acceleration is higher and the two effects cancel. During the bounce the force on the ball is quite large. For a ball falling to the ground at 35 miles per hour the force rises to a quarter a ton – about 500 times the weight of the ball.

The area of casing in contact with the ground increases during the first half of the bounce. The upward force increases with the area of contact, and so the force also increases during the first half of the bounce. At the time of maximum deformation, and therefore maximum force, the ball's vertical velocity is instantaneously zero. From then on the process is reversed, the contact area decreasing and the force falling to zero as the ball loses contact with the ground.

If the ball were perfectly elastic and the ground completely rigid, the speed after a vertical bounce would be equal to that before the bounce. In reality the speed immediately after the bounce is somewhat less than that immediately before the bounce, some of the ball's energy being lost in the deformation. The lost energy appears in a very slight heating of the ball. The change in speed of the ball in the bounce is conveniently represented by a quantity called the 'coefficient of restitution'. This is the ratio, usually written e, of the speed after a vertical bounce to that before it,

$$e = \frac{\text{speed after}}{\text{speed before}}.$$

A perfectly elastic ball bouncing on a hard surface would have $e = 1$ whereas a completely limp ball which did not bounce at all would have $e = 0$. For a football on hard

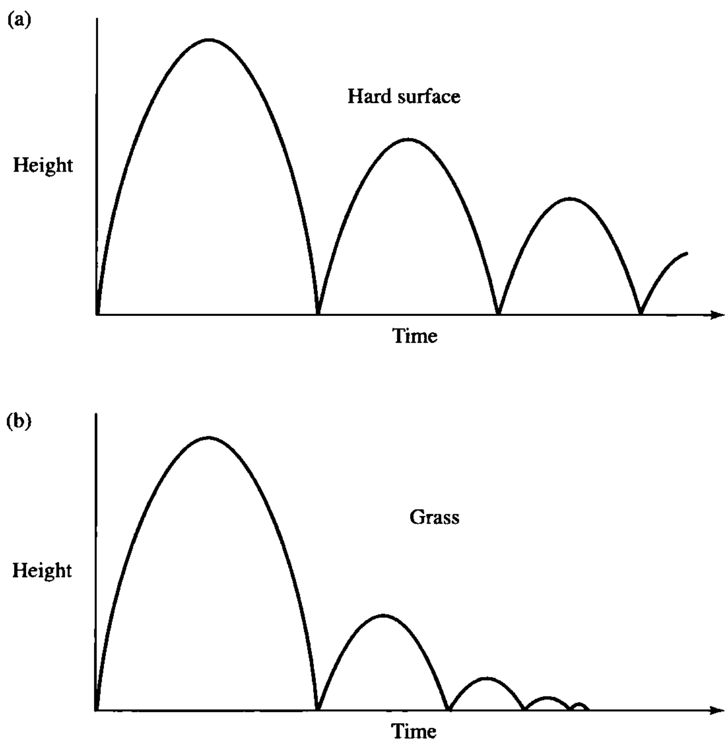

Figure 1.5. Showing how the bouncing changes with the coefficient of restitution.