12
Design and Materials in Athletics

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12.1 Introduction

Athletics has been described as many sports within a sport. There are 24 events in the Olympic competition programme, and these events may be grouped into sprints, middle-distances, long-distances, hurdles, relays, walks, jumps, throws, and multi-events. To excel in a particular event an athlete must be genetically endowed with an appropriate body size. The athlete must then undertake physical training to develop the required mix of strength, speed and endurance; and spend many hours practicing the technical and tactical skills of the event. Athletes who are successful in the international arena usually specialise in just one event.

Most athletics competitions are held under the rules and regulations of the International Association of Athletic Federations (IAAF), which was founded in 1912 and has about 220 member nations. Of interest to the sports engineer and sports scientist are the restrictions on the design of the competition facilities, the design of the athlete's equipment, and the techniques that the athlete may employ. An unstated but underlying philosophy in athletics is that the outcome of a competition should be determined by the physical and technical abilities of the athlete, and not by differences in the quality of the athletes' equipment (Julin, 1992). Most of the rules for the competition arena and the athlete's equipment are 'proscriptive' in that the material, construction, and dimensions are specified in detail and to high precision; whereas the rules for the athlete's technique are 'restrictive' in that they usually specify what is forbidden, rather than specifying how the movement must be performed.

Like many other sports, athletics places a strong emphasis on tradition and the historical continuity of record performances. The IAAF has been reluctant to approve technological innovations that change the nature of the event or which are aimed solely at improving the athlete's performance. In contrast, the governing body has welcomed innovations that reduced the incidence of injury to athletes and judges, reduced the incidence of judging errors, or enhanced the enjoyment of spectators. Financial costs are also considered when deciding whether to permit a technological advance. The IAAF endeavours to make athletics a 'globally accessible sport', with high participation rates by all peoples of all nations. An important aspect of retaining the universal appeal of athletics is through minimising the cost of participation; particularly the cost of competition facilities, competition implements, and judging equipment.

Figure 12.1 shows the trends during the twentieth century towards better athletic performances. However, in most events, very little of the overall improvement has been due to innovation in the design of sports equipment or the materials used. The main causes of improvement are socio-economic factors such as increased leisure time, increased professionalism of sport, state-supported sports systems, and the increased participation rate of women. Some of the improvement in performance may also be due to better coaching and training methods, particularly in strength training and cardiovascular training, and advances in sports medicine that have prolonged athletic careers. Figure 12.1 clearly shows temporary declines in performance due to World War I and World War II. In some events, particularly for the women, there is also a noticeable decline in performance starting in 1989. This is due to the demise of the organised sports systems in the Eastern European nations and the more expansive drug testing programs that were introduced following the disqualification of Ben Johnson at the 1988 Olympic Games.
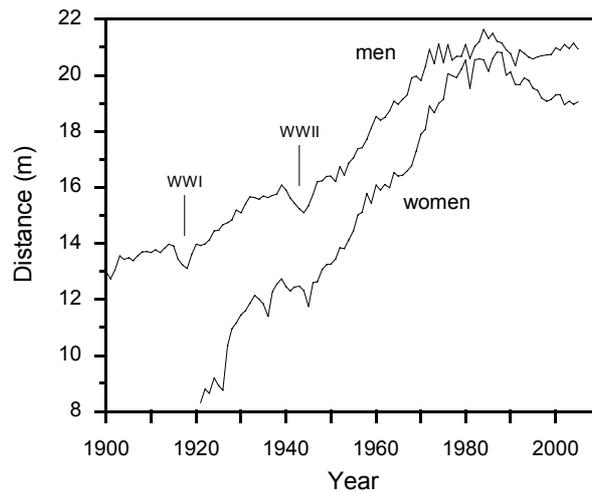
(a) 200m
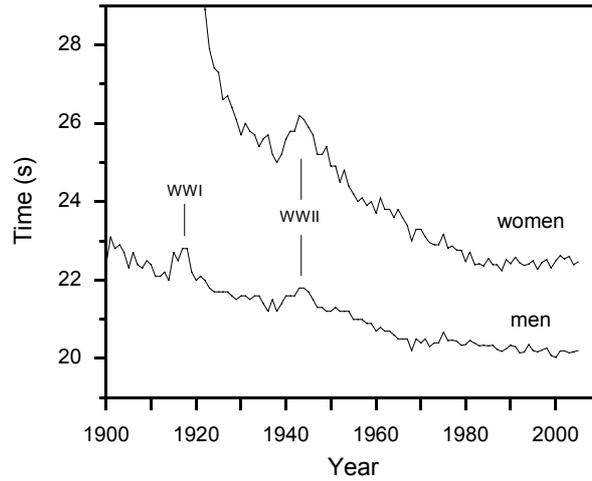
(b) long jump
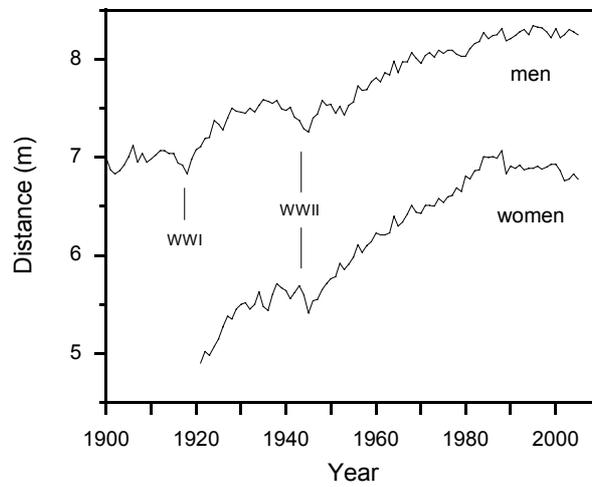
(c) shot put

Figure 12.1. Historical trends in athletic performances for men and women. Data points are the performances by the tenth-best athlete in the year: (a) 200m, (b) long jump, (c) shot put. Performances in these three events have not been greatly influenced by innovation in equipment design or materials.

This chapter looks at examples of innovation in design and materials under six main themes; 1) pole vault, 2) javelin, 3) other throwing implements, 4) hurdles, starting blocks and shoes, 5) running surfaces and other athletic facilities, and 6) timing and other equipment.

12.2 Pole vault design and materials

The most notable example of innovation in athletics implements is the flexible fibreglass pole. In the early 1960s performances rapidly improved when the relatively rigid poles made from steel or bamboo were superseded by highly flexible poles made of fibreglass. Pole vaulting with a highly flexible pole looks spectacular, but the mechanics of pole vaulting and the advantages of the flexible pole are not always appreciated by the viewer (Linthorne, 2000). Pole vaulting is mainly about converting running speed into height above the ground. In mechanical terms the aim of the vaulter is to generate maximum kinetic energy in the run-up, and then convert as much of this energy as possible into the gravitational potential energy of the athlete's body at the peak of the vault. The athlete uses a long pole to achieve this energy conversion. Once the pole is planted into the ground (actually a take-off box that is sunk into the ground), the athlete and pole rotate about the box, gradually transferring the athlete's horizontal speed into height above the ground. The faster the run-up, the longer the pole the athlete can rotate to vertical and the higher the athlete can vault. However, the transfer of kinetic energy to gravitational potential energy is not the only important energy transformation. When the pole is planted into the take-off box the athlete experiences a sharp jarring action, and so some of the athlete's run-up kinetic energy is dissipated in the athlete's body as heat. Also, during the vault the athlete uses muscular energy to lift his/her body up, and so adds to the height cleared.

The flexible fibreglass pole owes it success to its influence on these last two energy transformations. The main advantage of a flexible pole is that it reduces the shock experienced by the vaulter when the pole is planted in the take-off box (Linthorne, 2000). The vaulter therefore loses less run-up kinetic energy and so is able to rotate a longer pole to vertical. Mathematical models also suggest that the optimum take-off angle with a fibreglass pole is lower than with a more rigid pole, and so the vaulter retains more run-up kinetic energy because he/she does not have to spring up as much at take-off. When vaulting with a fibreglass pole the vaulter is able to clear a slightly greater height above his/her hand grip. This is probably because the athlete is able to place him or herself in a better mechanical position to add muscular energy to the vault.

Modern pole vaulting poles are hollow columns constructed from fibreglass or a mix of fibreglass and carbon fibre. These poles may be bent by over 170º without breaking and are able to store an amount of elastic strain energy that is equivalent to about one half of the athlete's run-up kinetic energy (Linthorne, 2000; Nielson, 2006). Pole vaulters do not need a highly flexible pole to successfully perform a pole vault (a rigid pole will do), but they can achieve a considerably greater height through choosing a pole with an appropriate stiffness. Most experienced pole vaulters bring several poles to a competition. Before each jump the athlete selects a pole of appropriate length and stiffness to suit their physical capabilities and the environmental conditions (wind, etc.). With a flexible pole the athlete must take account of the timing of the storage and return of energy in the bending pole. The pole vaulter wants a highly flexible pole so as to minimise the shock on his/her body during the pole plant and take-off (and hence minimise the loss of kinetic energy), but not so flexible that the pole returns the stored energy to the athlete too late. The athlete must select the pole stiffness so that the pole finishes its recoil at about the time when the pole has rotated to vertical (Hubbard, 1980; Ekevad and Lundberg, 1995). If the pole is too flexible the peak of the vault will be located beyond the crossbar, and if the pole is too stiff the peak will be achieved in front of the crossbar. The optimum pole length and stiffness is different for each athlete, and depends on the athlete's run-up speed, body weight, vertical reach, and vaulting technique. Male vaulters tend to use longer and stiffer poles than female vaulters. Typical pole lengths are 4.90 – 5.40 m for elite male vaulters, and 4.30 – 4.60 m for elite female vaulters.

The IAAF competition rules state that the pole may be of any length or diameter and constructed from any material or combination of materials (IAAF, 2006). Originally, pole vaulters used solid wooden poles made of ash, fir, spruce, or hickory (Ganslen, 1979). However, these poles were relatively heavy and so were not conducive to producing a fast run-up. By the early 1900s most good vaulters were using bamboo poles. A bamboo pole is hollow and therefore much lighter than a solid pole of equivalent structural strength. A lighter pole allows the vaulter to achieve a faster run-up. The bamboo pole also had greater flexibility than the other types of wooden pole, and so helped absorb some of the shock when the pole was planted in the ground. Unfortunately, bamboo poles were not particularly durable; they could be damaged or broken when over-stressed during vaulting or through rough handling. Durable and slightly flexible poles made from Swedish steel became available in the 1940s, and by the 1950s steel was the most popular material among the world's best vaulters. Light-weight aluminium poles were introduced in the mid 1930s, but these poles were less flexible than steel or bamboo poles and so did not see widespread use among the leading pole vaulters.

Experimentation with fibreglass poles began in the late 1940s, but it took several years before construction techniques were sufficiently advanced that a durable product with consistent bending properties was produced. The early 1960s saw widespread adoption of the highly flexible fibreglass pole and this resulted in a revolution in performance standards. In the three years from 1961 to 1964 the world record increased by 48 cm (10%). Figure 12.2 shows the increase in pole vault performance over the last century. Most of the improvement is due to the socio-economic and other factors mentioned in section 12.1. However, superimposed on this trend we can clearly see a sudden increase in performance in the early 1960s.
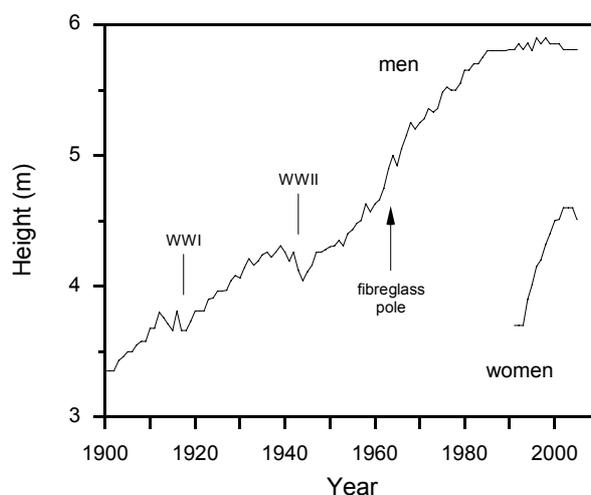

Figure 12.2. Historical trends in pole vault performances for men and women. Data points are the performances by the tenth-best athlete in the year. Note the sudden improvement in performance in the early 1960s when the fibreglass pole was adopted. The pole vault for women was introduced only recently and so the event is still developing.

12.2.1   Construction of a fibreglass pole

Fibreglass poles are constructed from woven fibreglass cloth that is impregnated with epoxy resin. The pole is heated during construction so that the resin bonds the layers of glass together to form a composite material. The stiffness, weight, and recoil speed of the pole are determined by the resin properties, the fibre properties, the orientation of the fibres, and the distribution of the fibres along the length of the pole. The two types of fibreglass used in pole vaulting poles are E-glass and S-glass. S-glass is slightly lighter, has a greater modulus of rigidity, and is more expensive than E-

glass. E-glass is used in some of the less expensive poles that are intended for use by less experienced athletes. The poles for these athletes are relatively short, and so the weight of the pole is not a limiting factor to performance. S-glass is more commonly used for the relatively longer poles used by good athletes, where a lighter pole can significantly improve performance by allowing a faster run-up.

A fibreglass vaulting pole is constructed over a heated metal mandrel, which is removed after construction. Different sized mandrels are used according to the desired length and diameter of the pole. A pole that is made using a larger diameter mandrel has a thinner wall thickness for a given pole stiffness, and hence will be lighter (Burgess, 1996). Any given athlete will have a preferred pole diameter, depending on the size of their hand, that allows a comfortable grip on the pole. Poles designed for female vaulters and junior vaulters are usually made using smaller mandrels.

Most fibreglass poles are constructed from three separate layers of woven fibreglass cloth. For the bottom layer, a narrow strip of fibreglass cloth is wound in a spiral around the mandrel. When a pole is bent during a vault, the material on the far side of the pole is stretched and the material on near side is compressed. The original circular shape of the pole tends to become oval-shaped and the compression side of the pole has a tendency to collapse inwards. The fibres in the bottom spiral layer of the pole are mostly orientated perpendicular to the long axis of the pole, thus giving the pole its 'hoop strength', or resistance to change in shape. The second layer of fibreglass cloth for the pole is a 'full body wrap'; which is a rectangular piece of fibreglass cloth that is the length of the pole. Most of the fibres in this layer are aligned parallel to the long axis of the pole, thus giving the pole its resistance to lateral deflection or 'bending strength'. A pole will have a specified number of complete wraps of cloth around the pole's circumference, and the number of wraps will determine the stiffness of the pole.

The third layer of fibreglass cloth is called the 'sail piece'. The purpose of this layer is to set the distribution of glass fibres along the length of pole, and hence its strength profile. A pole that has a uniform distribution of fibreglass along its length will experience greatest stress and lateral deformation at a point midway along its length. However, such a pole is heavier than is necessary. A better design that minimises the weight of the pole is to taper the distribution of fibreglass along the length of the pole so that there is more towards the centre and less towards the ends. This will give a more uniform distribution of lateral bending strength along the length of the pole. For a pole made from a material with uniform density and Young's modulus, the equation for the optimum distribution of material is a sine function (Burgess, 1996). Real poles are not designed so that the maximal bending stress is exactly the same along the length of the pole. The sail piece is usually in the shape of a trapezoid, which is then wrapped around the pole several times. The geometry of the sail piece and its position on the pole determine where the pole has the greatest bend. Some elite vaulters specify to the manufacturer the desired location of the pole bend so as to give a better match to their vaulting technique.

After the three layers of fibreglass are set on the pole, the pole is cured under high temperature and pressure to get the epoxy resin to flow in the fibreglass cloth. Pole vaulting poles are not perfectly straight; they are deliberately made with a slight curvature. This 'pre-bend' makes the initial stiffness of the pole lower, and so reduces the energy lost when the vaulter plants the pole into the take-off box. The pre-bend is set in the pole by orienting the mandrel horizontally and supporting it at each end when curing the pole. The horizontal mandrel sags under gravity, and so gives the pole a slight bend. The mandrel is also slightly tapered to allow easier removal of the mandrel after curing of the resin. Fibreglass poles therefore have a smaller diameter towards the grip end of the pole.

Pole manufacturers adjust the stiffness of a pole through varying the amount of fibreglass cloth in the body wrap and through the shape of the sail piece. Even so, they always perform a test measurement of the lateral bending stiffness of the final product. A static flex test is performed by supporting the ends of the pole and then loading the pole at the midpoint with a known weight (usually 50 lbs). The central deflection of the pole is measured and recorded on the pole. When

selecting poles, most elite athletes will specify to the manufacturer their desired pole lengths and flex ratings, and sometimes a preferred mandrel size.

Most poles weigh between about 1.5 and 3 kg. At first glance such a small weight would appear to have only a relatively small detrimental effect on the speed that the vaulter can attain in the run-up. However, the vaulter holds the pole towards one end, and so it is the 'carry weight' of the pole that is important. The carry weight is the force the vaulter must exert on the pole to hold the pole in a horizontal position, and can be many times greater than the actual weight of the pole. For example, a 5.0 m fibreglass pole used by an elite male pole vaulter has a carry weight of 170 N, or about seven times the actual weight of the pole (Nielson, 2006). Exerting such a large force to hold the pole inhibits the vaulter's natural sprinting action. The technique of starting the run-up with the pole pointing vertically upwards, and then steadily lowering the pole as the vaulter approaches the take-off, is deliberately used to minimise the detrimental effect of the pole weight on the vaulter's run-up speed. Even so, any reduction in a pole's carry weight is welcomed by the athlete. Pole manufacturers prefer to use materials that minimise the carry weight of the pole for any given pole length.

12.2.2   Carbon fibre poles

Carbon fibre has recently been used to produce lighter poles. The best material for a pole is one that maximises the ratio;

$$\frac{\text{(specific strength)}^2}{\text{(specific stiffness)}} = \frac{(\sigma/\rho)^2}{(E/\rho)} = \frac{\sigma^2}{\rho E} \qquad [12.1]$$

where σ is the maximum allowable bending stress, E is the Young's modulus, and ρ is the density of the material (Burgess, 1996; Wegst and Ashby, 1996). The best practical materials for a vaulting pole are carbon fibre reinforced plastic, followed by glass-reinforced plastic. Figure 12.3 shows the stress-strain curves for carbon fibre, S-glass, and E-glass. Carbon fibre and glass fibre have a similar density, but carbon fibre has a steeper stress-strain curve than glass fibre, so less material is required in a pole of equivalent strength. An important design constraint on a pole is that the maximum allowable bending stress of the pole must not be exceeded during the deformation of the pole. The failure strains of glass fibres and carbon fibres are sufficiently high that it is possible to construct a pole that can withstand a very large deformation.
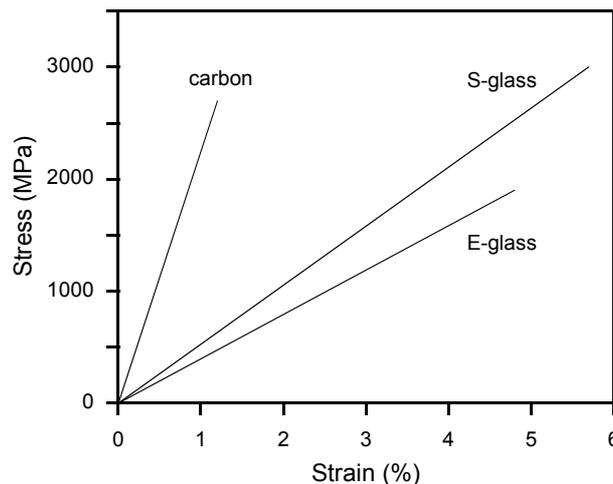

Figure 12.3. Stress-strain curves for glass fibre and carbon fibre.

Carbon fibre has been used in some poles since the early 1990s. In the poles made by Gill Athletic, carbon fibre is currently used only in the body wrap section of the pole. The carbon fibre maintains the mechanical properties of the pole, but reduces the weight by about 15-25% over a

pole made from S-glass. Although lighter than fibreglass poles, carbon fibre poles have not yet been universally adopted by the world's best pole vaulters and so there is no discernable influence of the pole on the historical trend of pole vault performances (see Figure 12.2).

12.3   Javelin design and materials

The javelin throw can trace its origins as a sport back to the Olympic Games of ancient Greece. In the modern event, the javelin must be thrown using one hand only, without the aid of a sling or other throwing device. Because an athlete can generate a greater release speed with a lighter implement, the competition rules in the throwing events always specify a minimum weight for the implement. In the javelin throw the minimum weight is 800 g for men and 600 g for women.

In the first half of the twentieth century many of the best throwers used javelins made of Finnish birch (Isaacs, 1992). The two basic design principles were to minimise the cross-sectional area of the javelin so as to minimise aerodynamic drag, and to make the javelin as stiff as possible so as to minimise aerodynamic losses arising from vibration of the javelin. Nowadays javelins are constructed from steel, aluminium alloy, or carbon fibre. A modern javelin differs from the early designs in that it has a much larger cross-sectional area. Dick Held is credited with introducing the 'aerodynamic' javelin in the 1950s. His experiments led to the realisation that it is better for the javelin to have a larger surface area to augment the javelin's flight capacity through producing a greater lift. Dick's brother Bud set a world record using his aerodynamic javelin in 1953. Ever since, the rules governing the flight enhancing capabilities of the javelin have been subject to considerable debate and controversy, and the rules have been tightened and changed several times.

The aerodynamic behaviour of a javelin is relatively complex. When a javelin is launched with an angle of attack the javelin acts as an airfoil and so generates lift as well as drag. If the javelin is asymmetrical in shape the centre of pressure of the javelin (the point through which the aerodynamic forces act) does not coincide with the centre of mass. The aerodynamic forces then create a moment about the centre of mass, causing the javelin to pitch up or down depending on whether the centre of pressure is ahead or behind the centre of mass. Wind tunnel tests on javelins in the 1970s revealed that there were three equilibrium points in the pitching moment curves of a typical javelin (Hubbard and Rust, 1984; Terauds, 1972). The centre of pressure is first behind, then in front of, and then again behind the centre of mass as the angle of attack is increased.

The rules governing the dimensions of the javelin were substantially changed in 1986. At the time, the world record in the men's event was about 100 m, which was making it increasingly difficult to hold the event within the confines of a standard athletics stadium. However, this was not the main reason for the change in rules, as is often reported. The main factor that motivated the change was that in many throws the javelin was landing nearly flat, placing large pressure on judges to determine whether the throw was valid or not. (A throw is valid if the tip of the metal head of the javelin strikes the ground before any other part of the javelin.) Also, the pitching-moment characteristics of most javelins were unstable in yaw, causing erratic throws which endangered athletes and officials (Hubbard, 1989).

The javelin was redesigned by shifting the centre of mass forward by 4 cm, while constraining the dimensions of the rear section of the javelin to effectively prohibit the centre of pressure from being moved forward as well (Borgström, 2000; Bremicker, 2000). The new design guaranteed that the pitching-moment profile of the javelin was monotonically decreasing, without ever attaining a positive value. As a result, the nose-down pitching moment now lasts throughout the flight, giving a greater incidence of tip-first landings.

The new specifications severely restrict the flight enhancing effects of the javelin, and the possible variations in javelin construction are now much more limited. Tests using javelin launching machines suggest that distances achieved with the re-designed javelin should be about 5 m less than those achieved under the previous rules. A drop in performance of about this magnitude is clearly evident in the historical record of competition performances (see Figure 12.4).

The high incidence of flat landings was also a problem in the women's event. In 1991 the dimensions of the women's javelin were changed so as to specify a minimum diameter for the shaft. However, the location of the centre of mass of the javelin was not changed. While this change in specifications produced fewer flat landings, they were not completely eliminated. The centre of mass was put forward by 3 cm in 1999, and this has been sufficient to create valid landings in most throws. As in the men's event, slight reductions in throwing distance arising from the rule changes are evident in historical record of competition performances (see Figure 12.4).

Most javelins experience a small lateral oscillation during flight (Hubbard and Bergman, 1989; Macari Pallis and Mehta, 2003). Lateral oscillation is detrimental to performance as it increases the aerodynamic losses. Many athletes attempt to minimise the magnitude of oscillation by using a straight line pull on the javelin during the launch phase; but this is very difficult or even impossible to achieve. Most of the best athletes prefer to use a stiff javelin that minimises any lateral deflection generated during the launch. The best javelins are also designed so that if an oscillation is produced, it is quickly damped out. The javelins used by most of the leading athletes are constructed from carbon reinforced fibreglass, but these implements are relatively expensive. Aluminium alloy is used in javelins used by the majority of lesser athletes.
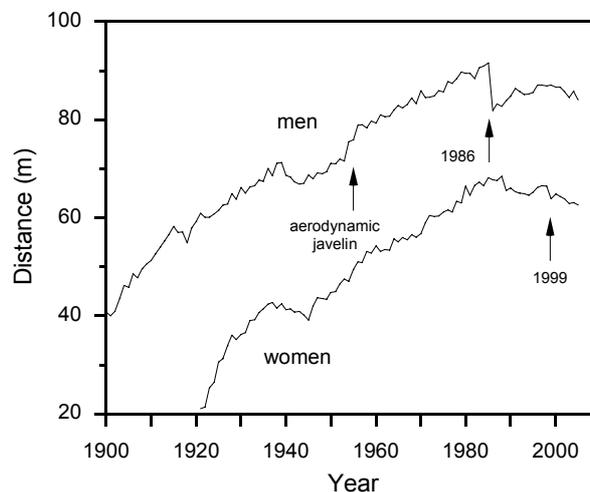

Figure 12.4. Historical trends in javelin throw performances for men and women. Data points are the performances by the tenth-best athlete in the year. The aerodynamic javelin was developed in the mid 1950s. Note the decrease in the men's performances in 1986 when the rules governing the dimensions of the javelin were changed. A slight decrease in women's performances is also evident following a similar rule change in 1999.

In the early 1990s, several world records were set by athletes using a javelin designed by the former Olympic Champion, Miklós Németh. This javelin featured surface roughness on the tail to reduce aerodynamic drag. However, the view of the IAAF was that surface roughness was a feature that was incorporated into the javelin purely to enhance the performance of the javelin relative to previous designs. The javelin was therefore banned, and all performances achieved with the implement were retrospectively disqualified. More recently, some manufacturers have incorporated an internal stiffening bar into the shaft of the javelin to reduce oscillation. These designs have also been banned.

12.4 Design and materials for the shot put, hammer, and discus

The shot put is probably derived from the Highland Games event of thrusting or 'putting' a heavy stone for maximum distance. Under IAAF competition rules the shot may be constructed from solid iron, brass, or similar hard metal. Nowadays, most of the better implements are made of stainless steel. The competition rules allow a range of about 15% in the diameter of the implement. A smaller diameter shot does not travel substantially farther than a large diameter shot that has the same launch speed. There is a negligible difference in range arising from differences in aerodynamic drag between the smallest and largest implements. Most elite athletes prefer to use a large diameter shot, claiming that they like the 'feel' of the implement. Some say the large shot gives them a 'larger area to push on', and so allows them to achieve a greater release speed.

The original implement used in the hammer throw was a sledge hammer like those used in ironworking and mining. Nowadays, the hammer head is a spherical ball of steel, and the wooden handle has been replaced by a steel wire that is attached to a special grip. Unlike the shot put, the diameter of the hammer head has a substantial influence on the distance achieved (Dapena and Teves, 1982; Dapena, Gutiérrez-Dávila, Soto and Rojas, 2003; Hubbard, 1989). Aerodynamic drag is considerably more substantial in the flight of the hammer than in that of the shot, mainly because the velocities are roughly twice as great. Also, the projected area of the hammer and the effective drag coefficient are both about 50% larger. Dapena et al. (2003) calculate that aerodynamic drag reduces the range of a 84-m throw by about 3.8 m (4.5%). Most elite throwers deliberately select a hammer that is close to the minimum diameter permitted by the competition regulations.

The length of the hammer wire has a very strong influence on the release velocity of the hammer. It is well known that the release velocity of a hammer is determined by the angular velocity of the athlete-hammer system just before release, and by the distance from the axis of rotation of the athlete-hammer system to the centre of mass of the hammer. A longer implement therefore results in a greater release velocity, and so most throwers deliberately use a hammer whose length is as close as possible to the maximum permitted by the competition regulations.

In major competitions the athletes are provided with a selection of certified implements from different manufacturers. Even so, competition officials must be vigilant in spotting implements that become illegal through damage suffered during the competition or through deliberate tampering by an athlete. For example, at the Sydney 2000 Olympic Games all the athletes in the final decided to use one particular hammer out of the range of implements on offer. The model of hammer in question had a design defect in its handle that caused the hammer to become stretched by 9 mm (Wilson, Guy and Matrahazi, 2006). The defect was quickly noticed by the athletes, but not by competition officials until the implements were re-measured after the competition was over. Changes were subsequently made to the competition regulations for the dimensions of the hammer handle in an endeavour to improve the reliability of hammer handles.

12.4.1 Design and materials for the discus

The competition implements used in the Olympic Games of ancient Greece were constructed from bronze and varied in weight from 1.5 to 4 kg (Quercetani, 2000). The modern discus has been standardised at 2 kg for men and 1 kg for women, and the dimensions of the implement are tightly specified. The materials used in the construction of the discus are chosen on the basis of durability and cost. A discus usually has sides made of aluminium, fibreglass, or wood; and a rim made of steel, bronze alloy, or brass alloy (Macari Pallis and Mehta, 2003). Although the minimum weight of the discus is specified, there are no restrictions on how the mass must be distributed within the discus. The moment of inertia of the discus has a strong influence on performance, and so the athlete must make an appropriate choice of implement.

The flight of a discus is strongly influenced by aerodynamic forces. The discus is a symmetric airfoil, and when launched with a small angle of attack it generates aerodynamic lift which prolongs its flight. Unfortunately, the aerodynamic forces acting on a spinning discus also produce torques which tend to pitch the discus upwards and sideways (Frohlich, 1981; Hubbard,

1989; Soong, 1976). However, the gyroscopic properties of the spinning discus may be used to stabilise its flight and minimise the adverse effects of these aerodynamic torques.

Elite throwers prefer an implement that has most of the mass concentrated in the rim, hence giving the discus a large moment of inertia. Elite throwers can launch such a discus with a relatively high spin and therefore a large angular momentum. A discus with a larger angular momentum has greater resistance to changes in the orientation of the discus that arise from the aerodynamic forces that act on the discus during its flight. A discus used by an elite thrower usually has a rim weight of about 80–92% of the total weight of the discus, and will be rated by the manufacturer as 'ultra high spin' or 'very high spin'. Less capable athletes prefer to use a discus with a lower moment of inertia. Such a discus has about 70–75% of the total weight of the discus in the rim, and will be rated as 'low spin'.

The differences in an athlete's preferred moment of inertia for the discus are probably due to differences in the launch speed that the athlete can generate. As well as maximising the launch speed of the discus, the thrower would like to maximise the angular momentum of the discus at the instant of release so as to give the discus the greatest stability in flight. At the end of the release phase of the throw, the discus is spun off the index finger or the middle finger of the throwing hand, spinning clockwise when viewed above for a right-handed thrower. A discus with a large moment of inertia will be more difficult to get spinning during the release phase, and so will have a lower spin at the instant of release. For any given release velocity there is probably an optimum moment of inertia that allows the thrower to produce the greatest angular momentum in the discus. The greater strength of elite throwers allows them to generate a higher speed in the throwing hand, and hence impart a high rate of spin to a discus with a larger moment of inertia. Some coaches have suggested that a discus with a larger moment of inertia remains in contact with the thrower's hand for a little longer, and so the athlete is able to generate a slightly greater launch speed.

12.5 Design and materials for the hurdles, starting blocks, and shoes for athletes

The design of the barriers used in the hurdles events has shown an evolution in design towards minimising the risk of injury to the athlete. The hurdle barriers of the nineteenth century were solid sheep fences that crossed over several lanes and were staked rigidly into the ground. Under such conditions the athletes were primarily concerned with making a safe clearance rather than a biomechanically efficient clearance to maintain running speed. Performances improved at the start of the twentieth century following the introduction of the movable individual hurdle in the form of an inverted T. Even so, the physical penalty to striking a hurdle varied considerably between meets because of differences in the weight and construction of the hurdle.

The modern L-shaped hurdle and set of design specifications was introduced in 1935. The hurdle must now be constructed in such a way that it will overturn if a force equal to a weight of between 3.6 and 4.0 kg is applied to the top edge of the crossbar. This change has lessened the chance of injury and consequently frees the athletes of much of the psychological hindrance. Because men, women, and junior athletes compete over hurdles of different heights, most modern hurdles are adjustable in height and have movable counterweights in the base so that the required overturning force may be obtained for each hurdle height. Some of the more advanced hurdle designs automatically move the counterweight in response to the height adjustment. At least one company manufactures a hurdle that has a bevelled edge on its base so that the crossbar of the hurdle is directly above the tip-over fulcrum. This ensures that the crossbar does not rise when the hurdle is hit or toppled. Modern hurdles are constructed from light-weight materials such as aluminium so as to make it easier for competition staff to place and remove the hurdles from the track. Splinterproof polycarbonate crossbars have now replaced the more dangerous wooden crossbars.

Several commentators have suggested that the women's hurdle should be higher than is specified by the competition regulations (Etcheverry, 1993; Stein, 2000). Under the present rules

the women's event places less emphasis on hurdling skill and more on sprinting ability than the men's event. The men's hurdle is about 57% of a typical athlete's standing height, but the women's hurdle is only about 50% of an athlete's standing height. Increasing the height of the women's hurdle to about 0.91 m would raise the technical demands of the women's event and give parity with the men's event.

12.5.1 Starting blocks

Starting blocks were introduced in the late 1920s and were used in the Olympic Games for the first time at the 1948 Games in London. Previously, athletes either had no starting aids or dug starting holes in the ground for their feet. Modern starting blocks usually have a heavy metal base and two adjustable foot pedals about 15 cm wide. The longitudinal spacing and angle of the foot pedals may be adjusted to the athlete's preferred setting.

In most starting blocks the foot pedals have a fixed lateral spacing of about 10 cm. However, this spacing may not be optimal. The footfalls of most elite sprinters have a lateral spacing of about 40 cm for the first few strides out of the blocks; reducing to about 17 cm at full speed sprinting (Ito, Ishikawa, Isolehto and Komi, 2006). This suggests that starting blocks should have a wider foot pedal spacing, allowing the athlete to produce a more direct linear exit from the blocks, with the feet landing directly ahead of the initial position of the feet in blocks. In recent experiments, athletes using blocks that were spaced laterally by about 20 cm produced faster times to the 20-m mark than blocks with the usual 10 cm spacing (Parry, Henson and Cooper, 2003). Some manufacturers have now produced starting blocks that have very wide foot pedals which permit the athlete to select their preferred lateral foot spacing.

12.5.2 Running shoes

For many athletes, running shoes are their most important piece of kit. Under IAAF regulations the purpose of the athlete's shoe is to give protection and stability to the foot and provide a firm grip on the ground. The shoe must not be constructed so as to give the athlete any additional assistance, and no spring or device of any kind may be incorporated in the shoe. The design of running shoes has shown a steady evolution towards minimising the weight of the shoe. A lighter shoe reduces energy consumption during a distance event, gives a quicker acceleration and a higher top speed in a sprint, and allows a greater vertical take-off speed to be produced in a high jump or long jump.

The stiffness of the baseplate of a sprint shoe can have a significant effect on performance (Stefanyshyn and Fusco, 2004). Adidas produces a 'performance plate', which is a rigid carbon fibre plate that is inserted into the sole to stiffen the shoe under the metatarsal joints. The energy that is normally dissipated during the initial bending of the metatarsal joints at touchdown is stored in the carbon fibre plate and returned to the athlete during the toe-off phase of the stride. Experiments on sprinters running over 20 m showed an improvement of just over 1% with a stiffening plate in their shoes.

12.5.3 High jump and long jump shoes

In the high jump, the design of the athlete's shoe is believed to have a small but significant influence on performance. Yuri Stepanov (URS) set a world record of 2.16 m in 1957 using a take-off shoe that had a 2–4 cm thick sole (Hymans, 2003; Lawson, 1997). The most obvious advantage of a built-up shoe is that the athlete's centre of mass is higher above the ground at take-off and so the height of the jump is correspondingly increased. Taken to the extreme, an athlete could wear what is essentially a pair of stilts and then simply step over the crossbar. The IAAF viewed the built-up shoe as giving 'unfair assistance' to the athlete, and it was banned shortly after being introduced. However, Stepanov's record was allowed to stand. Since 1958 the thickness of the sole of the high jump shoe has been restricted to 13 mm.

The restriction on the thickness of the sole also applies to long jump shoes. In the long jump the athlete wishes to project their body for maximum distance beyond the take-off line, and it is well known that the range of a projectile is greater the higher the launch position is above the landing position. In the long jump the angles of take-off and landing are usually around 20–30°, and so the athlete can be expected to jump about 2 cm farther for each 1 cm increase in take-off height. It therefore seems appropriate to place a restriction on sole thickness for long jump shoes as well as for high jump shoes.

Some shoe manufacturers have optimised the design of the sole within the restrictions that have been placed on the thickness. Adidas produce a long jump shoe that is described in their promotional literature as having a 'negative heel design'. The sole thickness is tapered, from thickest under the ball of the foot down to thinnest under the heel. The aim is to give the athlete an effectively longer take-off leg during the take-off. This advantage is maximised by making the difference between the length of the leg at touchdown (with the landing on the heel) and the instant of take-off (with the ball of the foot) as great as possible. A longer take-off leg may give a biomechanical advantage by allowing the athlete to generate a greater take-off velocity, and hence produce a longer jump.

12.6 Design and materials for running surfaces and other athletic facilities

Until the late 1960s, most major athletic competitions were held on surfaces of grass or cinders. Synthetic running surfaces were approved for competition by the IAAF in 1964, and the first major international competition to be held on a synthetic surface was the 1968 Olympic Games in Mexico City. The main benefit of a synthetic track is that it is 'all weather', with a constant performance standard under all environmental conditions. Unlike cinders and grass tracks, a synthetic track is relatively unaffected by rainfall. Synthetic running surfaces are durable and require less maintenance, but have a high initial capital outlay.

The running track, aprons and runways of a typical athletics arena are constructed in a series of layers (Buccione, 1999). The foundation layer usually consists of a ballast of loose stone, which is then overlaid with a binder layer of asphalt. The top layer is the synthetic running surface, which comes in four main types: pre-fabricated, solid polyurethane, sandwich system, and porous rubber crumb. Two of the more notable surfaces are *Rekortan M99* by APT, which has a baselayer of polyurethane-bound rubber granules overlaid with a layer of polyurethane and rubber granules; and *Sportflex Super X* by Mondo, which is a pre-fabricated surface of calendered, vulcanised and stabilised polyisoprenic rubber.

The performance of sports surfaces are measured by a battery of tests, including tests of resilience, deformation, spike resistance, skid resistance, and sliding behaviour. The most important performance test for a running surface is the measurement of resilience, and the IAAF has set an approved range of resilience for tracks intended for international competitions. The standard device for measuring the resilience of a sports surface is the 'Artificial Athlete Berlin', in which a 20 kg weight is dropped a distance of 55 mm onto a 3 kg measurement foot that incorporates a spring with a spring constant of 2000 MN/m (Kolitzus, 1984; Walker, 2003). The force-time curve is recorded during the bounce of the mass, from which the energy loss and force reduction of the surface may be calculated. Hard tracks are believed to be produce fast times for sprinters, but are associated with an increased risk of leg strain injuries, particularly in long distance athletes.

Mondo's *Sportflex Super X* is a favourite competition surface with many athletes, particularly sprinters and jumpers. Mondo surfaces have been installed in many of the venues used for major international competitions. This type of surface has an underlying honeycomb structure of small air-filled deformable cells. The side walls of the cells are angled at about 45° in the direction of running, which gives the track a greater stiffness to the horizontal-vertical forces generated by sprinters, while at the same time presenting a softer vertical surface desired by distance athletes. Also, with a Mondo surface it is not necessary for the athlete to have penetrating spikes in their

shoes. Instead, special cone- or pyramid-shaped spikes that merely deform the running surface are used. Mondo claim that non-penetrating spikes reduce the energy loss at each footfall, and thus increase the athlete's running speed.

12.6.1 Safety equipment

Considerable energy continues to be expended in efforts to make the competition environment safer and to reduce the risk of injury to athletes, officials, and spectators. The most obvious examples of safety equipment are the throwing cages used to capture wayward implements in the discus throw and hammer throw. The IAAF specifies the dimensions of the throwing cages, including the minimum strength of the cage netting (Laruel, Wilson and Young, 2004; Wilson, Guy and Matrahazi, 2006). The cage must be designed so as to stop an implement moving at a speed equal to that generated by an elite thrower, without allowing the implement to ricochet or rebound back towards the athlete or over the top of the cage.

The modern landing mat has played a vital but sometimes over-looked role in the progress of the high jump and pole vault (Guy, 1994). Without it, the Fosbury Flop and the uninhibited landings of today's pole vaulters would not be possible. Originally, the landing areas in the high jump and pole vault were just piles of sand, sawdust, or wood shavings. These were replaced in the late 1950s by mounds of loose foam rubber, and later by the integrated pits constructed from several large pieces of low stiffness polymer foam that we see today. The energy absorption of the landing mat is a direct consequence of the foam structure, in that air can be expelled from the mat, and the cell walls of the foam can collapse (Mills, 2003). Landing mats usually have a PVC cover to reduce damage to the foam from the UV component of solar radiation. The IAAF specifies the minimum dimensions of the landing pits for both the high jump and pole vault.

12.6.2 Visual design

Good design in athletics also includes the visual characteristics of the equipment and its influence on safety and performance. Obvious examples include the top beam of the steeplechase hurdle, which under IAAF regulations must be painted in black and white stripes (or other contrasting colours) to aid visibility and thereby reduce the risk of injury to the athletes. In the high jump and pole vault the crossbar is often painted in colours that help the athletes sight the bar, and in the long jump and triple jump the take-off board must be painted white to help the athletes sight the board and so reduce the number of invalid jumps. Recently, the IAAF specified that the plasticine indicator board must be a contrasting colour to the take-off board. (The plasticine indicator board is a 10-cm wide board that is placed after the take-off board to assist the judges in determining if the athlete has over-stepped the take-off line.) In competitions that used a white indicator board, many athletes were targeting it as if it were part of the take-off board and so tended to overstep the take-off line (Linthorne, 2005). An indicator board that is a contrasting colour to the take-off board is expected to minimise the number of invalid jumps and so improve the appeal of the event to spectators.

12.7 Design and materials in timing and other equipment

Accurate timing is essential for the recognition of record performances, especially in the sprint events. Initially, timing in athletics competitions was not particularly precise; most hand-held stop watches could only be read to a fifth of a second. The first Olympic Games to use timing to a tenth of a second was the 1912 Games in Stockholm. Fully automatic electronic timing to 0.01 seconds has been used in the Olympic Games since 1932, but the electronic times were not reported as the official time until the 1972 Olympic Games. Fully automatic electronic timing has been mandatory for the recognition of record performances since 1974. Electronic timing is usually about 0.23 s slower than hand timing because of the reaction time of the time-keepers to the starting gun and the

rounding of the time to the next highest tenth of a second. This difference is clearly seen in the historical trend of 100m performances (see Figure 12.5).

Video-based electronic timing systems have now replaced earlier systems that required the capture and developing of photographic images. In a fully automatic electronic timing system that is approved by the IAAF, the timing system is started by a sound signal or electrical signal from the starting gun. The delay between the report of the gun and the starting of the timing system must be less than 0.001 s. The leading edge of the finish line is recorded by a video camera through a narrow vertical slit in front of the camera lens. This produces a continuous image of the athletes as they cross the finish line. The photo-finish image is synchronised with the timing system, and the times and placings of the athletes are determined by moving a cursor on the photo-finish image. Performances can be determined to an accuracy of 0.001 s, and the more sophisticated timing systems can provide almost instantaneous results to television and to the stadium information system.
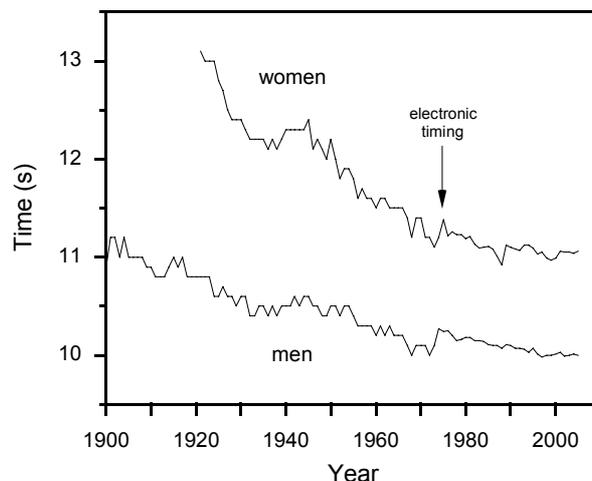

Figure 12.5. Historical trends in 100m performances for men and women. Data points are the performances by the tenth-best athlete in the year. Electronic timing to 0.01 s has been mandatory for the recognition of record performances since 1974.

12.7.1 Starting guns

The purpose of the starting gun is to give the athletes a fair start and to trigger the timing system. Seiko has developed a 'silent gun' which eliminates the disadvantage that is usually given to the outside lanes. In a normal starting system the athletes respond to the sound produced by the starter's gun. However, the athletes that are farther away from the starter are at a disadvantage because of the finite speed of sound. The speed of sound is about 350 m/s, and so 0.01 seconds is added to the race time for each 3.5 m between the starter and the athlete.

In a silent gun the starting gun itself makes no sound. Instead, the gun sends an electrical signal to the speakers on the athlete's starting blocks, which then produce a sharp sound. All the athletes therefore hear the starting signal at the same time, and the signal is heard almost as soon as the gun is fired. The silent gun has been used at recent World Championships, but not at the Olympic Games because the official suppliers of the timing systems have not developed such a device (Julin and Dapena, 2003).

12.7.2 False start detection

At major competitions, including the Olympic Games and World Championships, the athletes must use starting blocks that are linked to an approved false start control apparatus. If the force exerted by the athlete on the blocks exceeds a certain threshold before 100 ms after the gun is fired, the athlete is deemed to have committed a false start and the starter is alerted by a tone through a set of headphones. The false start time threshold is based on the assumption that the minimum physiological reaction time to an auditory signal is at least 100 ms, but this assumption has recently been questioned (Pain and Hibbs, 2007).

The threshold force required to trigger a false start (typically about 200 N) depends on the design of the blocks. Unfortunately, continual changes in technology and subtle refinements in equipment specifications make it difficult to compare start time data from different competitions. However, on average, female sprinters record slower reaction times on starting blocks than male sprinters, even though no gender bias is evident for reaction times in general (Martin and Buoheristians, 1995). The difference is believed to be due to the fact that male athletes are usually heavier and stronger than female athletes. A stronger athlete is able to generate a force that crosses the threshold sooner. Also, a heavier athlete exerts more force on the blocks in the set position, and so is closer to the threshold force. Therefore, male athletes appear to react faster than female athletes when measured using starting blocks.

12.7.3 Wind gauges

The wind can have a strong effect on athletic performances, and records in some events will only be recognised if the assistance from the wind is not deemed to be excessive. Excessive wind assistance was originally based on the subjective opinion of the referee, sometimes using observations of the movements of nearby trees, a hand-held cloth or handkerchief, or smoke from a small fire to determine the direction and strength of the wind. Since 1936 the wind must be measured using a calibrated wind gauge, and a record performance will not be accepted in the sprints, hurdles and horizontal jumps if there is a following wind of more than 2.0 m/s.

The most common type of wind gauge is the tube propeller anemometer, which consists of a light-weight and freely rotating propeller inside a tube about 10 cm in diameter and 40 cm long. The tube is placed parallel to the direction of running, and a 10 s wind measurement is taken during the event. (A 5 s measurement is used in the horizontal jumps.) A tube propeller anemometer gives a reliable reading in a steady wind. However, under fluctuating conditions the intrinsic inertia of the propeller leads to a time lag of several seconds while it adjusts to the change in wind velocity. The short measurement times required in athletics means that official wind readings taken with this type of device can be in error by up to 50% (Vanuytven, 1994).

A more accurate and more expensive device is now mandatory for major championships and international competitions. The device uses ultrasonic sound waves to measure the wind speed. A sound wave travelling through a stationary medium has a characteristic velocity (e.g. 343 m/s at 20ºC). Moving air from the wind will add to this characteristic velocity. In an ultrasonic wind gauge, time of flight measurements of short bursts of sound are made between small transmitters and receivers about 15 cm apart. The system measures the sound travel time in both directions to compensate for temperature, humidity, and air pressure effects.

12.8 Future trends

The preceding discussions should give the impression that opportunities for the innovative sports engineer to improve safety and event presentation in athletics are reasonably good. However, the conservative nature of the underlying philosophy of athletics leads one to be less optimistic about opportunities for developing equipment to enhance performance. Even so, many equipment manufacturers put considerable effort into optimising the design of their equipment within the often

quite tight boundaries set by the competition regulations. A product that gives a performance advantage to the athlete, however small, will have an advantage in the sports equipment market.

From the viewpoint of the sports engineer and sports scientist, it is important to recognise that the athlete's body should also be considered as a machine that can be engineered and optimised. The performance of the human machine may optimised through talent identification, where athletes of appropriate body size and body type are recruited to the sport; through athletic training, where the performance of the human machine is improved through strength training and physical conditioning; and through technique coaching, where the movement patterns of the human machine are optimised for its given set of physical dimensions and physical capabilities. Consideration of the athlete as a machine is an underused concept, and one that should lead to better athletic performances in the future. Until now, innovative athletic techniques have been almost exclusively developed by athletes and coaches, and not by sports scientists and sports engineers. In the future, scientists and engineers should look harder at discovering new athletics techniques. However, one must always be wary of developing a technique that will be banned because it changes the fundamental nature of the event or is dangerous. Current athletic techniques should also be optimised for the individual athlete. The optimum body size, level of physical conditioning, and technique for an event may be identified through mathematical modelling, and then verified with experimental studies on athletes.

12.9   Sources of information and advice

Any scientist or engineer working in the sport of athletics needs to become familiar with the competition rules. These are contained in the IAAF rule book, which may be obtained from the IAAF website (http://www.iaaf.org/). A good understanding of the history of athletic techniques and equipment may be obtained by reading *Track and Field Omnibook* by Ken Doherty, and *A History of Modern Track and Field Athletics* by Robert Quercetani. Alphonse Juilland presents some radical ideas on the future of athletics in his book, *Rethinking Track and Field*.

Most of the major sports equipment manufacturers have a website with details about their products. Useful websites include those for Gill Athletic (http://www.gillathletics.com/), UCS (http://www.ucsspirit.com/), Dima Sport (http://www.dimasport.fr/), Nordic Sport (http://www.nordicsport.se/), and Nemeth Javelins (http://www.nemethjavelins.hu/eindex.htm). For information about synthetic running tracks see the Mondo website (http://www.mondoworldwide.com/index.cfm?lingua=it), and for information about electronic timing systems see the websites for Omega Electronics (http://www.omega-electronics.ch/) and Finish Lynx (http://www.finishlynx.com/).

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