Materials and technology in sport

Mike Caine, Kim Blair and Mike Vasquez

An evolution from natural to highly engineered materials has drastically changed the way in which athletes train and compete. Thanks to challenging technological problems and unconventional commercialization pathways, universities can make a direct impact on the development of sporting goods.

In 1896, American Bill Hoyt won gold in the pole vault during the first modern Olympics in Athens, Greece. Today, the jump height of 3.30 m that secured him his medal — achieved with a fully wooden pole[1] — would fall considerably short of the standard required to even qualify for the 2012 Games in London. The current men's Olympic pole vault record is as high as 5.96 m, and Australian Steven Hooker set it in 2008 with a pole made of highly engineered composite materials. Although the physical conditioning of athletes has improved considerably over the past century as a consequence of advancements in technique and training methods, it is the evolution in materials that has been pivotal in enabling successive generations of athletes in pole vault, as well as other sports to surpass the achievements of their forebears.

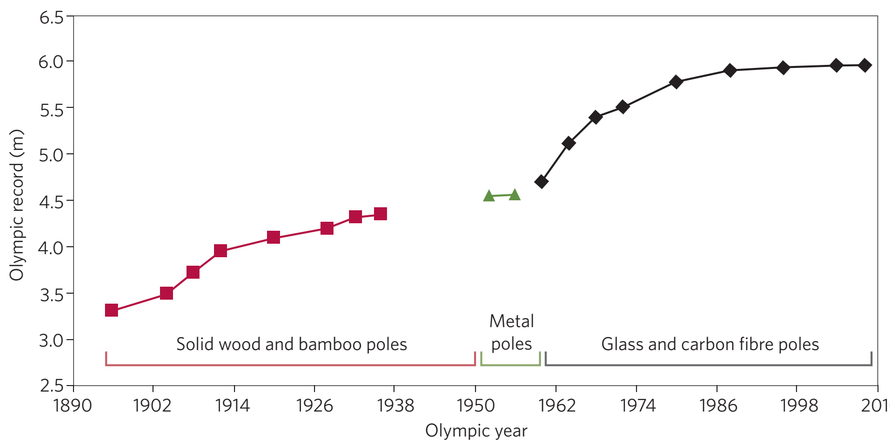

Figure 1 | Men's Olympic pole vault records.

A case study

International Athletics Association Federation rules state that the pole can be made of any single material or combination of materials, and that it can have any length or diameter provided the outside surface is smooth[2]. The unencumbering nature of the sport's regulations has paved the way for a string of technical developments in pole materials and methods of manufacture. Figure 1 tracks the Olympic records of vault height with the changes in pole construction over the past 122 years of the Olympics. Stepwise increases in athlete performance often accompany major materials changes, but these gains typically plateau over time. Early poles were made of solid wood, with ash and hickory both popular. These poles were replaced around 1900 with bamboo, which afforded a greater degree of flex and hence upward propulsion. By 1958, aluminium and steel were the materials of choice for the sport and the world record rose to 4.80 m. In the early 1960s fibreglass poles were utilized, thereby marking a new era for the sport.

Modern poles typically comprise multiple elements, incorporating both woven and unidirectional carbon fibre sheets wrapped around a hollow glass fibre core. Such an embodiment couples strength and flexibility combined with low mass. The driving force behind pole construction is to maximize the amount of kinetic energy imparted from the pole to the athlete during the run up, plant and take-off phase of the vault, which is constrained by the athlete's mass and approach rate. Poles can be different lengths and stiffnesses so athletes aim to customize their pole to match their particular jumping style and to maximize their vault height. Multi-constituent poles (as opposed to single materials like bamboo) enable athletes to select poles whose bending stiffness more closely matches their personal loading pattern during the vault.

The desire to design sporting implements that are both strong and lightweight and that can be manufactured to achieve a predetermined bending stiffness is not restricted to vaulting. This set of requirements is shared by other types of sport, and the pattern of materials development along the lines described for vaulting has been replicated in the evolution of tennis racquets, baseball bats, hockey sticks, rowing oars, sailing masts and cycling frames.

A historical context

Prior to the mass commercialization and monetization of sports, most games were simply created for leisure using whatever goods and materials were readily available. This meant that early sports equipment was made from natural products such as wood, leather and other animal parts. The first footballs (soccer balls) were composed of an outer leather shell and a pig's bladder that served as the air-containment unit[3]. Original golf clubs were made of wood, as were tennis racquets[4]. Tennis racquet strings were manufactured from animal intestine, with pig, sheep and cow gut all proving popular at various times. In fact, the term 'catgut' is probably an abbreviation of the term 'cattle gut'.

Once sport became more organized and competitive the influx of technology and the use of novel materials became routine. As the Cold War drew to a close many of the high-end materials manufacturers, for example, DuPont and Dow Corning, started to consider commercialization pathways for their technologies other than for national security. Sport turned out to be a prime candidate for materials such as aluminium and titanium alloys, Kevlar, and neoprene.

A hotbed for materials innovation

Why sport? First, rewards such as endorsement contracts, prize money, fame and notoriety are often catalysts for athletes adopting new materials and equipment in an attempt to gain a competitive advantage. Sport also facilitates innovation, in part because barriers to entry are, or certainly were until recently, commensurately low. Sporting goods companies and individual inventors tend to use human trials very early on in the development process, and elite practitioners often make willing early adopters. Moreover, the sports organizations responsible for determining the rules and regulations are often reactionary and many do not (or did not until recently) have specific bylaws outlawing the implementation of new materials. The primary reason for the lack of governance in the past is that accurate and quantitative measurements of equipment or athlete performance have only been developed in the later part of the twentieth century. Sports regulators are typically reluctant to make rule changes, particularly where the rules of the game may have remained unchanged in over a century. This allows sporting goods manufacturers to continually push the envelope of functionality and performance to create products that result in more brand exposure and ultimately increased sales.

How individual sports react to the introduction of 'game changing' materials and technologies can vary significantly. In swimming numerous records have fallen in recent years as a result of advanced swimsuits that mimic the properties of shark skin and provide the swimmer with reduced surface and form drag. The suit makes swimmers more hydrodynamic and consequently faster. Ultimately, the swimming governing body, the Fédération Internationale de Natation, decided to tighten the regulations concerning the materials and design properties of swimsuits[5]. The rules specifically outline constraints for suit coverage and buoyancy. There are many reasons for this change, but one major consideration that is perhaps an idiosyncrasy of sport, is the reliance of quantifiable metrics (like race times) to mark the evolution of human performance throughout history. The saying goes 'records are made to be broken', but if a record falls because of a new highly engineered suit, followers of the sport and even athletes and coaches question whether the prowess of the athlete or the superior technology contributed most to the setting of a new best time. In contrast, if all athletes are competing with similar equipment the skill of the athlete should ultimately be the deciding factor. This debate is not unique to swimming. Similar deliberations are commonplace in other mass participation sports such as golf, tennis and cycling, and in team sports, for example baseball and cricket, as well as in winter sports, such as skiing and skeleton bobsleigh. The term 'technological doping' has emerged, indicative of the concerns held by some witnessing the relentless innovation that characterizes many elite sports today.

Advancements are not always welcome

Although new materials are usually introduced into sports equipment to improve performance, unintended consequences occasionally result. One of the best examples is the development of baseball bats. At the highest professional level (Major League Baseball in the United States) a bat is required to be a single piece of wood. However, teams at lower levels from college, high school and Little League are allowed to use bats from other materials, which keep expenses low thanks to their improved durability. For many years such bats were constructed of aluminium alloys, graphite composites and most recently carbon fibre composites. However, there were two major consequences of introducing lighter and stronger materials into the bats.

First, players were able to hit the ball harder because materials engineering enabled manufacturers to optimize performance characteristics such as the coefficient of restitution and the moment of inertia. As a result, the rate at which balls could now be struck put players in the field at risk, especially the pitcher, who is positioned directly in front of the batter. In response to the increased potential for injury, the design of the bats must now follow a prescribed length-to-mass ratio, and bats must pass a series of performance tests to ensure compliance with the prevailing regulations. The latest regulation — the bat–ball coefficient of resolution — even specifies the ball exit speed after hitting the bat, which is now required to be less than half of the initial incoming speed[6]. Even with the new regulations there have been areas in the US that have banned the use of non-wood bats.

Another unwanted consequence — this time of the replacement of aluminium by carbon fibre — is related to player perception. The sound of a baseball striking an aluminium bat has a distinctive 'ping', and most players can tell from the sound of the collision alone whether the ball was struck cleanly on the sweet spot. In contrast, the sound that occurs from the collision of a baseball and a carbon fibre bat is conspicuously different. Rather than a high-pitched ping, the sound is more reminiscent of a dull thud. Carbon fibre bats are constructed from thin strips of material laid up around a cylindrical mandrel. The ability to orient precisely the carbon fibre strips enables engineers to construct bats with larger optimal hitting zones. The cured resin that binds the carbon fibre strips accounts primarily for the dull acoustic properties. Although the carbon fibre bats were designed to perform as well if not better than their aluminium counterparts, the peculiar sound that resulted from the bats caused many players to perceive that they were not striking the ball as well.

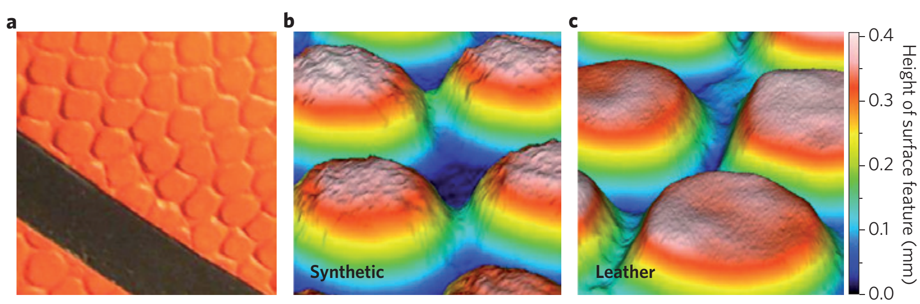

Figure 2 | The surface of a basketball. **a**, Photograph of a traditional ball. **b**,**c**, Surface details as captured by a scanning laser microscope. Traditional leather balls remain popular with the professional players despite attempts to introduce synthetic alternatives, which show larger surface roughness. The colours denote the depth or height (trough to peak) of the feature in view, in this case the basketball 'pebbles'. In this image you can see that the pebble features on both balls are about 0.35 mm deep.

Although they sometimes resisted, over time players typically recalibrated their sound expectation to match the on-field flight of the ball as a result of using the carbon fibre bats. So although performance is a top priority for implementing new materials, a balance must be struck as to how the resulting product affects the way that a player performs or perceives his or her skill.

Basketball is another sport where the introduction of 'advanced' materials was not wholly welcomed. In 2006 players in the USA's National Basketball Association league objected to the replacement of the traditional leather-encased balls with a microfibre composite alternative. Players complained that the synthetic balls caused minor lacerations to their finger tips. Figure 2 sheds some light on the possible cause of the problem, showing the surface of the synthetic ball to be much rougher than that of the leather version. Following sustained player disquiet the synthetic ball was subsequently withdrawn part way through the league season.

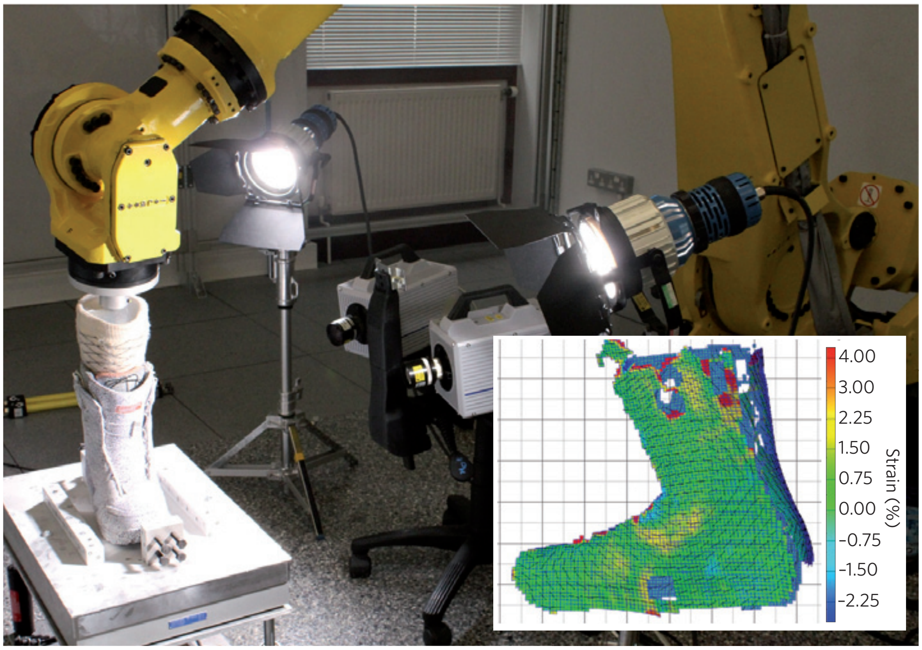

Figure 3 | Three-dimensional surface-strain measurement on a snowboard boot assembly. The inset shows the strain during simulated wear conditions. The colour scale shows the magnitude of surface strain expressed as a percentage change from the pre-stressed condition. Positive changes denote elongation, negative changes denote compression.

The role of governance

In many cases new materials in sporting goods enable changes to strategy (such as in golf or tennis) when shots that may not have been possible prior to the introduction of new technology slowly emerge as players adapt to the new performance boundary. For example, the length and layout of golf courses has changed to account for the increase in driving resulting from new club and ball technologies. New equipment can also extend careers of athletes by enabling them to perform at an elite level for longer. Such changes can be welcome, but where the essence of the sport is deemed to be under threat, it is the role of the governing body to intervene. At present, many governing bodies have set up capabilities (either external or internal) to help the introduction of new innovations into their sports and balance tradition with technology. Typically the governing bodies will establish the rules of the game and as technology evolution dictates tests are devised to ensure that equipment is meeting the prescribed regulation. This has now happened in most mainstream sports such as tennis, American football, baseball and golf. As a consequence, research institutions and universities can take pivotal roles in both developing cutting-edge applications for new materials in sports equipment and helping governing bodies develop bespoke testing fixtures and protocols to assess the properties of sporting goods. This need has prompted several universities to create full degree programmes and research centres focused on sports engineering and technology. Loughborough University in the UK is home to the largest academic research group in the world dedicated specifically to this field, and there are other major centres in Australia, France, Germany, Japan, the USA and the UK. The creation of sports technology research hubs, specifically focused on cutting-edge applications and even fundamental research, has fostered an environment where sport is no longer seen merely as an early adopter of materials and technologies pioneered primarily for other sectors. Rather, it allows researchers to advance creative solutions to complex human problems that can be subsequently applied elsewhere. For example, there is a current trend for sports materials and technologies to be migrated into healthcare applications, such as prosthetics, compression garments and wearable sensors.

Not just hard goods

At the same time that bats, clubs and racquets were undergoing tremendous change through the introduction of new materials, sports apparel was similarly transitioning from natural to synthetic materials. Most early (and even some current) athletic garments were constructed from animal hair, silk, cotton and flax[7]. These materials have been replaced partially by synthetic materials such as rayon, polyester, nylon and elastane because of their superior moisture management and thermal regulation properties. During a high-intensity, sustained athletic endeavour, an athlete's core body temperature starts to rise, with significant performance degradation if this changes by even one degree celsius[7,8]. Consequently, today most high-level sport has apparel and uniforms that are engineered to afford the athlete the most comfortable and functional playing conditions possible. This can be achieved in a variety of ways, for example, using fibres with multichannel cross-sections to promote capillary action and thus moisture wicking within the garment.

Likewise, sporting goods manufacturers and research institutes have been improving manufacturing processes. Recently, Loughborough's Sports Technology Institute collaborated with Burton Snowboards to develop laser-sintering polymers for snowboard-binding prototypes. The majority of polymer materials available for the process are rigid thermoplastics, which do not offer the mechanical properties required to fabricate the highly flexible elements of functional bindings. The academic partnership resulted in a targeted polymer selection methodology that was used to identify a flexible polymer to specifically fulfil Burton's laser-sintering needs[9]. Fundamental thermal and rheological characterization was performed to ensure the material could be processed with the technology. Secondary mechanical testing ensured that parts built from the material could sustain adequate loads needed to survive the rugged field conditions that can occur during snowboarding. It has enhanced the company's functional prototype capabilities and will streamline the process of taking a product from concept to mass production. Figure 3 shows the type of testing set-up used to evaluate the functionality of new boot and binding combinations and the measured material strain.

Possibilities for the future

Although the introduction of new materials into equipment and apparel has already led to significant changes in sport, the future probably lies in the adoption of multifunctional materials and adaptive technologies. Performance measurement is one of the most challenging aspects of sports technology. Recent developments make it possible for apparel to provide athletes and coaches with real-time feedback. In 2011, the US sports brand UnderArmour launched a sports garment with an embedded heart-rate monitor and accelerometer capable of delivering diagnostic capabilities[10]. Research at the University of Illinois shows the possibility of more integrated apparel sensors and epidermal electronics that could allow direct integration with the body[11]. Their sensors enable monitoring of bodily functions and are both stretchable and flexible to conform to the skin surface without breaking under deformation. A similar technology to create flexible silicon substrates has been developed, and Reebok in collaboration with a company called mc10 is now attempting to integrate the thin electronic strips into athletic garments[12]. These examples focus on monitoring and measuring performance, but integrated electronics in apparel could offer improvements to other parts of the athletic experience. For instance, it is not inconceivable that early-stage technologies such as stimulus-activated polymers that are responsive to light, thermal or electrical changes, could impact the way that garments fit or interact with the athlete during workouts[8]. This could be useful for increasing the visibility of runners or cyclists during periods of poor visibility, thereby improving the safety of the wearer.

Safety and personal protection is, and will continue to be, a major catalyst for the integration of new materials in sports. This is an area where self-healing polymers and composites could be usefully applied. These materials exhibit the ability to repair themselves and recover functionality when damage is incurred through a variety of mechanisms triggered during the damage event[13]. It is possible to imagine athletes of the future using protective padding or helmets that possess the ability to self-repair, thus retaining protective capabilities even after a damage event. Similarly, shear-thickening fluids being developed for body armour that are soft under normal use and become rigid on impact could provide increased opportunities for athlete injury prevention[14].

The generation and adoption of novel materials and technologies into sporting goods has irreversibly changed the way that athletes train and perform in nearly every sport. Natural organic materials have mostly been replaced by synthetic or highly engineered systems originating in other exacting industry sectors. The pursuit of a competitive advantage will continue to motivate athletes, equipment manufacturers and research institutions to investigate how technological innovations can be implemented into sports. The sports sector also offers a unique opportunity for future materials solutions because of the ability to rapidly introduce fundamental materials and technology changes without an onerous regulatory burden. This constantly challenges sport-governing bodies to find the correct balance of technological advancement while maintaining the traditions and essence of the game. The need to balance innovation and tradition in sport is set to remain an enduring and compelling challenge. ❐

Mike Caine[1], Kim Blair[2,3] and Mike Vasquez[1] are at [1]Sports Technology Institute, Loughborough University, Loughborough LE11 3TU, UK; [2]Program for Sports Innovation at Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA; [3]Cooper Perkins Inc, 10 Maguire Road, Lexington, Massachusetts 02421, USA.
e-mail: M.P.Caine@lboro.ac.uk; kbb@cooperperkins.com; mvasquez@alum.mit.edu

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