bulletin | cover story

GAME-CHANGERS: How ceramic and glass materials enhance performance and provide safety to sports

By April Gocha and Lisa McDonald

Sports are integral to society—not only do they provide entertainment, physical activity, and leisure, but sports are deep parts of identities, cultures, and economies worldwide. The $1.1 trillion sports market includes ripe potential for ceramic and glass materials in both established products and innovative new technologies.

At the Tokyo 2020 Summer Olympics, athletes set 20 new world records.[1] Yet human bodies today are not much different than they were decades ago—so how do athletes keep pushing the limits of what is physically possible?

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U.S. professional tennis player Serena Williams plays in the first round of Women's Singles at the Rio 2016 Olympic Games. Williams used a Wilson Blade 104 racket, which features a braided graphite and basalt frame to improve the flex of the racket.

Part of the continual improvement of athletic performance can be attributed to our enhanced understanding of human physiology, which allows for more strategic training plans and coaching, improved nutrition to fuel athletes' bodies, and better recovery to prevent injury. Yet physiology by itself does not tell the full story. Sydney McLaughlin's sprint at Tokyo 2020, which set a new world record in the women's 400-meter hurdles at a blistering 51.46 seconds, nearly one-half second faster than the previous world record, cannot be attributed solely to tailored training and recovery plans and proper nutrition.

McLaughlin and countless other track and field athletes who competed in Tokyo can probably attribute some of their swift success to the $1.5 million rubber track that they competed on. The track, developed by Italian company Mondo, consists of an upper layer of rubber granules engineered to provide bounce and a lower layer filled with air cavities to absorb shock, a two-part strategy that offers athletes better return of their energy. Mondo estimates that returning the energy rather than allowing it to dissipate provides athletes with as much as a 2% competitive advantage, a difference in performance that can mean setting a new world record.[2]

So, the question of how athletes keep pushing the limits is answered partly by technology. Advances in the materials for equipment, apparel, surfaces, and more within the sports industry have enabled bounds in performance and continue to push the limits of what the human body is athletically capable of achieving. We laud the athletes for their feats of incredible athletic performance—yet materials also play a pivotal role in enhancing and extending human performance in sports.

A big market means big potential for materials—ceramics and glass in sports

The global sports market is estimated to be worth $1.1 trillion, according to a recent report by Signa Sports United and Boston Consulting Group.[3] While that figure also includes sporting events and other sports-associated value, sports retail including equipment and apparel holds a significant share. "Sports retail is the largest part of the sports market, accounting for $475 billion of spending and anticipated to grow 7% annually to reach $670 billion in 2025—at 1.4x the rate of GDP growth," the report indicates.

In other words, sports is a big, growing market with big potential for materials (Table 1).

Figure 1. A look at the many uses of ceramic and glass materials in sports.

So how do ceramic and glass materials contribute to the world of sports? While metals and polymers might be more immediately recognized in some applications, ceramics and glass are found throughout sports as well, where the materials' desirable mechanical, electrical, and optical properties are often leveraged in combination with other materials. Though this article cannot cover every use of ceramic and glass materials in every sport around the world, we hope to show just how integral and valuable ceramic and glass materials are throughout sports (Figure 1).

Early iterations of most sports equipment relied on natural materials such as wood, cotton, rubber, and leather. Indeed, many sports still do—professional baseballs consist of a cork or rubber core wound with yarn (mostly wool, although the outermost layer is now a cotton-polyester blend) and encased in leather, a composition largely unchanged over decades of play.[4]

But countless other types of equipment evolved sometimes drastically over the years, often leaving behind natural materials in favor of the enhanced performance offered by engineered materials. Table 2 presents a small sampling of engineered materials in sports to demonstrate the enormous breadth of applications.

Many uses of ceramics and glass in sports are realized by composite materials, which dominate in modern sports equipment. Due to their low weight and high strength, composites have infiltrated nearly every part of the sports industry, finding applications in bicycles, rackets, golf clubs, hockey sticks, fishing rods, surfboards, skis, snowboards, boats, kayaks, canoes, race cars, bobsleds, skateboards, archery bows and arrows, gymnastics bars, and even some unusual sports (see sidebar: *Obscure sports*).

Many of the composite materials used consist of a polymer matrix reinforced with fibers of ceramic or glass materials. Glass or carbon fiber-reinforced composites are most common in sports equipment, although fibers made of silicon carbide or other materials can be found as well. Sometimes, both carbon fiber and fiberglass are incorporated together. Generally, however, such equipment can be found with different varieties of fiber-reinforced composites depending on the level of competition and price range of the equipment, among other sport, region, and/or athlete preferences.

The total global market for carbon fiber reached $4.3 billion in 2019 and is projected to be valued at $5.5 billion in 2025. Of that entire market, sporting

Table 1. Select companies involved in the sports industry*

Company (location)	Annual revenue (millions)*	Website	Role in value chain
Supply carbon fibers or carbon fiber composites			
Hexcel (Stamford, Conn.)	$1,502	www.hexcel.com	Manufactures advanced composites, particularly carbon fiber, for diverse markets including recreation and marine.
SGL Carbon (Wiesbaden, Germany)	$1,061	www.sglcarbon.com	Manufactures carbon and graphite materials, including fibers and composites, for diverse markets including automotive.
Teijin Carbon (Tokyo, Japan) Parent company: Teijin	– $7,513	www.teijincarbon.com	Manufactures carbon fiber composites for diverse markets including automotive and sporting goods.
Solvay (Woodland Park, N.J.)	$10,269	www.solvay.com	Manufactures various materials and chemicals, including composites, across diverse markets including sports and automotive.
Mitsubishi Chemical (Tokyo, Japan) Parent company: Mitsibishi Chemical Holdings	– $29,259	www.mca-golf.com	Manufactures composite golf club shafts.
Toray Industries (Tokyo, Japan)	$19,892	www.toray.com	Manufactures various chemicals and materials, including carbon fiber composites, for diverse markets including sports and automotive.
Supply glass fibers or glass fiber composites			
Owens Corning (Toledo, Ohio)	$7,055	www.owenscorning.com	Manufactures insulation, roofing, and fiberglass composite materials for building and industrial applications, including boating and consumer goods.
China Jushi Co. Ltd. (Tongxiang, China)	$1,770‡	www.jushi.com	Manufactures fiberglass for diverse product markets including sports and recreation, automotive, marine, electronics.
Saint-Gobain Vetrotex (Courbevoie, France) Parent company: Saint-Gobain	– $44,025	www.vetrotextextiles.com	Manufactures fiberglass for diverse markets including marine, automotive, electronics, and sports.
Nippon Electric Glass (Otsu, Japan)	$2,180	www.neg.co.jp/en	Manufactures glass products, including fiberglass, for diverse markets including automotive.
AGY (Aiken, S.C.)	$221‡	www.agy.com	Manufactures fiberglass for diverse markets including sports, automotive, and marine.
Johns Manville (Denver, Colo.)	$2,000‡	www.jm.com	Manufactures insulation, roofing, and engineered products including fiberglass and composites for diverse markets including automotive and marine.
Most valuable sports brands worldwide†			
Nike (Beaverton, Ore.)	$36,800	www.nike.com	Designs, develops, manufactures, and markets sports apparel, footwear, equipment, accessories, and services.
ESPN (Bristol, Conn.)	$13,100	www.espn.com	Sports media conglomerate that includes cable channels, broadcasting, and radio.
Adidas (Herzogenaurach, Germany)	$11,200	www.adidas.com	Designs, manufactures, and markets sports apparel, footwear, and accessories.
Gatorade (Chicago, Ill.)	$6,700	www.gatorade.com	Brand of sports-themed beverage and food products.
Sky Sports (London, U.K.)	$4,400	www.skysports.com	Group of British subscription sports channels.
Puma (Herzogenaurach, Germany)	$4,000	www.puma.com	Designs, manufactures, and markets athletic apparel, footwear, and accessories.
Under Armour (Baltimore, Md.)	$3,500	www.underarmour.com	Designs, manufactures, and markets sports apparel and footwear.
Ultimate Fighting Championship (UFC) (Las Vegas, Nev.)	$2,400	www.ufc.com	Mixed martial arts promotion company.
Yankee Entertainment and Sports (YES) Network (Stamford, Conn.)	$1,500	www.yesnetwork.com	Regional sports television network primarily serving the northeast U.S.
Reebok (Boston, Mass.)	$800	www.reebok.com	Designs, manufactures, and markets athletic apparel and footwear.

*Conversions per Google as of October 6, 2021. All financial data obtained from company reports unless otherwise noted.

‡Private company or data not available; revenue estimated from dnb.com or google.com.

†Statista data from 2019 (https://www.statista.com/statistics/253349/brand-value-of-sports-businesses-worldwide).

goods accounted for 15.7% of the carbon fiber market in 2019, representing nearly 16 tons of the material's annual use (Figure 2).[5] Carbon fiber composites are 40% lighter than aluminum, and thus offer significant weight savings in addition to high strength and stiffness and resistance to chemicals, corrosion, and fatigue.

Golf clubs account for the largest segment of sports uses of carbon fiber. Similar to most other types of modern sports equipment, golf clubs are multimaterial—various parts of the same piece of equipment may contain several materials, and different makes and models of the equipment may incorporate a range of materials as well.

For example, the shafts of golf clubs are often made of carbon or boron fiber-reinforced composites but also may be steel, aluminum, or "titanium carbon" (a titanium alloy and carbon composite). Club heads for drivers are usually made of carbon-based composites, metals, or woods (sometimes filled with polymer foam), while heads of irons, wedges, and putters are generally composed of metals such as steel, titanium, or tungsten. Face inserts on golf club heads (a separate piece of material positioned where the club comes into contact with the ball) may be zirconia ceramic or titanium metal matrix ceramic composite.[6]

For decades, Formula One vehicles have incorporated a substantial amount of carbon fiber to reduce weight, thanks to the sport's willingness to invest in composites despite its early expensive price. Modern F1 vehicles are composed of 80% by volume composite materials, most of which are carbon fiber.[7] As the price of carbon fiber decreases, motorsports in general continue to incorporate more carbon fiber composites to increase efficiency, in addition to the material's ability to enhance safety and handling through its high strength and stiffness.

Another place carbon fiber can be found, perhaps surprisingly, is on athletes' feet. (Table 2). A company called Carbitex (Kennewick, Wash.) developed an asymmetrically flexible carbon fiber/thermoplastic composite material that is flexible in one direction yet rigid in another, mimicking and protecting the

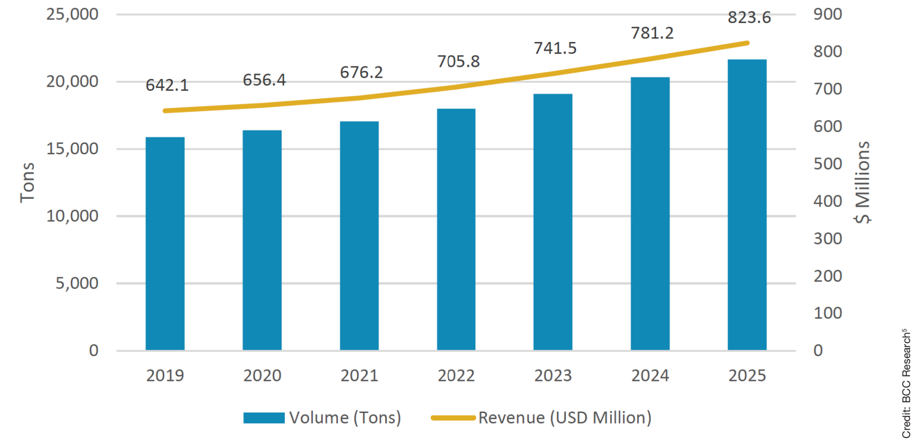


Figure 2. Global market for carbon fiber used in sports equipment, 2019–2025. The market is expected to grow at a compound annual growth rate of 5.7% during this time.[5]

OBSCURE SPORTS

Around the world, athletes engage in more than 200 sports recognized by national or international federations,[a] yet estimates suggest there are actually more than 8,000 indigenous sports or sporting games around the world.[b] No matter how you tally the count or what you consider a "sport," it is clear that humans find a lot of ways to play and compete.

While some of the more popular sports worldwide include soccer, football, baseball, auto racing, basketball, hockey, tennis, and golf, there are diverse ways that athletes engage. The following is a sample of some more obscure sports with which you may not be familiar.[c–e]

- **Lawnmower racing**—Competitors race modified lawnmowers around a track.
- **Underwater hockey**—also called octopush, players wear snorkels and play a form of hockey on the floor of a pool.
- **Bossaball**—Somewhat akin to volleyball, except that the game is played on a giant inflatable and involves a player on a trampoline designated as the "attacker."
- **Zorbing**—Racing downhill in large inflatable plastic balls, akin to a hamster ball.
- **Cheese rolling**—Racing down a hill on foot to try to catch a rolling ball of cheese, which can reach speeds of about 70 mph.
- **Bog snorkeling**—Racing through a 55-meter peat bog using a snorkel and flippers.
- **Chess boxing**—A hybrid of chess and boxing, with players alternating between the two.
- **Kabaddi**—A combination of wrestling, tag, and holding players' breath, originating from South Asia.
- **Cycleball**—A combination of bicycling, soccer, hockey, and basketball, in which players hit a ball using their bicycle wheels.
- **Extreme ironing**—Ironing clothes in extreme places such as while skydiving, on a glacier, or on the roof of a speeding car.
- **Face slapping**—Competitors take turns slapping one another until someone taps out or is knocked out. 100

[a]Topend Sports, "Complete list of sports from around the world," https://www.topendsports.com/sport/list/index.htm

[b]"How many sports are there in the world?" In World Encyclopedia of Sports (ISBN: 9780760316825). Archived copy available at: https://web.archive.org/web/20100723160638/http://www.sportencyclopedia.com/index.php?mod=book

[c]K. Baumer, "The 18 strangest 'sports' in the world," March 3, 2011, Business Insider. https://www.businessinsider.com/obscure-weird-sports-2010-11

[d]E. Ortiz, "Strangest sports in the world," June 4, 2021, Stadium Talk. https://www.stadiumtalk.com/s/worlds-strangest-sports-a8bef81c8b8941b3

[e]D. Gachman, "Meet the fearless women of the Lone Star Mower Racing Association," September 22, 2021, Texas Monthly. https://www.texasmonthly.com/arts-entertainment/meet-fearless-women-texas-lone-star-mower-racing-association

motion of human joints.[8] In another footwear application, Nike's Vaporfly 4% running shoes incorporate a curved carbon fiber plate in the shoe's midsole designed to maximize energy return in a runner's foot. That energy return amounts to an average 4% improvement in the energy a runner needs to exert to run a certain pace, called running economy.[9]

Carbon fiber, too, is finding its way into protective equipment applications. For example, professional baseball uses aerospace-grade carbon fiber composite helmets that are 300% stiffer and 130 times stronger than previous ABS plastic helmets. While those previous helmets could protect players from ball strikes up to 68 mph, the new helmets provide protection up to 100 mph.[10] As carbon fiber's price continues to decrease, the material is expected to find more applications in protective sports equipment.

Besides carbon fiber, Table 2 points to other carbon-based materials that find use in sports equipment for their high strength and low weight, including carbon nanotubes, carbon nanoparticles, and fullerenes, especially for applications to increase gliding, resist abrasion, and repel moisture.

Glass fiber-reinforced composites are another predominant composite in sports equipment. They similarly offer high strength and low weight yet at a lower cost than carbon fiber composites. Fiberglass composites can be found in many of the same sports equipment as carbon fiber composites, but they are often used in lower-cost versions, such as equipment marketed to amateurs and beginners. Composites reinforced with glass fibers are preferable to carbon fibers in some applications that do not require high stiffness

Protective sports equipment is an important use of fiberglass composites. The U.S. market for protective sports equipment reached $1.9 billion in 2016 and is expected to reach a value of $2.2 billion by 2022.[10] While the market is dominated by polymers due to their light weight and impact resistance, fiberglass can be found in the outer shells of many helmets and goalie/catcher masks. In addition to composites, other form factors of glass are sprinkled throughout sports for basketball backboards, safety barriers, reflective clothing, and more (Table 2).

Motorsports vehicles incorporate many sensors, electronics, and other components that use ceramic and glass materials. The rising popularity of racing series for electric vehicles, such as Formula E, offer additional opportunities for ceramic and glass materials in the vehicles' batteries as well.

Increasingly, athletes use wearable devices and electronics to track, time, and monitor athletic performance. These devices rely on ceramic and glass materials in diverse ways for the sensors, electronic components, and batteries. Further, ceramic components are found in LED lights that enable viewing of sports events and provide visibility and safety to athletes in the dark.

Other applications of ceramics include equipment that requires wear and corrosion resistance, which is especially useful for various wheel-based components that provide athletes with

Table 2. Sampling of ceramic and glass materials used in sports equipment

Carbon fiber composites	
Bicycles	Frames, forks, saddles, handlebars, wheels
Implements	Tennis rackets, hockey sticks, pole vaulting poles, ski poles, golf clubs, fishing rods
Skeleton sleds	Base plates
Racing sailboats	Up to 2,000 lbs in a 50-foot racer
Formula One cars	80% composite by volume (mostly carbon) Body components: spoilers, fenders, engine hoods, doors, roof Structural components: rear seats, roof frames, struts, door sills, pillar reinforcements System components: powertrain, motor block, brake system
Footwear	Snowboarding, cycling, watersports, running shoes, hiking boots
Protective equipment	Helmets, goalie and catcher masks
Carbon nanotube, nanoparticles, fullerenes	
Sliding sports	Ski wax, kayak coatings, ice skate blade coatings
Fiberglass composites	
Protective equipment	Helmets, goalie and catcher masks
Implements	Tennis rackets, hockey sticks, pole vaulting poles
Winter sports	Skis, snowboards, bobsleds, luge sleds
Water sports	Surfboards, paddleboards, canoes, kayaks
Field sports	Hurdles, goals and goalposts
Bulk glass	
Backboards	Tempered glass basketball backboards
Safety barriers	Hockey rinks, racquetball and squash courts, underwater aquatic viewing windows
Safety apparel	Reflective glass apparel
Electronic materials	
Auto racing	Sensors, Formula E electric vehicle racing batteries
Wearable devices	Sensors, batteries
Lighting	LED venue and athlete safety lighting
Ceramics	
Wheeled equipment (Bicycles, skateboards, wheelchairs)	Ceramic bearings, brackets, brakes, boron nitride lubricants
Shoes	Cleat tips
Skiing	Inrun ski jump tracks
Playing venues	Concrete courts, ceramic tile swimming pools, tiled aquatic arenas

SPORTS EQUIPMENT AT THE PARALYMPICS

While many eyes tuned in for the Tokyo 2020 Summer Olympics that took place in July 2021, another major international sports competition took place at the end of August—the Tokyo 2020 Paralympic Games.

The Paralympics are a series of international contests for athletes with disabilities that are associated with and held following the summer and winter Olympic Games. Developing from a 1948 sports competition for British World War II veterans with spinal cord injuries, the Paralympics has grown to welcome more than 4,500 athletes in 2021 to compete in 539 events across 22 sports.

Below is a look at some of the equipment used in the Paralympics that contain ceramic and glass materials.

Running blades

Running blades are prosthetic lower limbs used by amputee runners. American medical engineer Van Phillips developed the first running blade, called the "Flex-Foot," in the 1970s after losing part of his left leg in a motorboat accident. Unlike previous prosthetics that tried to mimic human bones, he focused on replicating ligaments and tendons. He observed animals like kangaroos and cheetahs as well as the mechanics of diving boards and pole vaulting to develop the blade design.[a]

Carbon fiber is the material of choice for running blades, from the very first Flex-Foot to today. Between 30–90 sheets of carbon fiber are fused together to form the blade. Running spikes are typically fitted to the blade to help with gripping to the track.

Engineers continue to explore improvements in running blade design. For example, in 2013, Paralympian runner Blake Leeper challenged attendees at the Industrial Designers Society of America to advance the technology of running blades. Two companies, Altair (known for product design and development) and Eastman (a chemicals and plastics manufacturing supplier) consulted with Leeper and together developed a new "F1" concept for running blades that differs from traditional blades in the following ways.[b]

- **The spike plate**. Running blades are normally flat planes, but the F1 concept features a curvature that acts like an ankle, providing increased speed and efficiency on corners.
- **Blade shape**. The F1 concept modifies the blade shape to direct more power forward instead of into the ground, improving aerodynamics.
- **Blade attachment**. To keep the blade from falling off, the F1 concept uses both a fabric shroud and latch to lock the socket into place.

Icelandic prosthetics firm Össur hf. is a main player in the running blade industry. They acquired the original Flex-Foot line of blades from Phillips in 2000,[c] but what they are most well-known for is the Cheetah line of blades, which features blades not only designed for short- and long-distance running but also for long jumps.[d]

Sports wheelchairs

Just like prosthetic limbs, sports wheelchairs must become one with the athlete's body, otherwise performance is negatively affected. Some considerations when designing sports wheelchairs include[e]

- **The seating system**. A snug and well-fitted seat ensures the shoulder joints are in a neutral safe position.
- **The seat dump**, i.e., the angle of the seat with respect to horizontal. A larger seat dump increases pelvic stability by holding the pelvis against the backrest and improves balance by reducing the angle between the thighs and the trunk.
- **The backrest.** Backrest height should be set as low as possible to provide support to the lower back and allow the upper torso to move freely.

Wheelchairs for different sports require different designs.[f] For example, fencing wheelchairs are equipped with leg straps and sturdy handles to help the athlete stay solidly seated while striking and dodging. Racing wheelchairs are designed for high speeds, so they often feature a third wheel in the front to enable a low, elongated shape, and smooth disks instead of spoked wheels to generate less air turbulence. For sports requiring maneuverability, such as basketball, the wheels are slanted to allow for faster and tighter turns.

Ceramic materials used in wheelchairs include

- **Carbon fiber**. Modern advancements have increased the use of carbon fiber in sports wheelchairs. For example, carbon fiber wheels and frames are used in racing chairs such as the Top End Eliminator NRG,[g] and custom molded carbon fiber seats are found in basketball chairs such as the RGK Elite CX.[h]
- **Ceramic bearings**. Well-made ceramic bearings roll faster thanequivalent steel bearings, thereby allowing an athlete to save their energy and achieve faster cruising speeds. AITA Ceramic–Australia International Ceramic, a Melbourne-based bearing business, worked with Australian Paralympic athlete Sam McIntosh to develop hybrid ceramic bearings specifically for wheelchair sports.[i] Draft Wheelchairs Ltd., a Godmanchester, U.K.-based company that provides equipment to people with disabilities, endorsed the ceramic bearings produced by Ceramic-Speed, a small specialist Danish manufacturing company, for use in racing wheelchairs.[j]

Wheelchairs feature different designs depending on the sport for which it will be used. Left, the gold medal game in men's wheelchair basketball at the Beijing 2008 Summer Paralympics. Right, wheelchair fencing at the London 2012 Summer Paralympics.

Credits: Left, Canadian Paralympic Committee, Flickr (CC BY-NC-ND 2.0). Right, Farrukh, Flickr (CC BY-NC 2.0)

[a] "Running blades and their evolution," *National Paralympic Heritage Trust*, n.d. https://www.paralympicheritage.org.uk/running-blades-and-their-evolution

[b] A. Schwartz, "These reinvented running blades could let more Paralympians into the Olympics," *Fast Company*, 14 Aug. 2014. https://www.fastcompany.com/3034308/these-reinvented-running-blades-could-let-more-paralympians-into-the-olympics

[c] "50 years of memorable moments, 1971–2021," *Össur*, n.d. https://www.ossur.com/global/about-ossur/our-company/milestones

[d] "All products," *Össur*, https://www.ossur.com/en-us/prosthetics/products

[e] "Wheelchair sports technology and biomechanics," *Musculoskeletal Key*, n.d. https://musculoskeletalkey.com/wheelchair-sports-technology-and-biomechanics

[f] S. Bushwick, "How Paralympic wheelchairs and prostheses are optimized for speed and performance," *Scientific American*, 31 Aug. 2021. https://www.scientificamerican.com/article/how-paralympic-wheelchairs-and-prostheses-are-optimized-for-speed-and-performance

[g] Top End Eliminator NRG, https://topendwheelchair.invacare.com/eliminatorNRG

[h] RGK Elite CX, https://rgkwheelchairs.com/wheelchairs/sport-wheelchairs/elite-cx.html

[i] "Wheelchair bearing," *AITA Ceramic–Australia International Ceramic*. https://aitaceramic.com/wheelchair-bearing

[j] "Ceramic bearings for racing wheelchairs and handcycles?" *Draft Wheelchairs*, http://www.draftwheelchairs.com/ceramic-bearings-racing-wheelchairs-handcycles

motion (summarized in Table 2 and the sidebar: *Paralympics*). Other examples of ceramics are found sporadically throughout sports. For instance, clay pigeons or clay traps, while not made of clay, are manufactured from petroleum pitch and calcium carbonate, and the inner weighted core of bowling balls contains a mixture of minerals embedded in a polymer resin. Readers will know of many similar applications.

In addition to sports equipment, ceramic and glass materials can be found in sports apparel (see sidebar: *A softer side*) as well as some athletic surfaces.[11]

Game-changer: Materials innovations shift sports

Materials often enable technologies for athletic performance—so it is no surprise that as the materials used in sports evolve, so too does athletic competition.

"If you would have watched tennis 20 years ago on the professional level, you would have seen a much slower paced game," says Jeff Bardsley, vice president of marketing for racket sports in North America at Head, a global manufacturer and provider of various sports equipment and apparel. "The ball would have been moving a lot slower, and therefore demands on the actual player wouldn't be as high as they are today. Today's game is very, very fast."

That evolution can be traced back to the equipment. By reducing the weight of tennis racket frames while simultaneously increasing their stiffness, modern composite tennis rackets can be swung faster and generate more power than early wooden tennis rackets. Modern composite rackets are 22.4% lighter on average that wooden versions,[12] resulting in 17.5% faster serve speeds overall since the game's inception in the 1870s.[13] "Rackets now offer more power, more spin, and that's been changing the game up just in terms of how the game is played," Bardsley says.

Modern tennis racket frames are made of various lightweight materials, depending on the level of competition and the price point. For instance, Head manufactures lower-price rackets intended for beginners made from aluminum nylon frames. The company also manufactures mid-level rackets from graphite composites, a combination of aluminum and graphite fiberglass or graphite composite. For its higher-level rackets, Head uses graphite, which is more expensive due to higher material cost and its more complex construction. There are variations of these types of materials in each category, but most of Head's tennis rackets consist of carbon-based and fiberglass materials.

Despite this slight variability in materials, tennis rackets have not changed much in the past several decades, partially based on parameters set by the ruling body, the International Tennis Federation, that restrict variability in tennis rackets. "Looking at a tennis racket, there's really only so much that you can do because it has to have a head, it has to have some form of throat, and it has to have a handle," Bardsley says. Manufacturers can adjust some external parameters of a tennis racket frame, such as the racket length and head size, but they are relatively limited in terms of completely redesigning a racket that can be used in competition play.

That does not mean all tennis rackets are the same, however—and some of these small changes can have a significant impact on the resulting equipment. For instance, adjusting how a tennis racket is balanced from the head to the handle impacts performance. Perhaps even more adjustments can come from internal changes to the racket frame. Part of these adjustments come from changing the materials, but also changing the orientation of the materials' fibers in one part of the frame or another, Bardsley says.

"We can also change by placing materials at different areas on the actual head of the racket to determine how the racket is going to play. The size of the sweet spot is going to be determined by the placement of the materials, the layup on the materials. By taking a similar tennis racket construction and changing the layup, changing the actual balance point of the racket, changing minor configurations, you can take two different rackets that look exactly the same and they will play completely different," he says.

Overall, though, these variations result in relatively minor tweaks to tennis rackets. Manufacturers generally are not drastically altering the design or researching entirely new materials to incorporate into the frame. They are altering the fiber orientation, slightly adjusting the frame dimensions, or testing the effect of adjusting a material in certain areas of the racket, for example.

Yet that is not to say that Head does not innovate with new materials in tennis rackets. In the early 2000s, Head introduced a new line of tennis rackets, the Intelligence collection, that incorporated piezoelectric fibers in the frame. "Our concept with the piezoelectric fibers was transforming mechanical energy into electrical energy, causing a faster snap back, giving us an opportunity to stiffen up the throat section of the racket," Bardsley says. Those lead zirconate titanate fibers, supplied by Advanced Cerametrics Inc. (Lambertville, N.J.), generated an electrical current when the racket deformed upon contacting a tennis ball.[14] A chip located in the racket's handle amplified the signal, stiffening the frame to generate more power and reduce vibrations.

The Intelligence rackets, despite an expensive price of about $400 almost 20 years ago, sold much better than Head anticipated. Yet Head discontinued the high-end line after being on the market for less than a decade. "We didn't necessarily abandon it. It was more just moving on in terms of technology goes," Bardsley says.

Today, Head's primary focus for new technology in its tennis rackets is on graphene. The 2D carbon material provides the ability to further decrease the weight of a racket by using less material, without sacrificing stiffness or strength. While Head initially used graphene in only key limited areas of the racket—focusing on the throat section, which is a high point of distortion on the racket—it is now incorporating graphene all along the racket head and throat with its Graphene 360+ technology. "So that gives us the opportunity to really play different, and it gives a consistent and solid feel for the racket where we've got a consistent flexpoint, which allows more of a consistent hit or performance when the ball actually is coming off the racket," Bardsley says.

A SOFTER SIDE: CERAMIC AND GLASS MATERIALS OFFER FUNCTIONALITY TO SPORTS FABRICS

Athletic apparel is a significant segment of the sports industry. In 2020, total global revenue for sports apparel exceeded $188 billion, with expectations of reaching nearly $208 billion by 2025.[a]

While synthetic fabrics that provide stretch, breathability, odor control, and moisture-wicking capabilities dominate sports apparel, this segment of the sports market is not entirely devoid of ceramic and glass materials.

Apparel designed to make athletes visible in low-light conditions, such as runners jogging at night, use retroreflectivity to maximize the light reflected light back to its source, such as a vehicle's headlights. This reflection is via microscopic yet precise glass beads, which reflect light directly back rather than scattering it. Often applied as a film on top of another fabric, retroreflective materials are found on a wide variety of shoes, jackets, apparel, and accessories.

In 2017, 3M released a new retroreflective material, Carbon Black, that appears black in daylight, as opposed to the silver color of most retroreflective materials. The company achieved the black color through a proprietary process that "makes the color inherent to the material's construction," according to a 3M press release.[b]

3M's Carbon Black technology appears black in daylight yet contains small glass beads that are highly retroreflective. Most retroreflective materials appear as a silver color.

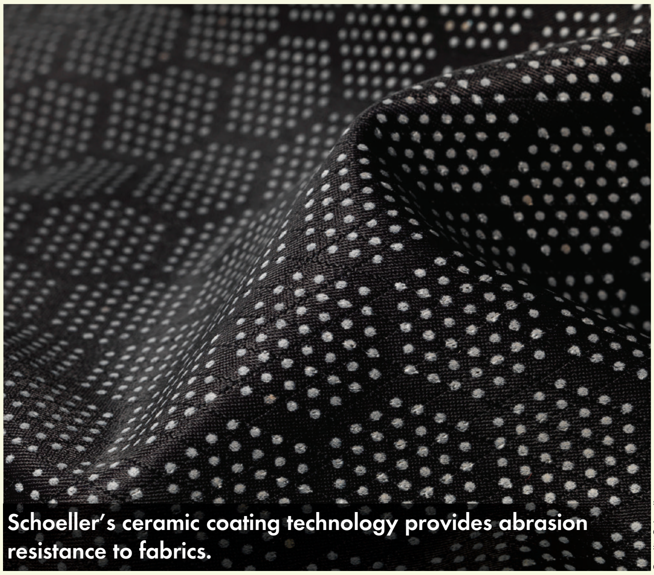
Credit: 3M

In addition to visibility, ceramic materials can be found on sports apparel fabrics designed to provide abrasion and wear resistance.

For example, Swiss company Schoeller manufactures a durable and abrasion-resistant textile with a ceramic coating for applications such as cycling. "The ceramic finishes fit together with the selected raw materials and the textile design to offer not only abrasion resistant materials with ceramic coatings, but also fall protective materials in the motorcycle or bike category," the company says.

One version of the ceramic-coated fabric, called ceraspace, is Schoeller's "particularly high-performance" fabric for applications that require maximum protection such as motorcycling. The company puts its materials through rigorous performance tests, including standardized tear and tensile strength, abrasion, elongation, pilling, weight, deformation, and weather tests, in addition to the company's own unique testing methods. According to its testing, Schoeller says ceraspace provides around three-times the abrasion resistance of high-quality leather.[c]

While the composition of the ceramic is proprietary, Schoeller says the coating can be applied as either a finishing or printing process, with the ceramic applied in various designs such as small dots. The durable coatings stay on the fabric even after washing. As the company says, "they are developed to last the lifetime of the garment." 100



Schoeller's ceramic coating technology provides abrasion resistance to fabrics.

Credit: Schoeller

[a]Statista, 2021. https://www.statista.com/statistics/254489/total-revenue-of-the-global-sports-apparel-market

[b]3M, "3M reinvents reflective material for activewear with Carbon Black technology," 2017. https://news.3m.com/2017-05-02-3M-Reinvents-Reflective-Material-for-Activewear-with-Carbon-Black-Technology

[c] Schoeller. https://www.schoeller-textiles.com/en/technologies/ceraspace

Head's approach is reflective of that of other major companies manufacturing sports equipment in more mature product markets, in which they offer equipment manufactured with various materials for different levels of athletes. They innovate with materials and design to sell more pieces of equipment, often incrementally pushing those markets in one direction or another. But are there opportunities for bigger innovations in the sports world?

A testbed for materials innovation

"Sports is actually a great market to test your materials. You can show off your material, you can market your material, you can test your material in the very extreme conditions," says Erik Khranovskyy, CEO of Grafren AB (Linköping, Sweden). Grafren specializes in graphene-coated textiles, which provide the ability to incorporate sensing and power functions within clothing, including athletic apparel (Figure 3).

Many sports markets are well-funded, willing to take chances to gain a competitive advantage, and offer a relatively lower-risk testing environment compared to medical or aeronautical markets, for example.

In addition, while regulatory bodies set guidelines or standards for use of technology in sports competitions, those rulings often are reactions to new developments rather than in anticipation of potential innovations. For instance, Speedo's LZR Racer swimsuit, which debuted at the Beijing 2008 Summer Olympics, featured a lining with thin yet stiff polyurethane panels that reduced skin friction drag by 24% compared to the company's previous racing suit fabric.[15] The swimsuit improved swimmers' performance and speed so much that 98% of swimming medals won at the 2008 Olympics were by swimmers wearing the LZR Racer. The suit was so fast that some claimed it amounted to "technological doping," and by 2010 the LZR Racer and similar types of suits were banned by the international body that regulates competition in water sports.

Yet unless regulations ban or exclude certain technologies—and there often is not a precedent to do so until that technology debuts on the market—the world of sports is usually wide open to innovation, creating a ripe environment for new materials.

For example, Grafren's nano-engineering process wraps graphene flakes precisely around individual fibers of a textile, allowing control of the graphene layer's thickness. Because every fiber is coated with a thin layer of graphene, the overall weight and porosity of the textile changes very little, making it ideal for sports apparel that needs to be breathable.

The first step of Grafren's three-step process is infiltrating graphene into the fiber. "We learned how to put the flakes inside, in the depth of the fiber," Khranovskyy says. "The second step in the process was how to fix the flakes on every single fiber, so that they lay down on the fiber."

Grafren's technique causes the graphene flakes to wrap around the textile fiber, bonding individually to the fibers. "It involves both physical forces, weak van der Waals forces, but also depending on the material, much stronger chemical bonds as well," Khranovskyy says.

The final step builds up the depth of graphene flakes on the fibers. "That's what I called graphene mâché, in analogy to papier mâché. Every flake coming in surrounds the fiber more and more, so you actually have a core–shell structure around the fiber." The graphene flakes overlap one another, creating a dense yet thin coating on individual fibers.

Grafren's water-based process does not use any binders, resulting in homogeneous, precise, and durable graphene coating of individual textile fibers. And the process can be applied to natural fibers like cotton, synthetic fibers like polyamide, and even glass and carbon fibers.

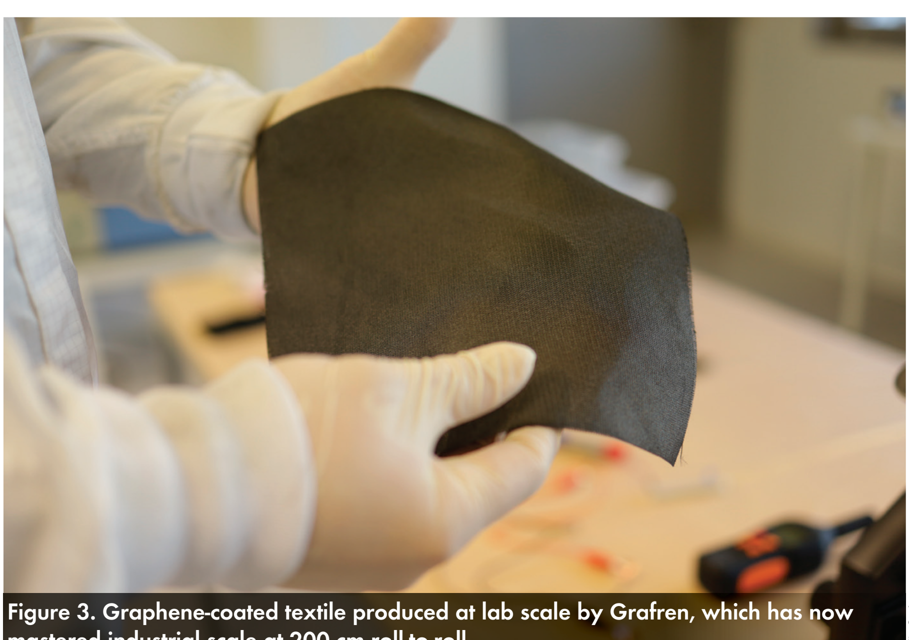


Figure 3. Graphene-coated textile produced at lab scale by Grafren, which has now mastered industrial scale at 200 cm roll-to-roll.

Credit: Grafren

Further, Grafren's fiber-coating process can be applied to other 2D materials, Khranovskyy says, noting that Grafren already filed a patent related to this technology. "Those ideas which researchers are discussing on flat surfaces, they can be realized inside of fabric on individual fibers as well," he says.

Because of graphene's conductivity, Grafren's coated fabrics offer several functional capabilities. The fabrics can collect signals from the body to act as a biomonitor or biosensor; they provide thermal management, either removing or providing heat to an athlete depending on the surrounding conditions; they can function as a strain sensor if the graphene is coated onto a stretchable fabric (so that stretching changes conductivity); and they can function as pressure sensors or impact sensors by creating an electrically conductive channel from several fibers grouped together.

"Imagine shoes—the soles could measure pressure. The more points you have, you can actually measure pressure distribution" Khranovskyy says. "The shoe could also measure the force when you kick a ball. Or consider boxing gloves that could measure pressure. So any textile, any fabric, any clothing which is in contract may be active and may provide a signal about the force and the place where it was applied."

In addition to performance, such sensors could play an important role in athlete safety as well. "If we imagine any type of a sport activity where we have helmets, then the pressure sensors can be simply integrated in the lining," Khranovskyy says. Helmet-affixed sensors could provide valuable information for assessing player injuries, such as the strength of the hit, the area of the head where the impact was localized, and when the athlete gets up from the impact.

Khranovskyy says that one of the biggest challenges Grafren faces is the vast possibilities for graphene-coated fibers—

just deciding which direction to pursue can be difficult.

"From our experience, graphene provides several functions to textiles, which enable 10 times more directions of further product development, and the amount of products is even 10 times more." Grafren works with its customers to tailor its graphene-coated textiles to a particular application.

"For every product the value may be different. So in order to commercialize it, we have to really identify what is it exactly customers would like to enable," Khranovskyy says.

A potential direction that Grafren currently is working on with one its customers is to develop heatable clothing. The company already developed a functioning prototype of its graphene-coated heated textile—although it looks nearly indistinguishable from a standard athletic textile, the fabric is coated with graphene and incorporates conductive threads running throughout the fibers that, with the press of a button on a connected energy source, gently warm the fabric.

Such fabrics have applications for athletes in cold environments but also could provide warming at specific locations for therapeutic purposes, to enhance athletic recovery.

Thermal management is a hot topic in sports apparel, with other similar types of developments using fabrics coated with carbon fibers or incorporating ceramic nanoparticles to warm or cool athletes depending on the surrounding environment.[16]

Grafren's conductive textiles demonstrate just one possible application of graphene in sports, for which there is diverse potential due to the material's long list of desirable properties.

The Graphene Flagship, a joint research venture funded by the European Commission, already helped develop several other sports-related applications of graphene, including an impact-resistant graphene-coated motorcycle helmet,[17] a transdermal patch to monitor fitness using graphene optical sensors, [18] and a graphene-based lubricant for auto and motorcycle engines.[19]

Sensing the future: Optimizing performance and enhancing safety

Sports equipment was once designed solely for mechanical performance, but advanced materials offer new design freedoms and thus new functionalities to change how sports are played, experienced, and enjoyed.

"Now, within the past decade or so, we're starting to get multifunctionality, so the materials offer say thermal control or odor control, or they're able to sense things like the pH of your sweat or your heartbeat. And that's an area really where ceramics and glasses can play an important role and already do in sports," says Jud Ready, principal research engineer at Georgia Tech Research Institute, deputy director of innovation initiatives at the Institute for Materials, and adjunct professor in the School of Materials Science and Engineering at Georgia Institute of Technology. Ready teaches a popular Georgia Tech course on materials science and engineering in sports.

The power of sensors is that they provide physical data about how athletes play sports, to inform sports strategy and improve safety, as well as physiological data about how athletes' bodies function during and after athletic exertion, to enhance performance. While vast sensors and sensing technologies are already widely incorporated into motorsports—such as ceramic oxygen sensors in motor engines—technological developments have more recently enabled biosensors and biomonitors to track a vast array of individual parameters of athletes as they practice, compete, and recover.

Devices that monitor physical performance and safety collect data on an athlete's position, motion, impact, and biomechanical forces. These devices include wearable devices to monitor head injuries in contact sports to prevent concussion or traumatic brain injury, such as helmets, headbands, caps, or neck-worn collars.

For example, several companies developed mouthguards with embedded sensors to monitor head impacts. One such device contains embedded sensors that detect collision intensity, providing a visual readout with front-facing LED lights that can alert trainers and coaches about dangerous impacts. Other developments include wearable sensors to monitor joint mechanics during play as a means to prevent injury.[20]

Other sensing devices monitor athletes' physiological status to optimize performance, collecting data on parameters such as heart rate and sleep. Optical sensors to monitor heart rate are relatively well-established technologies, with new trends toward development of skin-worn patches as well as integrated textiles that can measure heart rate. Yet while heart rate provides a global measure of physical activity and exertion, it cannot provide information on the response in specific muscles—data that is important for professional athletes seeking to optimize their performance.

In response, an emerging trend is monitoring muscle oxygen saturation to inform how specific muscle groups respond to activity, using optical technologies to measure oxygenation of blood in muscles with near-infrared light.[20]

While more widely available wearable sensors currently measure these physical and physiological parameters, there also exists vast potential to monitor biochemical parameters that affect athletes' performance, and many sensors are being developed in this space as well.

Such devices can sample sweat or saliva to measure biochemical signals such as electrolytes, enzymes, and neurochemicals, providing a means to noninvasively monitor health and performance in real time. These types of biosensors include mouthguards that detect chemicals in saliva that indicate muscle fatigue, contact lens sensors for ocular diagnostics, or skin-based sensors to monitor neurochemical markers of stress in sweat.

Biochemical sports sensors also offer corollary functions within medical diagnostics, and some of these sensors are adapted from existing medical technologies. For example, healthcare company Abbott (Chicago, Ill.) developed a commercial wearable continuous glucose monitor for athletes. Applied to an athlete's arm, the small wearable device, called Libre Sense, uses a thin filament inserted just under the skin to measure glucose levels in the fluid surrounding cells.

"The biosensor is designed to provide a glucose monitoring experience that will enable athletes to understand the efficacy of their nutrition choices during training and competition," according to company's website.[21]

The device is similar to that used by diabetics, but it is tailored to athletes by providing more frequent minute-by-minute glucose readings. "It will therefore inform athletes about how to fuel appropriately, to fill their glycogen stores prior to a race and to know when to replenish during a race to maintain athletic performance," the company's website explains.

Conversely, technologies developed to monitor athletic parameters are often not confined to sports contexts, as these innovations can extend into markets and aspects of life beyond sports as well. For example, innovations in sensor technologies to track athletes often can be adapted to monitor or manage health aspects in a medical context, providing much wider value to these technologies.

That is something Grafren CEO Erik Khranovskyy recognizes for its graphene-coated textile sensor technologies. "So all the sensors which I described, they can bring a lot of value to one athlete and one nation once per four years," he says. "On the other hand, they can bring a lot of value to millions of people on a longer-term perspective."

Despite the technological capability to measure and collect such rich data, however, interpretation to the athlete often lags behind. For instance, in the case of Abbott's Libre Sense, blood sugar and performance have a complicated relationship—low blood sugar levels do not necessarily mean performance will suffer, and conversely elevated blood sugar levels will not ensure maximum athletic performance, especially in high-functioning endurance athletes. These parameters are variable with time, exertion, and athlete, so interpretation of the data is nuanced. More extensive datasets and further data analyses are needed to improve data interpretation to an athlete's performance.[22]

Despite the lag in data interpretation, the possibility to track and collect such rich data for athletic performance will continue to push development of all kinds of sensors across the sports industry in the future. These trends offer significant potential for the ceramic and glass components that enable these sensors, monitors, and electronic components with the lucrative sports industry.

Similarly, many wearable devices and sensors require a power source, another area that offers significant potential for ceramic and glass materials in the future of the sports industry. The continued push for batteries with higher power density that offer longer life in smaller form, allowing smaller devices that can provide more functionality, provides opportunity for innovation with new

PLAYING THROUGH A GLOBAL PANDEMIC

The global COVID-19 pandemic has affected businesses around the world, disrupting supply chains for seemingly everything and drastically impacting the workforce. Not surprisingly, the world of sports was not spared.

Cancellation of major sports events in early 2020 were some of the earliest indications to many people of just how serious the pandemic was, as trends within sports often reflect larger trends in society. Gyms and fitness centers closed, entire sports seasons were missed, and perhaps most telling, the Tokyo 2020 Olympic Games were postponed until 2021.

While the cancellations, closures, and postponements had a negative economic impact on the sports industry, the pandemic's effects on sports were not all negative.

"If you would have asked me 18 months ago, pre-COVID, the tennis business was struggling," says Jeff Bardsley, Head's vice president of marketing for racquet sports for North America. "Participation was down, people were playing other sports, people weren't engaged in sports, period. I think all sports for the most part were struggling."

The pandemic shifted that dynamic for many sports as people worldwide increasingly turned to sports and outdoor activities for physical as well as mental health benefits. That statement is particularly true for sports that offer the ability to play while maintaining social distance—games like golf, tennis, and disc golf saw increased participation and market value as a result of the pandemic.

In the U.S., golf experienced a 2% increase in the number of individuals playing at least one round of golf in 2020 compared to 2019, the largest increase in the game in nearly two decades. And this participation is not limited to only seasoned players pulling their clubs out of the closet, according to a *CNBC* report.[a] "'New participants are increasingly younger; they're hooked on the game and they want to get better,' David Maher, CEO of golf conglomerate Acushnet Holdings, said on the company's second-quarter earnings call with analysts in August. 'A lot of the energy is coming from avid dedicated players who are simply playing more and consistently; more juniors, more women, more younger [players], and more families.'"

For golf, that increased enthusiasm for the sport translated to manufacturers and retailers as well—Acushnet, the company that owns popular golf brands Titleist and FootJoy, reported 117.1% growth in net sales in the U.S. in the second quarter of 2021. Golf brand Callaway and sporting goods store Dick's also noted growth in golf sales.[a]

Tennis also saw pandemic-fueled gains, with participation rising 22% in the U.S. in 2020 compared to 2019.[b] Bardsley says Head has had difficulty keeping up with the surge in demand. "We have struggled over the last 18 months to try and keep product on shelves. We're the largest producer of tennis balls in the world, and we can't supply our retailers in the U.S., North America, globally with tennis balls."

Bardsley is hopeful that the increased interest will not wane with the pandemic. "From the trends that we've seen so far in sporting goods sales, I definitely perceive that as an upward trend… In my 29 years in business, I've never ever seen anything like this—so I'm hopeful for the sport." 100

[a]CNBC, "Golf's growth in popularity is much bigger than a pandemic story," September 26, 2021, *CNBC*. https://www.cnbc.com/2021/09/26/callaway-dicks-sporting-goods-score-with-growth-of-golf.html

[b]M. Futterman, B. Pennington, "The pandemic drove people to tennis and golf. Will they keep playing?" March 11, 2021, *New York Times*. https://www.nytimes.com/2021/03/11/sports/tennis/tennis-golf-participation-pandemic.html

materials. For example, the Whoop fitness tracker is powered by a slim yet high-density battery that continuously monitors heart rate, sleep, recovery, and more. The battery gets a boost from technology by Sila, a company that developed a silicon powder that replaces conventional graphite anodes with higher-density silicon anodes, offering up to 20% higher energy density.[23] Other batteries technologies and developments are sure to find their way into wearable sports sensors as well.

Yet another possibility could be ditching the power source altogether, and instead leaning on self-powered piezoelectric materials to provide power to wearables and sensors, as the ability to convert mechanical energy to electrical energy is well-suited for sports contexts. While the heyday for incorporating piezoelectric fibers into sports equipment—which included not only Head's Intelligence tennis rackets, but also various skis, snowboards, mountain bicycles, baseball bats, and golf clubs—seems to have passed (as this equipment often relied more heavily on marketing rather than enhanced performance to sell piezoelectrics' possibilities[24]), new future potential for the materials might be found in the ability to power sports sensors.

Fans get in the game

Beyond enhancing athletic performance and improving safety, sensors offer another function that is likely to be significant in the future of sports—the fan experience.

"You can use that same data that you're collecting to measure athletic performance, health, wellness and prevention, to create an immersive fans' experience," says Leslie Saxon, professor of medicine and executive director of the University of Southern California's Center for Body Computing, in a *BBC News* article.[25] "What if I record my own heart rate while watching my favorite football player play, looked at my response and compare it to his response on the field?"

Digital technologies to enhance fan engagement experienced a significant boost since the start of the COVID-19 pandemic, as health and safety precautions shifted in-person experience of sports events to virtual platforms (see sidebar: *Playing through a global pandemic*). Continued investments in the infrastructure to support streaming platforms, digital content, and even augmented and virtual reality experiences will continue moving the trend forward, incorporating the data provided by athlete-worn biosensors to further engage fans.

"As this technology matures, there will be more and more biosensors out there," Saxon says in the article. "It is truly the next frontier in sports and technology."

American professional golfer Bryson DeChambeau, above, uses graphite shafts made from carbon fiber in all his clubs. His choice contrasts with other professional golfers, who generally only use graphite shafts in their driver and other wood-type clubs.

Ensuring fair play

As technology continues to play an increasing role in sports, moral questions begin to arise. One long-standing question involves equity in access, as expensive technologies introduce disparities between those who can afford the devices and those who cannot. Yet another quandary surrounds the potential for technologies to extend beyond simply sensing and instead offer functional improvements to athletic performance.

"What about if there's an opportunity to make an implant on your bone that could make it more structurally sound so you could run further, or it's a piezoelectric sensor that measures the stress in the bone?" says Ready. "Maybe that's bad to use in competition because it's giving feedback that you can actively use in competition, but maybe it's useful during rehabilitation—so is it okay in one scenario and not in the other?"

The line between where materials enhance athletic performance and where materials provide an unfair advantage or artificially exaggerate human capabilities is colored in various shades of gray. And it is often difficult to discern or quantify just how much advantage a technology might provide to an athlete, further complicating the picture.

Yet Ready suggests that sports are based on advantage and competition. "That's the whole point of sports—you're trying to prove that you're better than somebody else," Ready says. Technologies provide means to improve the game, and as long as they follow the rules, innovation is fair game. "That is, I think, what materials science tries to do, is to give you an unfair competitive advantage. But we do it in a rules-compliant way, whether that rule does not yet exist, and therefore we're in compliance with it, or because we go right up to the boundary," he says.

So what does the future of sports look like? Despite debates about the fairness of new technologies, materials science offers the ability to enhance and improve existing aspects of sports as well as innovate in new and sometimes unexpected ways. Technology will continue to infiltrate sports, in some ways enhancing athletic performance and improving the safety and fan experience of the game. Athletes, enabled by technology, will continue to get better, setting new world records—and those feats of athleticism will be backed by materials science.

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