Introduction

How Materials Effect Performance in Sports Events: Contrasting Contributions

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HOW MATERIALS EFFECT PERFORMANCE IN SPORTS EVENTS:
CONTRASTING CONTRIBUTIONS

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Abstract

The various issues in designing and implementing new sports equipment are discussed, including whether use of new technology will lead to fundamental changes in the sport and cost concerns. The performance of athletes in various sporting events is then reviewed; including, in one case, our equine friends. In an event such as running design/material, has had only a minimal effort, while in pole vaulting, javelin throwing and bicycling the effect has been substantial. In events such as golf, tennis and softball/baseball where absolute records are hard to define qualitative improvements have occurred.
Introduction

The broad area of sports engineering is an interdisciplinary subject, which encompasses and integrates not only sports science, materials science, biomechanics (a science concerned with the mechanical stresses and strains that the human body is exposed to in sporting activity) and engineering \(^1\), \(^2\). There are also much broader political/social issues that are important in developing and implementing new sports technology \(^3\). Improved designs and materials, which enhance sporting capabilities, cannot be introduced in isolation. Amongst the issues which must be addressed are whether the new technology will lead to (a) a fundamental change in the sport, so that prior performances (the tradition of the sport in question) become meaningless, (b) improved performance but with a dramatic increase in injuries and (c) a cost of the equipment which makes it only affordable to rich or elite athlete (armed with a sponsor)? Having a totally illegal “trampoline effect” golf driver and hitting the ball 400 yards sounds great but this reduces a “full length” course to virtually a par 3. And vaulting poles costing almost $10,000 apiece which last only a few weeks is crazy—yes, it’s crazy, but that the current situation at the top level of pole vaulting.

Rules may also be used to promote interest and even sex-appeal (e.g. prescribed use of bikini type shorts in beach volley-ball). The serve has “created” the modern game of tennis and it may “destroy” it unless new rules are put in place to alleviate the dominance of the serve. Now, new regulations relating to the turf used in tennis courts, size and weight of the tennis ball are being examined.

The philosophy of the ancient Greek and Roman athletes was that the aura of their prowess gave them prestige \(^3\). This situation is quite different in sports today where we have a global business driven by performance and records. The extensive media coverage of sporting events serves to heighten public awareness of sports and of top sports people, as well as to sustain and increase sales of sporting goods and services through aggressive branding and marketing in a highly competitive global marketplace. The quest for new markets, records and sports supremacy has led to millions of dollars being spent on research and development of sport technique and equipment. The size of the sports and recreation equipment market in the USA alone is about $18B \(^4\).

Clearly some sports such as pole vaulting have benefited much more from advances in design/materials than others, such a running; this will be discussed in more detail later in this paper.

Advanced Materials

Advanced materials with mechanical and physical behavior characteristics well in excess of those exhibited by conventional high-volume materials such as steels and aluminum alloys have contributed significantly to the heightened performance of transportation systems in aerospace, automobiles, and trains. The important characteristics include strength, ductility, stiffness (modulus), temperature capability, forgiveness (a collective term including fracture toughness, fatigue-crack growth rate, etc.), and low density. Advanced materials also play a major role in the construction of sports equipment. For many high-performance applications, high cost is accepted, although in some sports, such as golf a user backlash has led to creative lower cost concepts \(^5\).
To meet the requirements of sports equipment, the materials of choice often consist of a mixture of material types—metals, ceramics, polymers, and composite concepts. These are fabricated into the desired equipment, making use of creative design concepts with due attention given to biomechanical requirements. By comparing specific properties (i.e., taking the difference in density of competing materials into account), the attributes of difference materials can be better evaluated. Thus, if we want a material that features the highest possible stiffness for the least possible weight, we would select the material with the highest specific stiffness. Cellular concepts win out as compared to monolithic materials in this regard since the density of cellular materials is less than that for the solid article. In the actual design of complex sports equipment, a specific design criterion needs to be defined to allow the optimum materials selection to be made.

**Sporting Events**

**Running**

There is little in the way of technology in the 100 m sprint apart from shoes and the surface. Although these factors do affect performance, it is likely that the majority of improved performance in this event over the last 100 years is due to improvements in the athlete. Figure 1 shows the winning times for the 100m sprint at the Olympic games from 1896 to 1996. It is likely that the improvement is due to better training methods, coaching, physiology, nutrition and a drive for success.

![Figure 1. Winning Times for the 100m Sprint at the Olympic Games since 1986.](image-url)

This continuous downward trend in the times for the men’s 100 meters winning times in the Olympics (Figure 1) is not repeated, if we examine the winning times for horses in the Kentucky Derby. Here a distinct leveling off occurred in the middle of the twentieth century (Secretariat’s record time in the early 1980’s stands out), Figure 2. To the writers the only difference between man and horse is mental—i.e. the human desire to win has increased (“fame is the spur” as Milton aptly stated) while the horse is not so driven.
Figure 2: Winning Times in the Kentucky Derby.

A final note on running very recently (Jan. 2001) Alan Webb of South Lake High School in Reston, Va. broke the 4 minute barrier for the mile. Alan is the only fourth high schooler to do so, and the other three (Ryan, Danielson and Liguori) did it in the 1964-1967 time period. A 34 year hiatus. Why?

Pole Vault
In complete contrast to running the performance in the pole vault has been dramatically influenced by improved design/materials (Figure 3). The 1896 Olympics saw a height of ten feet, six inches achieved with a solid hickory pole. Bamboo poles were introduced in 1904 (by A.C. Gilbert then of Moscow, Idaho) and were used for almost the next 50 years. By the 1950’s improvements in performance between Olympic games was minimal. A brief use of aluminum poles had little effect but a major change occurred in 1964 when poles made from complex graphite-epoxy composites were introduced \(^1\). These poles were lighter and less stiff than previous poles and allowed the athlete to change style, performing a relatively complex maneuver of rotating upside down to go over the bar feet first. Thus it is the change in technique that has allowed the athlete to improve performance as a result of the technology. Today, the world class pole vaulter utilizes a highly sophisticated composite pole, resulting in a 1996 Olympic record of 19 feet, five inches.

Figure 3: Gold Medal Winning Heights For The Pole Vault At The Olympic Games Since 1896.
Bicycling
A number of advances have contributed to the high efficiency of the modern-day bicycle, including the development of spoked wheel, the chain concept, pneumatic tires, and accessories (e.g., seats, brake levers, and pedals). However, the two major advances are in the frame and wheels.

The bicycle can be considered as a modified spaceframe such as that found in bridges, cranes, etc. The diamond frame of the bicycle and the alternate-structure cross frame are constructed from thin-walled tubular components that must resist tension, compression, bending, and torsional stresses when in use. The optimum material is the one with the highest specific strength and carbon-fiber composites are the materials of choice if there is no concern over cost (1). Aluminum, magnesium, and titanium are also attractive. If cost is a concern, then steel (which is not that far behind the other materials) is the obvious material for selection.

Wheels with increased stability and rigidity for off-road bikes constructed from glass-fiber-reinforced nylon and disc wheels have been constructed. In disc wheels, discs made of aluminum alloys or carbon-fiber-reinforced composites replace the spokes in conventional wheels. Developments also include three- or five-spoked wheels for rigidity and cross-wind aerodynamics.

The improvements that advanced materials have produced in bicycling can be gauged in the enhancement in the Olympic pursuit records. In 1964, Daler won the 4,000 meters individual pursuit with a time of five minutes, five seconds; in 1992, Boardman won the event in three minutes, 22 seconds.

Tennis
Tennis is a sport in which absolute achievements cannot be compared. Yet who can argue that Bobby Riggs, with his 1939 wooden racket, would have no chance against Pete Sampras armed with an oversized composite racket with an enlarged “sweet spot?”

Until about 25 years ago, tennis rackets were made from wood, with ash, maple, and okume leading the way (1). In the late 1960s, metal frames, generally fabricated from steel or aluminum, were introduced. Presently, composite rackets are all the rage both from the viewpoint of efficiency (accelerating the ball across the net) and in terms of damping the dangerous vibration that can lead to tennis elbow.

The impact force experienced by a player on returning a tennis ball traveling at 160 km per hour is approximately equivalent to jerk-lifting a weight of about 75 kg. These forces can transmit a high load to the lateral epicondyle, located on the outer side of the elbow, leading to damage to the small blood capillaries in the muscles and tendons around the elbow joint – “tennis elbow”. Better technique can help, but an improved racket can also make a major contribution.

The goal in designing modern tennis rackets is to increase the size of the sweet spot: the central part of the racket that leads to little or no shock to the player and where minimal vibration occurs upon impact with the ball. This depends upon the stiffness of the frame and the size and shape of the handle and has now resulted in an upper limit in the size of the racket being imposed.

Today, tennis rackets are produced from monolithic metals including steel, aluminum, magnesium, titanium, and metal-matrix composites. However, the high stiffness of carbon-fiber-reinforced composites makes them superior to the metals in imparting high forces to the ball. To
reduce the high-frequency vibration upon impact, racket handles are constructed of multiple fiber-reinforced layers wrapped around a soft inner core, which is often an injected polyurethane foam or honeycomb construction.

**Golf**

As with tennis, it is very difficult to compare achievements of the past with those of today in absolute terms. Clubs have evolved tremendously (7), and it is difficult to imagine that Bobby Jones, using hickory shafts, could compete (at least in length) with Tiger Woods or Ernie Els armed with a shaft constructed from a graphite-epoxy and an oversized hollow titanium head.

The materials evolution for the golf driver is shown in Figure 4. The overall weight has decreased, and the length of the club has increased from 109 cm to 114 cm. The grip and shaft weight has been reduced from 165 grams down to 115 grams or less. The weight of the head remains the same at about 200 grams, but by using a hollow titanium (casting) construction, the head is now much bigger, with the mass concentrated around the outside of the hitting face. The net results is a club that claims to give greater distance (greater clubhead speed because of the longer arc) but also a straighter (bigger sweet spot) shot (5,7).

Figure 4. The materials evolution for the golf driver.
Baseball/Softball

Aluminum baseball bats are banned in the major leagues because they would make the baseball stadiums obsolete (too many home runs). Despite this ban in baseball, both new aluminum bat concepts (such as the ultralight bat with a double-walled barrel construction) and titanium bats are revolutionizing softball (Figure 5). These bats have a bigger sweet spots and lead to greater velocity off the bat. However, the softball associations are concerned particularly with an increase in injuries to infielders who cannot react fast enough to this higher velocity. A bat with a combination of titanium on aluminum has been approved by the softball associations and is said to offer top performance combined with high durability.

Figure 5. Susan Abkowitz of Dynamet Technology, Inc. holds a softball bat with a powder metallurgy titanium alloy outer shell

The Javelin

The javelin was an event enjoyed by the Mycenaean’s at least 3000 years ago \(^8\). The Greeks of 500 BC used thin wooden javelins with a cord wrapped around its center of mass. When thrown, the thrower held onto the end of the cord to make the javelin rotate through the air. The rotation acted to stabilize the javelin by averaging any non-symmetry in its construction about a central axis.

The modern javelin has relatively strict rules concerning its construction \(^8\). Essentially the modern javelin must be smooth and has strict geometric rules to ensure the positioning of the center of mass. The reason for this can be seen in Figure 6 which shows winning throws at the Olympic games from 1904 onwards. At the Athens Olympic games in 1908 the winning throw was just over 50 m. In 1984 Uwe Hohn (from the then East Germany) threw a staggering 104.80 m. Given the dimensions of stadia and the fact that it was becoming unsafe for spectators it was decided fairly quickly by the IAAF that the javelin had to be re-designed to “under-perform”. This was done by moving the center of mass forward by 4 cm, which caused a dramatic loss in lift, and a consequent reduction in the distance traveled.
Figure 6 shows that the distances for the new rules javelin were approximately 15 m less after the center of mass rule change. As far as the rule makers are concerned there are two advantages; 1) the javelin doesn’t fly as far and 2) the javelin clearly lands tip first. Although this reduces overall throw distances, the new rule does give the athlete one advantage. The old rules javelin was very sensitive to the initial throw conditions and even a small change could reduce distances by 20 m. The new rules javelin is much less sensitive to initial conditions partly because it always has a negative pitching moment. This is likely to allow the athlete to produce more consistent throws.

As with the pole vault, technology strongly influences the performance of javelin throwers, and the IAAF successfully used an equipment change to reduce the length of throws from the mid 1980’s. As Figure 6 shows, however, it might not be too long until a further rule change is required!

Concluding Remarks
Sporting performance has increased dramatically over the past millennium. While much of this performance enhancement can be attributed to better training, diet, desire to win etc it is clear that advanced designs and the materials of construction have made a major impact in some sports.

In the 100 m sprint, it is likely that the strength, power, and will to win of the athlete is dominant and that no technological development has arrived to require a rule change. The pole vault has seen heights increase dramatically with the introduction of flexible poles in the 1960’s. Here the adaptation of the athlete to the new equipment and the capabilities of the equipment have produced the gains. The technology is available to all athletes and the ruling bodies have not deemed it necessary to alter the rules to keep heights low. The rules of javelin have been altered by mandating the equipment that can be used to reduce throw lengths and make the sport safer for fellow athletes and spectators.

Thus, there is a balance between technology and tradition and the sport ruling bodies either allow technology to advance a sport (such as in the pole vault) or use it to under-engineer a sport (such as the javelin). Is it cheating? Well, as long as the same technology is available to all competitors at the same time, then ultimately it comes down to the ability and skill of the
athlete. Problems only arise when technology is available exclusively to only one group of athletes. Happily, a century on from Baron de Coubertin’s original vision of the Olympics, the motto “swifter, higher, stronger” is ultimately still dependent upon the skill of the athlete.

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