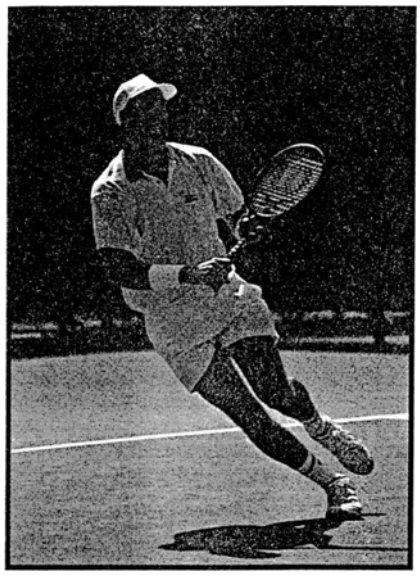
Is the Use of Advanced Materials in Sports Equipment Unethical?

F.H. Froes



Advanced materials can significantly enhance sports performance and dramatically tilt the playing field. This article discusses the use of advanced materials in sports and presents some ethical questions surrounding their use.

Editor's Note: The author will present a tutorial luncheon lecture on this subject on Monday, February 10, as part of the 1997 TMS Annual Meeting in Orlando, Florida. A hypertext-enhanced version of this article can be found at http://www.tms.org/pubs/journals/JOM/9702/Froes-9702.html. The tennis photograph is published with permission of the U.S. Professional Tennis Association.

INTRODUCTION

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. For many high-performance applications, high cost can be accepted, although the level of acceptance depends upon the industry in question (Figure 1).

This article addresses the role of advanced materials in sports. At the highest professional level, sports are a highly competitive occupation with millions of dollars depending upon fractions of a second or tenths of a centimeter. However, even the dedicated amateur is willing to invest a great deal of money to improve his or her performance. Thus, just as in other fields, the use of advanced materials in athletics can be justified if it leads to enhanced performance.

Just as in the transportation industry, the materials of choice for sports have shown a major evolution over the last 100 years. From naturally occurring materials such as wood, twine, gut, and rubber, we have progressed to high-technology metals, polymers and ceramics, and synthetic-hybrid materials including composites and cellular concepts.

In this article, we first consider how sporting equipment is designed, drawing examples from a number of sports. We will examine in more detail how measurable (absolute) records have been impacted by these advanced materials.

SPORTS EQUIPMENT DESIGN

The optimum design of sports equipment requires the application of a number of disciplines, not only for enhanced performance but also to make the equipment as user-friendly as possible from the standpoint of injury avoidance. Clearly, this design encompasses materials science, mechanical engineering, and physics; however, it also necessitates a knowledge of anatomy, physiology, and biomechanics. Biomechanics can be simply defined as the science of how the body reacts to internal and external forces. Thus, it is an attempt to apply the basic laws of physics and mechanics to the joints, ligaments, and tissues of the body as they are subjected to loading (Figures 2 and 3).

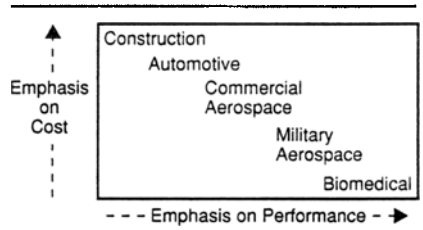


Figure 1. The impact of cost in various industries.

In designing sports equipment, the various characteristics of materials must be considered. Among these characteristics are strength, ductility, density, fatigue resistance, toughness, modulus (damping), and cost.

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 different materials can be better evaluated (Table I). Thus, if we want a material that features the highest possible stiffness for the least possible weight, we would select the materials 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

Table I. Typical Mechanical Properties of Materials Classes

Material	Young's Modulus (E) (MPa)	Density (ρ)(Mg/m^{-3})	E/ρ
Metal	40,000–210,000	~2-8	24,000–30,000
Glass	73,000	~2.5	~30,000
Ceramic	400,000–700,000	~3.5	100,000–230,000
Fibers (B, C)	~400,000	~2.4	~170,000
Carbon-Fiber Composite	200,000	2.0	100,000
Wood	14,000	0.5	28,000

be defined to allow the optimum materials selection to be made.

THE IMPACT OF ADVANCED MATERIALS

Running

Shoes, in particular, have shown substantial improvements in the running events. However, it is this author's contention that this improvement has been much more in the comfort/avoidance-of-injury arena rather than in absolute performance enhancement. Thus, during the first Olympics in 1896 when Spiridon Loues won the marathon (which was actually somewhat shorter in distance than it is today), all of Greece celebrated with him as he just broke three hours with a time of two hours, 59 minutes. Almost 100 years later, the Olympic record is two hours, 12 minutes, and 36 seconds, about a 30% improvement. The majority of this improvement can be attributed to an improvement in human performance.

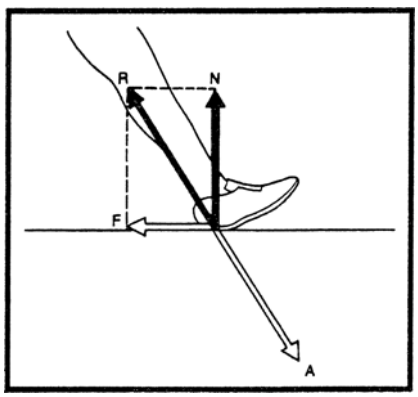


Figure 2. The relationship between the action (A)/ reaction (R) force, the normal (N) force, and the friction (F) force. (Courtesy of K.E. Easterling).

If we turn our attention to the Paralympics, a totally different situation exists. There were no Olympic games in 1896 for those requiring prosthetic limbs. The paraplegic could hardly move, never mind compete in athletic competition. However, in 1992, the paraplegic could not only compete, but could also outperform the majority of us who have use of all of our limbs.

Paraplegic Joe Gaetani broke world records in both the 100 meter (12.23 seconds) and 200 meter (24.82 seconds) sprint events in 1992 at the Paralympics in Barcelona, Spain. Gaetani made use of the amazing Springlite II prostheses device, which features a thin carbon fiber/epoxy pylon that provides the right balance of stiffness and flex at a substantially reduced weight as compared to conventional materials such as wood (1 kg compared to 4.5 kg). An energy-storage return aids performance and contributes to the capability to walk or run greater distances with much less fatigue and discomfort than with traditional devices. The cost of the Springlite II is about $850.

Born without feet, Tony Volpentest won gold medals in Barcelona in the 100 meter (11.63 seconds) and 200 meter (23.07 seconds). Volpentest runs on carbon-graphite feet bolted to carbon-composite sockets (built by Flex-foot) that encase his legs (Figure 4). The arrangement acts like a springboard. With each step, the runner punches the track, which catapults him or her forward more efficiently than if he or she were running on two human feet. And the long-distance runner is not forgotten—it is stiff and springy for sprinters, but shock-absorbing for the marathon runner.

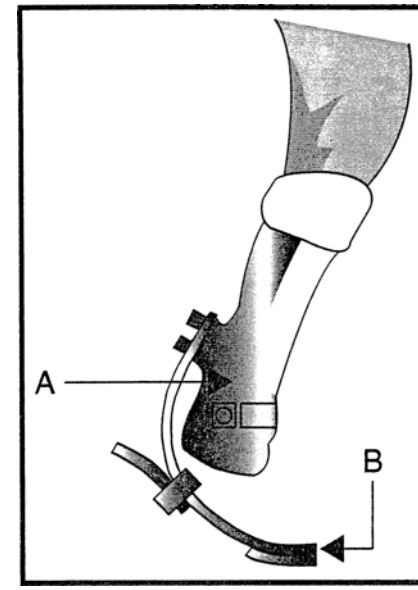


Figure 4. A schematic of the prosthesis used by Tony Volpentest. The socket of the prosthesis (A) is flexible, allowing for various muscles, tendons, and bones to function inside. It also features a flexed toe (B) that ensures landing on the forward 5 cm of the toe—the normal gait for sprinting.

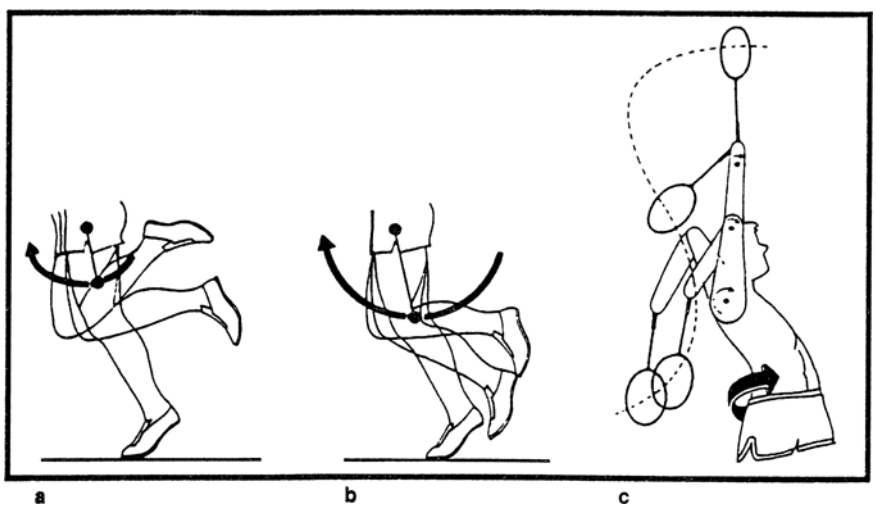


Figure 3. The biomechanics of sports: the analysis of forces and stresses that act on the body in various sports. (Courtesy of K.E. Easterling).

Pole Vault

The 1896 Olympics saw a height of ten feet, six inches achieved with a bamboo pole in the pole-vault event. In the 1960s, after the pole-vault record had inched upwards for 60 years, records began to fall as aluminum poles were introduced. Today, the world class pole vaulter utilizes a highly sophisticated composite pole, resulting in a 1996 record of 19 feet, five inches.

The materials requirements for a vaulting pole and the corresponding materials of choice are shown in Table II. It can easily be shown that the specific design property is given by

$$\frac{\sqrt{E}}{\rho}$$

If we refer to Table I and also add the requirement of durability, the material of choice is the carbon-fiber composite, with bamboo not too far behind. If we add the minimal-twisting requirement, the carbon-fiber composite becomes even more attractive (Figure 5), with three layers of different fibers being used to optimize the performance—an outer layer of high-strength carbon fiber pro-

Table II. Material Requirements for a Vaulting Pole

Requirement	Possible Material
Light (Low Density)	Bamboo
Buckling Resistance (Stiffness)	Aluminum
Strong (Resistance to Plastic Strain)	Steel
Minimal Twisting (High Torsional-Strain Resistance)	Magnesium
Cost	Carbon Fiber Composite

viding high stiffness and an intermediate webbing of fibers together with an inner layer of wound-glass fiber building resistance to twisting. The glass fiber consists of 80% longitudinal and 20% radial fibers.

Bicycling

Cycling is a highly efficient form of transportation, with energy consumption lower than that of a walker and much lower than that of powered vehicles. The Chinese recognize this, building more than 10 million bicycles per year. The bicycle has been around for almost 200 years, maturing from the 1817 Draisienne (walking device) to the modern day Rover safety bicycle designed by J.K. Starley in 1885.

Today, advanced materials, in combination with aerodynamic consideration, have led to vastly improved bicycles. Greg LeMond won the 1989 Tour de France (3,420 km) by only 8 seconds, a success made possible by a clip-on extension of his handlebars and a padded tube that enhanced his aerodynamic shape.

A number of advances have contributed to the high efficiency of the modern-day bicycle, including the development of spoked wheels, 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 bicycle has a diamond frame (Figure 6). The diamond frame 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 requirements and possible materials of choice are shown in Table III.

These materials requirements can be simplified to the minimization of the bending of a cantilever beam, then the mass is given by

$$M = \text{Constant} \times \rho/E$$

Thus, the optimum material is the one with the highest specific strength, r/E. Based upon the data shown in Table I, carbon-fiber composites are the materials of choice if there is no concern over cost. 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.

In addition to the carbon-fiber-reinforced composite frames, frames have recently been produced from magnesium, aluminum, titanium, and metal-matrix composites. In addition, hybrid frames such as carbon-fiber-reinforced composites combined with titanium have been produced.

[*For more detail on the use of advanced materials in bicycle frames, see the Structural Materials section of this issue's* NEWS & UPDATE.]

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.

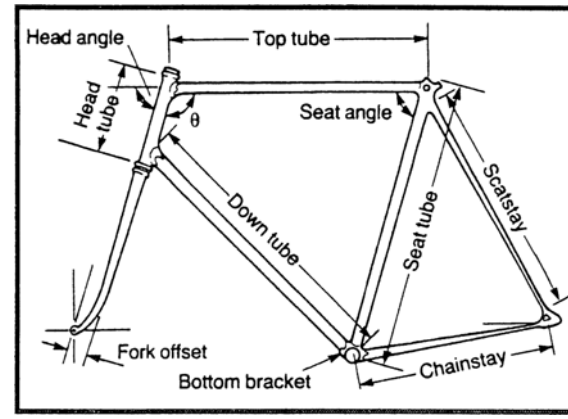


Figure 6. The bicycle diamond frame. (Courtesy of K.E. Easterling.)

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 Andre Agassi 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. 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. 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 head. The International Tennis Federation has now imposed an upper limit in the size of the racket.

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

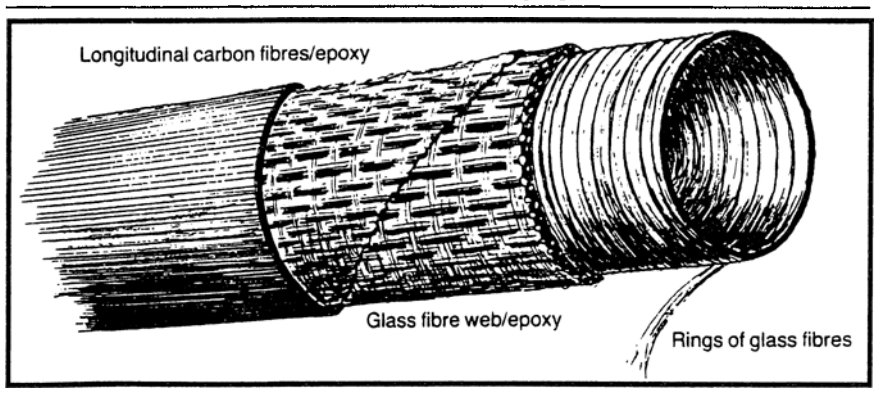


Figure 5. The vaulting pole, showing the three layers of different fibers used to maximize stiffness while minimizing twisting during use. (Courtesy of K.E. Easterling.)

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.

An example of a state-of-the-art tennis racket is the Wilson FPK, which consists of a urethane core, 84% graphite, 12% Kevlar, and 4% fiber FP (a pure form of ceramic aluminum oxide). The graphite provides strength and stiffness, minimizing head deflection, and also helps to prevent twisting of the racket head when the ball impacts outside the sweet spot. The Kevlar fibers lead to additional strength and durability and contribute to damping vibrations. The fiber FP produces even greater stiffness and damping to this type of tennis racket.

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, and it is difficult to imagine that Bobby Jones, using hickory shafts, could compete (at least in length) with John Daly, Freddy Couples, or Tiger Woods armed with a shaft constructed from a graphite-epoxy and an oversized hollow titanium head.

At first sight, driving distance would seem to be an absolute criterion that could be tracked versus the material of construction. However, despite checking with the Professional Golfer's Association (PGA) and various golf magazines, this data could not be obtained (it is available for the past few years; for example, John Daly led the way in 1995 with an average driving distance of almost 256 meters). A further complication is that balls have also evolved tremendously (did you know there is now a titanium ball?), with the most lively being banned because they would obsolete current golf courses.

The materials evolution for the driver is shown in Figure 7. 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 result 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.

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. These bats have bigger sweet spots and lead to greater velocity off the bat. However, the Softball Association is concerned particularly with an increase in injuries to in-fielders who cannot react fast enough to this higher velocity.

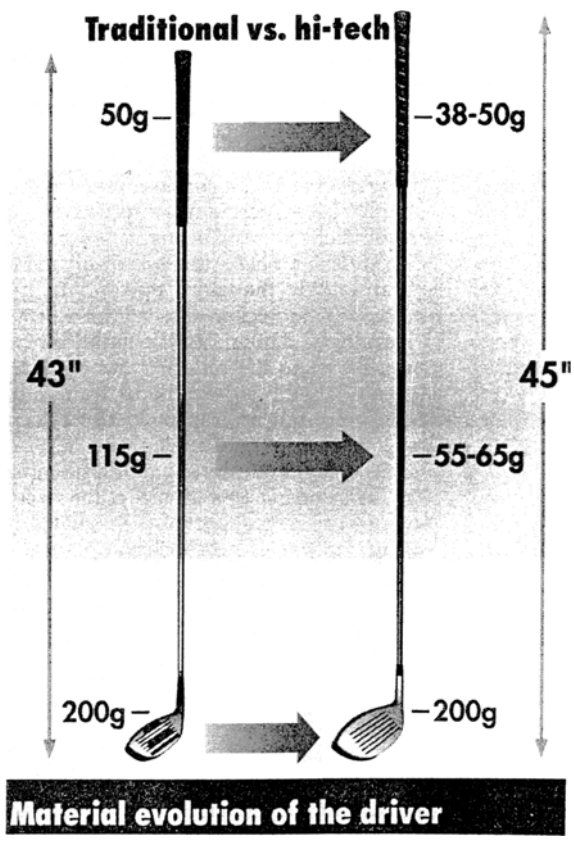


Figure 7. The materials evolution for the golf driver.

ETHICAL CONSIDERATIONS

Although some examples of the use of advanced materials in sporting goods have been discussed, there are certainly more possible. Where the sporting achievement can be gauged in absolute terms, tremendous improvements have been made in those sports where equipment is critical. However, the use of advanced materials in sports equipment presents some ethical* questions. We can clearly enhance behavior by allowing the use of advanced materials, but where should the line be drawn, or should there be no restrictions? The solution, according to a young man in one of my classes at the University of Idaho, is that if you have the patent, you (and only you) can use this material or design.

Table III. The Materials Requirements for a Bicycle

Requirement	Possible Material
Light (Low Density)	Carbon-Fiber Composites
Stiffness	Aluminum
Strength	Titanium
Toughness	Magnesium
Fatigue Resistance	Steel
Corrosion Resistance	Metal-Matrix Composites

This brings us to a second question—should we allow competition at the highest level to be only affordable to the elite because of the high cost of equipment? In turn, this leads into what is perhaps the most controversial issue—if we allow certain classes of materials/designs, but not others, we can actually favor the class of people who will excel.

The carbon-fiber vaulting pole, javelins with spiral tails, golf balls with special dimple patterns, stiffer carbon-fiber tennis rackets, bicycles with new types of wheels and the egg position, discuses with their weight distributed as close as possible to the perimeter, and America's Cup yachts (forget it, this one is too complex) all lead to "further and faster." Where should this end? Can we ensure that people are competing and not the advanced materials? Certainly, we do not want to force Gaetani or Volpentest to go back to a wooden pylon. But how about electronically guided darts, heat-seeking missiles for grouse-shooting (allowable provided the grouse is still edible, according to a young lady in one of my classes), solar-energy-enhanced bicycles, and terrain-following golf balls that automatically find the lowest local elevation on a putting surface (the bottom of the hole)?

Earlier, I discussed the prosthetic devices used by Gaetani and Volpentest. The devices "allow the runner to be catapulted forward more efficiently than if he or she were running on two human feet" (for a cost of up to $7,000). Let us develop similar devices to be incorporated into the shoes of 1996 Olympians Donovan Bailey (winner of the 100 meters in Atlanta, Georgia, in a world record 9.84 seconds) and Michael Johnson (winner of the 200 meter in Atlanta in a world record of 19.32 seconds). Any bets on

* The dictionary defines ethics "as pertaining to acceptable principles of right and wrong governing conduct —in a group." Other, more loose, definitions include "no rule against it, so it must be OK" or "if you're not caught, there is nothing wrong." You choose what you like.

whether Bailey and Johnson could then break nine seconds and 18 seconds in their respective events? Is the answer here "nothing beyond the 'natural' springiness is allowed?"

What is the answer to high costs? Many sports rules committees feel that a reasonable compromise is to keep their sport affordable to many athletes, rather than to the elite few. For example, disc wheels were initially banned from Olympic bicycling competition because they were so expensive that they were not considered to be available to most cyclists. Should all canoes and kayaks conform to a single hull design? Should the Hoyt bow, composed of tiny glass beads embedded in a rigid foam matrix, be allowed to compete against the traditional wooden bow? The lack of change in behavior with temperature and minimal moisture absorption by the new bow has led to winning scores of 1,350 (out of 1,440) compared to about 1,100 30 years ago—but at a price.

How about the paraplegic who is constrained to a wheel chair? For the Paralympics, read high technology and high cost. No heavy steel frames here—instead, there are bike-like wheels, the use of aerospace carbon fibers and titanium, and computer-aided design of the suspension. Now there is a chair for each sport: basketball, racing, and even tennis. For example, tennis chairs are built with sharply slanted back wheels so the athlete can move quickly from side to side. In basketball, forwards have high seats, while guards have more slant in their chairs in order to turn quickly. Cost? Top wheelchairs are in the range of $2,000–$3,300 apiece.

Let us take two examples of how legislation regarding advanced materials can significantly determine who wins an event. Elite rowers stand about 2 meters and weigh about 95 kg. In contrast, elite kayakers stand 15–30 cm smaller and weigh nearly 14 kg less. This relates to allowable boat dimensions—a rowing boat can be as long as desired, favoring strength even at higher weights (longer boats can distribute more weight over a larger area without riding too low in the water, which leads to excessive drag); in contrast, the length of a kayak is restricted, leading to an optimized aerobic strength-to-weight ratio.

When the javelin was redesigned to be lighter and more aerodynamic, finesse was required to make it float correctly. Masters of this new art such as Uwetlohn of East Germany (1984) deftly projected the javelin more than 100 meters, much to the danger of spectators and other athletics warming up "safely" on the far side of the stadium. The 1986 ban on the new design led to a dramatic drop of 20 meters in the world record.

Lots of questions, few answers. What do you think?

ACKNOWLEDGEMENTS

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Suggested Reading

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ABOUT THE AUTHOR

F.H. Froes earned his Ph.D. in physical metallurgy at Sheffield University in 1967. He is currently the director of the Institute for Materials and Advanced Processes at the University of Idaho. Dr. Froes is a member of TMS.

For more information, contact F.H. Froes at University of Idaho, College of Mines, Mines Building, Room 321, Moscow, Idaho 83844-3026; (208) 885-7989; fax (208) 885-4009.

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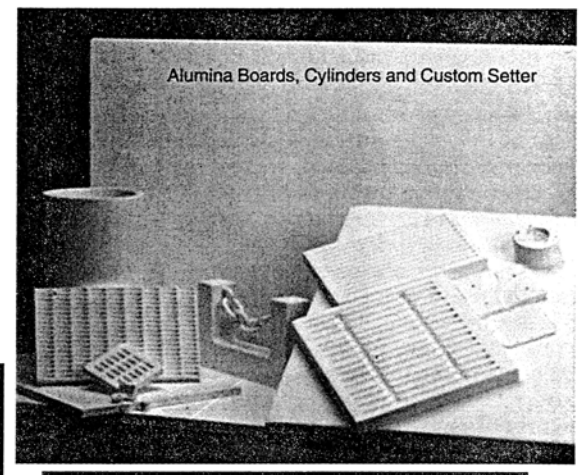

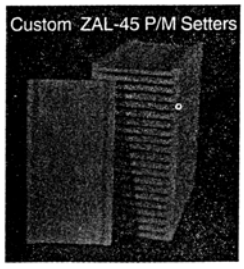

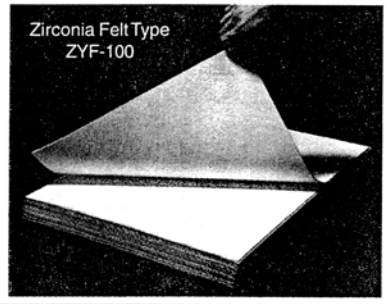

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