

A close look at the recently actualized real-world advances related to sports and outdoor performance textiles

Abstract

Over the past two decades, sports and outdoor performance textiles have undergone a transformation driven by breakthroughs in materials science, advanced manufacturing, and sustainability imperatives.^{1,2} Innovations in fibers, membranes,³ and coatings have redefined moisture management, thermal insulation, weather protection, compression, and aerodynamic performance. Elite apparel and gear now integrate engineered microfibers, breathable membranes,³ active insulation,⁴ and high-strength yarns⁵ to optimize comfort, mobility, and protection in extreme environments. Aerodynamic and hydrodynamic textile engineering—often developed in collaboration with aerospace and biomechanical research has pushed performance limits in swimming and cycling. In contrast, smart textiles and e-wearables have enabled real-time physiological monitoring.⁶⁻¹² Protective gear has evolved through the use of impact-responsive materials^{5,13} and abrasion-resistant fibers, achieving unprecedented safety with minimal bulk.

Equally significant are the advances in production and sustainability^{2,14-16} that enable these performance gains. Seamless knitting, bonded construction, electrospun membranes,³ and laser-cut precision^{17,18} have enabled targeted ventilation, zoned compression, and lighter, waste-minimizing garments. The global industry has shifted toward recycled and bio-based fibers, waterless dyeing technologies, and closed-loop manufacturing, with leading brands such as Nike, Adidas, The North Face, Patagonia, and Gore-Tex embedding environmental responsibility in their elite gear. These combined advances have yielded sports textiles that are lighter, stronger, more adaptive, and more sustainable than ever before^{1,7,10,11,16} thus reshaping how athletes train, compete, and interact with their environments.

Keywords: performance textiles, smart fabrics, sustainability, sportswear innovation, moisture management, weather protection, compression support

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Radhakrishnaiah Parachuru

Principal Research Scientist, Emeritus Status, Georgia Institute of Technology, MSE, USA

Correspondence: Radhakrishnaiah Parachuru, PhD, Principal Research Scientist, Emeritus Status, Georgia Institute of Technology, MSE, Atlanta, GA, USA

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Introduction

Recent years have marked an unprecedented period of innovation in sports and outdoor performance textiles, reshaping how athletes and adventurers engage with their environments. The demands of elite sport have driven textile development far beyond the capabilities of conventional fabrics. Performance textiles are no longer simply garments or gear; they are integrated systems of engineered fibers, membranes, coatings, and constructions designed to regulate temperature, manage moisture, reduce aerodynamic and hydrodynamic drag, enhance safety, and withstand the extremes of nature. At the same time, advances in manufacturing and sustainability have transformed how these products are conceived, produced, and distributed globally.

The performance textile sector has drawn on breakthroughs from both corporate R&D and academic research, with industry leaders such as Nike and Adidas often working alongside materials science institutes, aerospace engineers, and biomechanical specialists. These collaborations have yielded a wide range of innovations: moisture-wicking microfibers, active insulation technologies, air-permeable waterproof membranes, dilatant impact-absorbing compounds, and high-tenacity fibers like Dyneema and Kevlar. Equally transformative are the improved manufacturing processes, such as 3D knitting, laser cutting, bonded seams, and electrospun nanofiber membranes. These developments permitted precise zonal performance, reduced weight, and improved comfort.

In parallel, the industry embraced an environmentally friendly approach. The integration of recycled polyester from plastic bottles, bio-based rubbers and fibers, and waterless dyeing technologies reflects a broader shift toward closed-loop systems and reduced ecological impact without compromising performance. This dual focus, maximizing athletic output while minimizing environmental footprint, has become a defining feature of the sector's evolution. This paper examines the significant global advances in sports and outdoor performance textiles during 2005-2025. It organizes the information by application area. Also, the author believes that this paper should be viewed as a narrative review that summarizes what is known about a broad topic. It provides a big-picture view of the field and covers multiple sources of development.

Major developments in the arena of sports and outdoor performance textiles

Advances have emerged from research labs and industry leaders alike, resulting in clothing and gear that enhance athletic performance, comfort, and safety. Below is a comprehensive summary of significant developments since the early 2000s, including innovations in apparel and gear from leading global companies.

Moisture management and cooling technologies^{1,3,6,10,11,16}

One of the fundamental shifts in sports apparel has been the adoption of *moisture-wicking fabrics* to keep athletes dry and cool. In the early 2000s, Under Armour popularized tight-fitting synthetic

base layers that wick sweat away from the skin, a stark contrast to heavy cotton shirts. A sweat-soaked heavy cotton shirt can weigh 2 to 3 pounds, whereas an Under Armor poly microfiber shirt saturated with sweat weighs about 8 ounces.¹⁹ These lightweight, moisture-wicking shirts (second-skin designs) became ubiquitous across sports, reducing heat stress and chafing for athletes. Nike's Dri-FIT (polyester microfiber) and Adidas' ClimaLite/ClimaCool lines similarly pull perspiration outward to evaporate quickly, helping athletes stay cooler than with cotton.^{19,20}

To further improve cooling, *engineered mesh fabrics* and ventilation zones have become common in high-intensity sportswear. Mesh panels in jerseys, shorts, and shoes allow air to circulate, helping prevent overheating.²¹ For example, Adidas Climacool apparel (and the related *Climacool* shoe line) emphasized breathability with vented fabrics and air channels. Nike's Aeroswift track uniforms and Vapor jerseys feature knit-in mesh holes at heat zones to dump excess heat and moisture. Such designs keep athletes dry and reduce the discomfort of sweat accumulation.^{19,20}

Innovators also introduced *cooling fabric treatments*. One notable technology is *Coldblack®* by Schoeller, a nano-coating that reflects solar radiation. Dark textiles usually absorb heat, but a Coldblack finish makes even black fabric reflect up to 80% of incident heat, keeping the material (and the athlete) noticeably cooler under the sun.²² This improves heat management and also provides UV protection without affecting the look or feel.²² Coldblack has been integrated into cycling and triathlon kits by brands like RYZON and has been used in Under Armour's run apparel.²²

Some brands embedded *phase-change or cooling polymers* in fabrics for heat relief. Columbia's Omni-Freeze Zero uses a ring-shaped polymer that swells when wet (from sweat), creating a cool sensation against the skin. Likewise, Xylitol-infused fabrics (found in some tennis apparel) impart a cooling effect when perspiration activates them. These developments, along with moisture-reactive ventilation (e.g., materials that open structure as they get wet), have given athletes new tools to regulate body temperature in hot conditions.²³

Anti-odor and hygiene are also part of moisture management. Many performance textiles now feature *antimicrobial treatments* (such as silver-ion or polyamine coatings) that inhibit bacterial growth and reduce sweat odors. For example, Lululemon's *Silverscent* line incorporates silver threads to keep gear smelling fresh. Merino wool garments also gained popularity for base layers because merino is naturally odor-resistant and thermoregulating.²⁴ While synthetics dominated 1990s sportswear, merino wool saw a resurgence in the 2000s, offering moisture management, a soft, non-itchy feel, and odor control, albeit at a higher cost.²⁴ This rediscovery of natural fibers in activewear provided a sustainable, functional alternative to petrochemical fabrics.²⁴

Thermal insulation and heat retention^{1,4,5,10,11,13,16}

For outdoor and winter sports, *insulating textiles* have advanced to keep athletes warm without overheating or bulk. Traditional insulation (down or puffy synthetics) excels at retaining heat when static, but can cause sweat buildup during activity. A breakthrough came with *active insulation* that breathes. Polartec introduced *Polartec® Alpha*, the first active insulation designed for start-stop exertion.^{25,26} Unlike conventional batts, Alpha insulation is a stable lofted knit that can be used with air-permeable fabrics, allowing heat and moisture to escape while still trapping warmth.²⁵ It dries dramatically faster than down and keeps insulating even when wet.^{25,26} Alpha proved so effective

that it became standard issue for military cold-weather gear, replacing multiple layers with a single breathable midlayer.²⁶ By 2013–2014, outdoor brands like Patagonia and Rab were using Polartec Alpha in breathable puffy jackets, enabling athletes to stay warm *and* sweat during activity without constant layer changes.

Another area of development is heat-reflective materials. In 2010, Columbia Sportswear launched *Omni-Heat* foil lining in jackets and ski gear—a pattern of aluminized dots on fabric that reflects the wearer's body heat back toward the body. This provided a warmth boost (approximately 20% warmer) without added weight, creating a lightweight space-blanket effect inside apparel. Other companies followed with their own reflective linings for winter running and mountaineering gear.²⁶

Traditional insulations were improved, too. Down (nature's lightest warmth material) was made more resilient by applying water-repellent treatments to feathers (e.g., DownTek). Hydrophobic down resists clumping when wet, giving down jackets some of the quick-dry, all-weather advantages of synthetics. Synthetic fills also evolved. *Primaloft* continued to refine its microfiber insulation for softness and warmth when wet, and Polartec created *Thermal Pro High Loft* fleece that mimics high-pile fur for better warmth-to-weight. Notably, some brands experimented with *aerogel*, an ultralight space-age insulator, embedding aerogel particles in foam or fabric for extreme cold gear. While aerogel tech is still niche, it represents cutting-edge R&D in thermal textiles.

In *cold-weather sports*, better insulation is extended to accessories and gear. Ski apparel began using stretchy, softshell fabrics with bonded fleece linings (e.g., Schoeller's WB-400) to provide breathable warmth and mobility, replacing old, rigid ski suits. High-loft wool blends and Merino wool base layers became standard for mountaineers and winter athletes, valued for moisture regulation and warmth even when damp. The overall trend has been warmth without weight, allowing athletes to train and compete in lighter, smarter layers that adapt to their body output.

Weather protection (Waterproof & Windproof)^{1,5,10,11,13,16,27}

Outdoor athletes demand protection from rain, snow, and wind. This led to major advances in waterproof/breathable fabrics. *Gore-Tex*, the well-known waterproof membrane, faced new competition and also innovated its own lineup. In 2011, Gore introduced *Gore-Tex Active Shell*, a lighter, more breathable version of its membrane aimed at runners and cyclists [16]. This came as rivals launched air-permeable membranes like *eVent* (which allowed direct venting of moisture) and *Polartec NeoShell*, which sacrificed some waterproof rating for much higher breathability. The result for consumers was a range of *hardshell* jackets that were far more comfortable during intense activity than the earlier heavy rain gear. Using thinner membranes and breathable backer fabrics, these shells kept rain out but allowed sweat vapor to escape.

A radical innovation in this area is the *Gore-Tex Shakedry* technology. Shakedry jackets completely remove the outer face fabric; the membrane itself is the outer layer. Rain beads on the slick surface and can be shaken off, since there's no outer textile to soak through. This makes for an extremely light jacket that does not get wet in sustained rain. Multiple brands adopted Shakedry for elite running and cycling jackets.²³ The tradeoff is somewhat reduced abrasion resistance, but far superior performance in foul weather.

Softshell materials also gained traction for windproof and water-resistant gear. *Softshells* became popular for ski-touring, climbing,

and cycling because they breathe better than full waterproofs while blocking wind and light rain. Companies like Schoeller led this with fabrics that had 3XDry® or NanoSphere® DWR finishes – nanotech-based durable water repellents that made water bead off. Over the last decade, the industry has also grappled with making DWR finishes more eco-friendly. Traditional long-chain *perfluorinated* coatings have been phased out due to environmental persistence. New PFC-free DWRs and smaller carbon-chain (C6) formulas were adopted by most major brands to maintain water beading without harmful chemicals, marking an important environmental advance in textile finishing.

Windproofing saw improvements via lighter laminates and coatings. *GORE Windstopper*, a windproof, breathable membrane, has proven successful. It has been utilized as a panel in hybrid garments (e.g., front of a windproof jacket). Some windproof jackets skipped membranes altogether in favor of ultra-tight woven textiles (like *Pertex® Equilibrium* or Japanese *micro nylon weaves*) that stop wind by their construction while remaining air-permeable. These super lightweight windbreakers (often under 100 g) became staple gear for runners and cyclists, showing how fabric engineering alone can achieve weather protection with almost zero bulk.

An exciting newcomer in waterproof fabrics emerged in 2019, when The North Face launched *FutureLight*, developed through nanofiber electrospinning. This process creates a porous membrane by spraying polyurethane nanofibers, resulting in a fabric that is highly breathable and soft while still staying waterproof. *FutureLight* aimed to balance air permeability and weather protection, a trend also seen with startups making electrospun membranes for ski apparel. The continued refinement of electrospinning techniques in this period suggests that the next generation of shells will be more air-permeable (for comfort) without sacrificing full waterproofing.²³

Finally, seam sealing and construction improved across the board. High-end rain jackets now use thinner, stretch-sealed seams and omit sewn seams in some areas (bonding or welding) to eliminate leakage points and reduce weight. Water-resistant zippers (with polyurethane coatings) became standard, keeping rain out without needing flaps. These incremental advances, combined with the major fabric innovations, mean today's elite weather gear allows athletes to perform in storms with far less encumbrance than 20 years ago.

Compression and support apparel^{2,5,7,12,16,18}

Over the last two decades, compression garments have moved from niche to mainstream as athletes seek an edge in support, circulation, and recovery. Pioneered by Under Armor in the late '90s with tight compression shirts and shorts, this category exploded in the 2000s and 2010s. Compression fabrics (typically high-elastane blends) are designed to fit snugly, squeezing muscles to reduce vibration and improve blood flow.²¹ The purported benefits include enhanced endurance, less muscle fatigue, and faster recovery due to improved circulation and reduced oscillation of muscle fibers.

Most major sportswear companies launched their own compression lines: *Nike Pro* and *Adidas TechFit*, for example, offer base layers that provide muscle support. These garments often target specific muscle groups – some Adidas TechFit apparel even incorporates TPU power bands in the fabric to add support along key muscle chains (mimicking Kinesio-taping effects). Similarly, brands like *CW-X* and *2XU* engineered varying compression zones in tights to support joints (knees, hips), which can also reveal muscle anatomy with different knit structures.

Beyond enhancing performance during activity, compression recovery wear became popular for post-exercise use. Graduated compression socks and leg sleeves help flush out metabolites and prevent swelling, a concept borrowed from medical compression stockings but now common in running and triathlon communities. Companies also integrated far-infrared (FIR) emitting minerals into compression fabrics; for instance, Under Armor's *UA RUSH line* infused crushed minerals that absorb body heat and reflect it as FIR energy back into muscles, claiming to boost blood circulation. Though such claims are debated, it shows how textile science (embedding bio-ceramic particles) is being leveraged in compression gear.

Another supportive innovation is integrated support structures in apparel. Some high-tech training shirts and tights include built-in elastic bands or extra-weave panels that act like muscle support or posture braces. For example, exoskeleton-like clothing prototypes have used flexible bands to aid movement or stabilize joints. While still experimental for sports, the idea of apparel that not only compresses but also actively supports is being explored in R&D labs.

In summary, compression apparel became a staple for elite athletes in sports from basketball to distance running. The last 20 years took compression from a novel idea (tight Under-Armor undershirts) to a highly technical field with fabrics that are tighter, more breathable, and strategically engineered for both performance enhancement and injury prevention. Even if the physiological benefits sometimes outpace peer-reviewed evidence, athletes have widely adopted compression gear as part of their kits for the perceived improvements in support and recovery.

Aerodynamics and drag reduction^{5,7,10,11,16,17}

For sports where speed is king, textile developments have focused on reducing aerodynamic drag. High-performance suits for sprinters, cyclists, skaters, and swimmers saw dramatic innovation.

In *swimming*, the introduction of the *Speedo LZR Racer suit* ahead of the 2008 Beijing Olympics was a watershed moment. This suit, developed with help from NASA, used ultra-smooth polyurethane panels and compression to minimize drag and muscle oscillation. It reportedly reduced skin-friction drag by 24% compared to previous fabrics.²⁸ The impact was immediate: 23 out of 25 world records broken at Beijing 2008 were in the LZR suit.^{28,29} By 2009, other brands launched full polyurethane suits that further boosted buoyancy and speed, leading to an astonishing flurry of record times. However, these super-suits were deemed too advantageous – and were banned by FINA as of 2010, with new rules limiting swimwear to textile-only materials and more coverage restrictions.^{28,29} Nevertheless, the *LZR Racer's* development (with welded seams, low-drag surface, and compression) pushed the envelope of textile engineering, and its legacy lives on in the textured swimsuits used today.

In cycling, where aerodynamics is critical, racing suits (skinsuits) and even jerseys have seen major innovation. Teams now use textured fabrics on areas like shoulders and arms to trip airflow from laminar to turbulent mode, reducing drag. For instance, the *British Cycling* team's suits for track cycling and time trials featured vortex generators and special ribbed textures to gain an edge. Castelli's *World Tour TT suits* and wind-tunnel-tested cycling kits use multiple fabrics – smooth in some places, rough in others – to optimize aerodynamics. Even *cycling helmets* and shoe covers were redesigned with textile covers for smoother airflow.

These developments in aerodynamics are not just about exotic materials but also strategic fabric placement and construction. Laser-

cut seams and bonded edges are used to prevent the wrinkling or flapping that creates drag. Form-fitting compression also helps by keeping the athlete's profile streamlined. The gains in speed can be small but meaningful. For elite athletes, a 1–2% reduction in drag from a high-tech suit can be the difference between podium or not.

Outside of apparel, *footwear* has also been influenced by textile engineering for performance. In 2012, Nike introduced *Flyknit* technology for running shoe uppers—a one-piece knitted fabric upper that is virtually seamless and extremely lightweight.³⁰ By knitting the shoe upper as a single unit (using computerized flat knitting machines), Nike eliminated overlays and excess material, reducing the shoe's weight significantly.³⁰ This not only improved runner speed due to less weight (Flyknit shoes were 19% lighter than comparable models³⁰), but also minimized aerodynamic drag on the foot and created a snug second-skin fit that likely reduced micro-turbulence. Adidas followed with its similar *Primeknit technology* in 2012, and today, most running shoe brands offer knit uppers on their racers. While the primary benefit is weight reduction and fit, the seamless design also avoids any odd surfaces that could catch the air; it is a small factor, but at elite marathon speeds, every detail counts.

In summary, apparel companies working with sports bodies (and even NASA or aerospace firms) have treated *air* and *water* as opponents to be conquered with textile science. The last two decades showed how far we could go in reducing drag—and also established the limits of what is acceptable in sport.^{28,29} Even within the allowed scope, today's elite athletes universally wear gear that is slicker and faster than what came before.

Smart textiles and wearable technology^{6,8,9,10,11,16,31}

The convergence of electronics and textiles led to smart sportswear that can monitor performance and even adapt in real time. In the last two decades, researchers and companies have developed garments with embedded sensors, conductive yarns, and responsive materials, bringing a new dimension to training and athlete health.

One high-profile example is the *Ralph Lauren Polo Tech shirt* unveiled at the 2014 U.S. Open Tennis tournament. This snug compression shirt is woven with conductive threads and sensors that track the wearer's heart rate, breathing, stress, and energy output.³² Ball boys at the event wore the shirts to demo the technology, which included a small detachable transmitter that sent data to a smartphone app.³² Developed in partnership with OMSignal (a tech startup), the shirt showed that biometric data could be captured seamlessly through clothing rather than cumbersome chest straps or gadgets. The garment essentially acts as an ECG and respiratory monitor, taking advantage of clothing's constant contact with the body to get a strong signal.³² This was one of the first times a major fashion/sports brand integrated wearable tech into apparel.

Since then, several startups and teams have introduced sensor-equipped garments. For example, *Hexoskin's smart shirt* records heart rate, breathing volume, steps, and sleep quality, allowing athletes to log all-day data. Sensoria developed socks with pressure sensors to analyze running form (foot strike and cadence). Athos created workout apparel with embedded EMG sensors to show which muscles are firing during an exercise. These innovations help athletes and coaches gain insights into training load, technique, and recovery by literally wearing their fitness tracker in their clothing.³²

Another branch of smart textiles is responsive materials – fabrics that change properties in response to conditions. Labs have created temperature-sensitive textiles that become more breathable as the wearer gets hot and sweaty. One such approach uses biopolymer

coatings that expand to increase fabric porosity when humidity rises. There have been experimental jackets using living microbes: MIT's biotech lab demonstrated a biofabric with vents that open when the wearer's sweat triggers bacterial cells; an imaginative example of material that *responds* to the body's state. While not commercial yet, it shows the future potential for garments that dynamically adjust ventilation or insulation on the fly.

We have also seen heated apparel (battery-powered) become popular for outdoor sports and spectatorship – thin carbon fiber or metallic wires integrated into jackets, gloves, and even insoles that warm up at the press of a button. By 2020, many ski and hunting gear makers offered heated jackets with rechargeable packs. On the flip side, cooling vests using phase-change materials (PCM) or evaporative cooling inserts have been used by athletes to pre-cool or stay safe in extreme heat (e.g., marathoners wearing ice vests before races). PCMs, which absorb heat by melting at a set temperature, were applied to some athletic wear as well. *Outlast®* technology, originally a NASA offshoot, put microencapsulated PCMs into linings that buffer temperature swings.

Additionally, conductive textiles have enabled new kinds of on-body electronics, such as stretchable circuits and garment-integrated flexible sensors. For instance, some compression sleeves now have built-in LED indicators or haptic feedback for training cues. Energy-harvesting fabrics are under study, too. While many of these ideas are still emerging, the past two decades established the foundation – conductive fibers, stretch sensors, Bluetooth modules – for clothing that is as smart as the devices we carry.

A key challenge that remains is durability. Progress is ongoing in creating washable e-textiles and using novel materials like graphene for flexible circuits. Notably, a Rice University lab wove carbon nanotube threads into athletic textiles to continuously measure heart rate via EKG, demonstrating that nanoscale fibers can function as sensors when sewn into fabric. As these technologies mature, we expect sports uniforms themselves to become the athlete's personal monitoring system, providing real-time feedback on exertion, technique, and even injury risk.

Protective gear and impact absorption^{1,5,17}

Athletes not only seek performance but also protection. Advances in impact-resistant textiles have improved safety in sports like skiing, motorcycling, American football, cycling, and more. A standout innovation is the use of *dilatant materials* – soft, flexible compounds that harden upon impact in protective gear. The most famous is *D3O®*, an orange polymer developed in the 2000s, used in thin pads for impact protection. D3O technology debuted on the global stage at the 2006 Winter Olympics, where the U.S. and Canadian ski teams used D3O pads in their suits for better crash protection without restricting movement.³³ The material's molecules flow freely during regular use (soft and flexible), but upon sudden impact, they lock together into a stiff structure, absorbing and dissipating the force.³³ This allows for low-profile armor in clothing, for example, soft knee and elbow pads that bend comfortably but harden to guard against a fall. Over the past two decades, D3O and similar shear-thickening materials have been integrated into everything from snowboarder crash shorts to mountain bike pads and even soccer goalkeeper gloves, elevating protection levels without the bulk of traditional hard padding.

Another protective development is in abrasion and cut resistance. High-strength fibers like aramid and UHMWPE have been woven into sports apparel to prevent cuts or wear-through. For instance, speed skaters wear suits with Kevlar/Dyneema lining in certain areas to protect against skate blade cuts. In motorsports and motorcycling,

jackets and racing suits now often have Kevlar or Dyneema blended panels for abrasion resistance in case of a slide, yet these can look and feel like regular fabric. Some basketball shoes and soccer cleats even incorporate Kevlar fibers in their uppers or laces to resist stretching and withstand intense forces.

High-strength textiles also transformed climbing and outdoors gear, which is a form of protective equipment for adventurers. Ropes and harnesses transitioned to lighter, stronger materials. Dynamic climbing ropes today commonly use high-tenacity nylon cores, but accessory cords and slings often use Dyneema® (UHMWPE) fibers that boast extremely high tensile strength at a fraction of the weight. A Dyneema line can be 15 times stronger than steel by weight.²³ This led to ultralight yet ultra-strong climbing slings, paragliding lines, and tent guy-wires. Similarly, Dyneema Composite Fabric emerged from high-end sailboat racing into outdoor gear like tents and backpacks. Its appeal lies in its incredible strength-to-weight ratio and near-zero stretch. Tents made of Dyneema Composite can withstand fierce winds

and rain while weighing only a few hundred grams, making them ideal for alpine expeditions.²³ Brands like Hyperlite Mountain Gear built packs and shelters from these fabrics, enabling new frontiers in weight savings for endurance athletes and thru-hikers.

Even the humble helmet improved via textiles: padded liners now use multilayer foams and slip-plane textile liners. While helmets are hard goods, the comfort pads and shells incorporate advanced textiles that wick sweat and better manage impact energy than foams alone.

In summary, protective textile technology over the last 20 years has focused on making protection invisible – meaning gear that doesn’t encumber the athlete until the moment it saves them. Whether it’s a paper-thin pad that hardens in a crash or a lightweight fabric that resists a high-speed slide, modern sports protective gear leverages state-of-the-art materials (dilatant fluids, aramid/Dyneema fibers, etc.) to keep athletes safer without sacrificing mobility or comfort (Table 1).³³

Table 1 A review of the performance metrics of select technologies

Performance need	Tech examples	Core mechanism	Typical performance metrics	Strengths	Weak spots
Impact Protection	D3O®, Poron XRD®, EVA foams, TPU inserts	Rate-dependent viscoelastic energy absorption	Shock attenuation (% reduction), peak force (kN), thickness vs. protection ratio	High protection at low bulk, repeatable performance	Can get stiff in cold temps, high cost, sometimes sweaty AF
Compression Support	Spandex blends, warp-knits (PWX, Lycra® Sport), graduated compression sleeves	Controlled elastic tension to improve muscle stabilization & venous return	Compression pressure (mmHg), stretch/return %, fatigue delay, proprioceptive feedback	Performance boost, reduced soreness, tight fit	Too tight, numb feet, durability, & creep over time
Moisture Management	Coolmax®, Nike Dri-Fit, microfiber poly knits, merino wool	Capillary wicking + quick evaporation	Wicking speed (sec), drying time (min), moisture regain %, air permeability	Comfort in a sweaty state- keeps you looking less tired	Oils & fabric softeners, performance drop, cost
Thermal Insulation	Primaloft®, Polartec® fleece, Aerogel composites, Down	Trapped air + low conductivity	CLO value (insulation), weight/loft ratio, warmth when wet	Lofty warmth, some stay warm even when soaked	Bulk and stink, down dislikes water
Antibacterial/ Odor Control	Silver ions, zinc oxide, triclosan (phasing out), chitosan, copper fibers	Microbe cell disruption or metabolic inhibition	Antibacterial reduction (%) after 24h, durability after washes	Works in the absence of laundry day	Fading due to wash, regulatory scrutiny on some chemistries

Sustainable materials and processes^{1,2,31,34}

Sustainability has become a significant theme in the sports textile industry over the past two decades.

One of the most impactful shifts was the widespread adoption of recycled fibers, mainly recycled polyester from post-consumer plastic bottles. As early as 2010, Nike outfitted national teams (Brazil, USA, etc.) in soccer jerseys made entirely from recycled PET bottles – each jersey used about 8 plastic bottles, which were melted down and respun into polyester yarn.³⁵ Nike’s 2010 World Cup kits diverted nearly 13 million bottles from landfills³⁵ and proved that recycled fabric could meet elite performance standards. Since then, Nike has used recycled poly in the majority of its Dri-FIT team apparel, and other giants followed suit; Adidas launched its partnership with Parley for the Oceans in 2015, turning marine plastic waste into high-performance yarn for shoes and apparel. By 2020, Adidas had made tens of millions of shoes with *Parley Ocean Plastic* uppers. It even introduced fully recyclable running shoes made of a single thermoplastic material

that can be remolded. These efforts not only reduce the use of raw petroleum but also raise awareness of ocean pollution.

Recycled nylon also emerged, e.g., Econyl yarn (made from reclaimed fishing nets and nylon carpets), which brands like Arena and Speedo used for eco-friendly swimwear and Patagonia for some shell jackets. Additionally, companies incorporated *recycled elastane* (*Spandex*) in some stretch garments to complete the loop.

Beyond recycling, bio-based materials gained traction. A notable example is *Yulex® natural rubber*, which Patagonia famously used to make the world’s first neoprene-free wetsuits in 2016.³⁶ Traditional neoprene is a petroleum (or limestone) based synthetic rubber, but Patagonia’s suits replaced it with FSC-certified natural rubber from hevea trees, achieving equal performance in warmth and flexibility with a dramatically lower environmental footprint.²³ This was a breakthrough in a product as technically demanding as a wetsuit (which must insulate and stretch); Patagonia won industry awards for this eco-innovation. Similarly, Adidas experimented with

biofabricated spider silk: in 2017, they unveiled a concept shoe made with *Biosteel fiber* (a silk-protein-based yarn) that was 100% biodegradable. While not mass-produced, it showed the potential of biotech in sports textiles.

Another primary focus was on clean manufacturing processes. Dyeing textiles is traditionally water- and chemical-intensive, so companies sought alternatives. Nike developed a *supercritical CO₂ dyeing* technology (ColorDry) in the mid-2010s that uses zero water; supercritical CO₂ infuses dyes into fabric, eliminating millions of gallons of water and chemical waste. Nike opened a plant in Taiwan utilizing this process, and DyeCoo (the company behind the tech) partnered with other brands to implement waterless dyeing. Likewise, *digital printing* (sublimation) became more prevalent for adding color and logos to sportswear, as it is more efficient and less wasteful than older screen-print methods.

Brands also started closing the loop on products. Patagonia was a pioneer with its Common Threads Recycling program (recycling worn polyester fleece into new yarn since the 2000s). In the 2010s, more companies set up take-back programs and began integrating recycled content year over year. By the late 2010s, sustainable collections were mainstream: e.g., “Nike Move to Zero” and Adidas’s Sustainable product lines were clearly labeled with recycled or organic content. Even high-fashion athletic collaborations (Stella McCartney for Adidas) emphasized eco-friendly materials like organic cotton and recycled ocean plastic.

Speaking of organic fibers, while most high-performance gear is synthetic, there was a return to natural sources under the banner of sustainability. Examples include *organic cotton* in lifestyle athletic apparel, *Tencel (lyocell)* fibers (wood-pulp-based) for soft, breathable training shirts, and, as mentioned earlier, merino wool for performance base layers. These fibers are renewable and biodegradable, addressing end-of-life concerns of synthetics. The challenge has been balancing sustainability with the technical demands of sports.

Lastly, companies tackled the microplastics issue; awareness grew that each wash of synthetic garments sheds microfibers into waterways. This prompted research into fiber constructions that shed less, bio-based fiber alternatives, and protective washing bag products. It’s an ongoing challenge, but sustainability considerations now permeate R&D discussions in sports textiles, alongside raw performance metrics.

Advanced manufacturing techniques and customization^{7,9-11,17}

Underpinning many of the above developments are the production processes that allow cutting-edge textiles to be created. Manufacturing innovations in the last two decades have been crucial in turning new materials into viable products and enabling designs that were previously impossible.

One key advance was the rise of seamless and 3D knitting. We can see this clearly with Nike’s Flyknit technology, where programmable flat-knitting machines produce a whole-shoe upper in one piece.³⁰ The machine precisely lays down yarns of various types (polyester, Flywire Kevlar cables, etc.) in specific areas to provide structure or stretch as needed. The result - minimal post-knit assembly and a seamless, form-fitting product. This concept extended to apparel as well – companies like Adidas and Uniqlo leveraged circular knitting to make seamless base-layer tops and tights that are more comfortable and use less material. 3D knitting enables engineered textiles in which properties change within a single garment: e.g., a single-knit running

shirt can have a vented mesh back, more elastic shoulders, and a cushioned compression band at the hem, all knit continuously. Such complexity would require many sewn panels in traditional cut-and-sew methods, but advanced knitting machines handle it in software, knitting different stitches and yarns on the fly.³⁰

Another innovation in assembly is the bonding and welding of seams. Instead of sewing with thread, many high-end sports garments now use heat bonding or ultrasonic welding to join pieces. This yields flat, smooth seams that don’t rub the skin and also reduce weight. For example, competitive cycling skinsuits and running shorts often feature bonded hems (no stitching at the leg openings) to eliminate flutter and discomfort. Likewise, waterproof rain jackets use tape-sealed seams and increasingly laser-cut pattern pieces that are glued together, which improve waterproofing and streamline the garment.

Laser cutting is widely used now for precision and to vent garments. Brands laser-cut tiny perforations in patterns to add extra breathability exactly where needed. This precise control was not feasible at scale until laser cutting tables and CAD became common in apparel factories in the 2000s.

Electrospinning and nanofiber production are also emerging techniques. As noted in the weather protection section, The North Face’s FutureLight membrane is made by electrospinning polyurethane nanofibers. Similarly, researchers are electrospinning nanofiber meshes for advanced filters or even smart. While these are more on the R&D side, they represent a manufacturing approach capable of creating entirely new textile structures – extremely fine, web-like fabrics that are lighter and could have unique properties (such as high surface area for moisture transport or the ability to incorporate functional nanoparticles).

3D printing has also penetrated sports textiles. Some sportswear components are made by additive manufacturing: for example, Adidas’s Futurecraft 4D running shoe midsoles are 3D-printed from a resin lattice. Designers have also 3D-printed elements onto fabrics – such as rubber grips on a cycling glove or even entire lattice-like garments. Reebok’s *PureMove Bra* used a 3D-printed array of liquid resin within the fabric to create a responsive support structure that firms up during high-impact activities. These hybrid techniques demonstrate how traditional textiles can be augmented with printed frameworks to enhance functionality.

Finally, the digital age has enabled mass customization in sports apparel. Brands now use 3D body scanning and digital pattern adjustment to offer custom-fitted gear to both pros and consumers. On-demand manufacturing platforms can knit a bespoke sweater or print a unique jersey graphic in small batches, moving away from the era of huge inventories. This trend, while more business-model-oriented, is supported by the flexible manufacturing techniques above – e.g., a computerized knitting machine doesn’t care whether each piece it knits is a different size or design, allowing one-off or custom runs just as easily as mass production. Also common is the rise of personalized prints and colors through sublimation printing, especially in cycling and running communities, where small brands can create wild designs without the cost of traditional setup.

In summary, the last two decades saw the sports textile industry not only invent new materials but also reinvent how they make products. Seamless knitting, bonded construction, laser precision, and even experimental techniques like electrospinning and 3D printing have all contributed to gear that is lighter, stronger, and more tailored to athletes’ needs than ever before.³⁰ Significantly, many of these processes also reduce waste (e.g., Flyknit reportedly reduced

Nike's footwear manufacturing waste by 60% by using only the yarn needed), aligning with the sustainability goals noted earlier.³⁷

Expected future directions for research, consumer choice, and industrial production

In the near future, people will have ample opportunity to choose smart fabrics that monitor hydration, muscle fatigue, and biomechanics in real time, without bulky electronics, thanks to conductive yarns, printed sensors, and flexible energy harvesting. End products will be much lighter, but quite durable, driven by nanofibers, bio-based polymers, and high-strength composites. Adaptive textiles that literally change behavior with the environment (membranes that develop pores under sweat, for example), powered by phase-change materials, shape-memory fibers, and active moisture-management technology, can be expected to be widely available. Sustainability will assume greater importance, leading to recyclable mono-materials, biodegradable coatings, and water-free dyeing.

Industrial practices can be expected to move towards:

- 1) Scalable knitting/weaving/printing of electronics, permitting cost reduction
- 2) Supply-chain transparency, traceable bio-based materials, and compliant manufacturing
- 3) Modular mono-material design, which makes recycling practical
- 4) High-speed customization — mass-personalization using 3D knitting & automated fit algorithms
- 5) Durability upgrades for harsh outdoor and sports applications
- 6) More partnership ecosystems — OEMs, textile mills, and sensor companies may be co-developing solutions

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Conflicts of interest

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