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Sportswear: Acumen of Raw Materials, Designing, Innovative and Sustainable Concepts

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Abstract

Sportswear constitutes an integral part of technical textiles and encases great potential as far as technological and design innovations are concerned. The sports textiles have witnessed tremendous evolution and that too at a much faster pace compared to ready to wear segment. The sports clothing is no longer restricted to sportsperson involved in performance sports or strenuous physical activities. However, there has been a surge for sports apparels and accessories among health conscious, fitness freak and gym enthusiasts. Accordingly, the sportswear industry has witnessed revolutionary advancements in development of different sportswear categories like active wear, leisurewear and athleisure to fulfill the requirements of sportsperson as well as health conscious millennials. The basic and functional requirements of comfort, breathability, light weight, anti-static and anti-odor properties can be engineered into sportswear by optimum selection of fibers, yarns, fabrics and garments' designing aspects. The chapter will provide an insight on the classification, requirements, design aspects, raw material procurement, innovative and sustainable concepts employed in sportswear to enhance the functionality and comfort characteristics of sportswear. Furthermore, the role of technology and fashion in sportswear transformation is also covered in the last sections of the chapter.

Keywords: Accessories, Active wear, Comfort, Sportswear, Knitted fabrics, Leisure Wear

1. Introduction

Sportswear has emerged as one of the most promising and technologically driven textile segment with massive innovations and advancements involved right from raw material procurement to design and development of sports specific clothing. The field is promising and innovative with several avenues as far as research and development, pioneering new technologies and trailblazing concepts are concerned.

The basic requirements of thermo physiological as well psychological comfort, dexterity, agility to wearer, breathability, moisture management, light weight, anti-microbial and anti-odor properties can be incorporated into sportswear by correct selection of fibers, yarns and fabric variables for sportswear. The sports clothing is

no longer restricted to sportsperson involved in performance sports or strenuous physical activities. However, there has been a surge for sports apparels and accessories among health conscious, fitness freak and gym enthusiasts. Accordingly, the sportswear industry has witnessed revolutionary advancements in development of different sportswear categories like active wear, leisurewear and athleisure to fulfill the requirements of sportsperson as well as health-conscious millennials. Apart from functional requirements, a lot of emphasis is being laid on esthetic aspects as well considering increasing number of females involved in yoga, gyming and other sporting activities who give precedence to silhouette, colors and other design details of sportswear. Accordingly, the technological as well as ergonomic advancements in sportswear design and development have opened new avenues for researchers to explore the field further.

2. Sportswear categorization

The sportswear can be categorized based on a number of factors such as:

- Sportsperson's level of physical activity and fatigue
- Stress involved during strenuous activity
- Duration for which the sportsperson doffs the clothing
- Ambient conditions.

2.1 Categorization based on level of physical activity

The sportswear can be classified into active and leisure wear based on the sportsperson's level of physical activity.

2.1.1 Active wear

Active wear also referred to as professional sportswear encompasses the sportswear attire that are usually worn by sportspersons for short time duration when indulging in rigorous, high level of physical activities such as skiing, long jump, high jump and other such adventure sports etc. All such sports demand active, stressful and maximum physical performance thereby resulting in profuse sweating (sensible perspiration) experienced by the sportsperson. The designing of active wear is not as challenging a task as the design considerations for leisure wear because sportsperson during the entire duration of active sport is exposed to constant ambient conditions within the boundaries of the playing ground irrespective of indoor or outdoor conditions. Moreover, the factors like sportsperson's age, gender and frequency of doffing the clothing is predetermined which can serve as quick guide for designers while designing active wear.

2.1.2 Leisure wear

Leisure wear comprises sportswear worn during sports activities like cricket, hockey and golf. The aforesaid sports activity demands intermittent performance with alternating active and rest phases by sportsperson and with prolonged exposure to varying ambient conditions. Leisure sportswear are worn by players

belonging to varying age and gender groups and those indulging in low to moderate physical activity. Moreover, the duration and frequency of wearing and ambient conditions are all variable during the course of the activity. Consequently, the designing of leisure wear is a challenging task for designers as they need to consider the varying ambient conditions and extended durations on the field to which wearer would be subjected. The wearer is expected to don the clothing the entire day or several hours at stretch in changing environmental conditions. Thus, the designing of leisurewear needs special consideration of wearer's physiological requirements and changing environmental conditions to which sportsperson will be exposed while indulging in sports activity. Furthermore, casual and exercise wear, parkas, hoodies, pants, and crew neck fleece sweaters that provide a combination of esthetic, style, comfort, and functionality in a less competitive mode can also be included in category of leisurewear.

2.2 Categorization based on sport specific requirements

The sportswear can also be classified based on specific requirement of sports. Different sports involve different level of physical exertion and are performed in varying ambient conditions. Consequently, the clothing worn for a particular sport like cycling may not be suitable for another sport such as under water sports, mountaineering etc. performed in contrastingly different environment. The sportswear can be classified into dry, damp and wet fast action sportswear based on sports specific requirements.

2.2.1 Dry fast action sportswear

Dry fast action sportswear are worn during sports activities such as football, rugby, tennis and track games that demand optimum moisture management properties enabling quick sweat absorption and dissipation thereby providing cooling effect to wearer.

2.2.2 Damp-fast action sportswear

Damp-fast action sportswear is suitable for sports where rapid sweat evaporation from the skin surface is a prerequisite. Apart from rapid transfer of liquid perspiration, the sportswear should ensure good water vapor permeability, water proofing and protection from cold along with high degree of stretch ability.

2.2.3 Wet-fast action sportswear

Wet-fast action sportswear is specially designed for sporting activities like swimming and other under water sports activities which require a high degree of stretch and form fitting. The clothing plays a vital role in enhancing the athlete's performance by reducing drag and fatigue.

2.3 Categorization based on weather conditions

The weather conditions to which sportsperson are exposed during the activity also dictates the classification of sportswear. Accordingly, the sportswear may be classified as cold, moderate and hot weather sportswear. The material selection and design aspects for three categories will vary drastically owing to different set of properties required for each clothing type.

2.3.1 Cold weather sportswear

Cold weather sportswear is generally worn during ice skating, mountaineering and any such winter outdoor activity where the wearer is at risk of heat loss and thus hypothermia. The cold weather sportswear should be able to trap the body heat and provide protection against cold and humid conditions. Consequently, the clothing is designed in such a manner that it exhibits high thermal insulation for entrapment of body heat and breathable for moisture vapor sweat to easily escape out but prevent the ingress of liquid from external sources through clothing.

2.3.2 Moderate weather sportswear

Moderate weather sportswear is preferred by sports enthusiasts when ambient conditions are conducive with moderate temperature and humidity. Accordingly, sportswear worn in moderate climate should be breathable, permeable to air and heat passage to ensure dry and comfortable feel to wearer.

2.3.3 Hot weather sportswear

Hot weather sportswear are generally preferred when the ambient temperature is high and the wearer may be at risk of hyperthermia as he experience profuse sweating (sensible perspiration) and elevated body temperature as a synergistic effect of his own metabolic heat generation and the hot weather. The clothing should thus be light weight, quick drying, and wick able to push the liquid moisture away without sweat absorption in next to skin layer and should exhibit high thermal conductivity for rapid heat dissipation thereby ensuring dry and cool feel next to skin [1–3].

The requirements and key design aspects of sportswear will be discussed elaborately in the next sections of the chapter.

3. Requirements of sportswear

The categorization of sportswear discussed in previous section highlighted that sportswear are categorized based on level of wearer's physical activity, specific sports and ambient conditions. The requirements for each sportswear category will be drastically different as the clothing is worn in altogether different ambient conditions, for varying durations and frequency. Sportswear designed as active wear for outdoor applications should provide protection to wearer against external elements and environmental extremities such as wind, sunlight, rain and snow. Moreover, the clothing should possess optimum thermal and moisture management properties in order to maintain the heat balance between the metabolic heat produced as a result of physical activity and the outside environment. Perspiration both in vapor (insensible) and liquid (sensible) form should be readily dissipated to the outside environment to provide dry microclimate next to skin for the wearer. This requirement can be met by designing the sportswear that exhibit low resistance to heat transfer and evaporative heat loss. Sportswear should ensure rapid liquid transfer by means of wicking and should have good drying ability to prevent condensation of liquid sweat near skin. However, a high level of thermal insulation is prerequisite for cold weather sports clothing so as to prevent body heat to escape to outside environment. Contrastingly, low thermal insulation is desirable for sportswear intended for warmer climates. The concept of "Onion-skin" principle encompassing clothing system with several layers and consisting of several clothing items is

applied in sportswear to achieve variable thermal insulation as per the capricious ambient conditions. The clothing can thus be adapted to the changing environment by donning or doffing individual clothing items for effective protection against the external elements [1–4].

Furthermore, the requirements for sportswear can be as categorized into functional and esthetic requirements, both of which play a crucial role in determining the performance and consumers acceptability for the clothing. Functional attributes of sportswear pertain to light weight, low fluid resistance, high tenacity, stretchability, thermal regulation, UV protection, vapor permeability, and sweat absorption and release while esthetics requirements entail softness, surface texture, handle, luster and color of the sportswear.

In general, the most common characteristics sought in sportswear can be enlisted as follows:

- Optimum thermal and moisture regulation
- Good air and water vapor permeability
- Rapid moisture absorption and wicking property
- Absence of dampness & dry feel next to skin
- Rapid Drying ability
- Low water absorption of next to skin layer clothing
- Dimensionally stable even when wet
- Durable, easy care and lightweight
- Soft and pleasant touch
- Effective protection against external elements such as extreme cold, sunlight, wind, rain etc.
- Stretch ability, form fitting and shape retention
- Antimicrobial & antistatic properties.

4. Fiber, yarn and fabric interplay for sportswear design and development

The type of sport, ambient conditions and level of physical activity as discussed in the previous section dictates the functional requirements and performance characteristics of sportswear.

Sportsperson involved in high active sports such as tennis and soccer usually experience heat stress owing to high amount of metabolic heat generation and profuse sweating. Therefore, the thermo-physiological comfort aspect of sportswear is of utmost importance for such sports to ensure well-being of sports person without any hindrance to their performance and efficiency. Dry microclimate for wearer involved in intensive physical activity and in hot, humid conditions is ensued by engineering fabrics exhibiting effective moisture vapor and liquid moisture

transmission through fabric. The effective heat and moisture dissipation through fabrics intended for active wear requires special consideration of geometry, packing density and structure of the constituent fibers in yarn and fabric construction.

Thermo-physiological comfort properties of sportswear are influenced by multitude of fiber, yarn and fabric variables that influence inter yarn spaces, capillary geometry and in turn the moisture vapor and liquid moisture transmission through textile structures.

Sportswear engineered with specialized fibers, yarns and fabric structures exhibit excellent moisture management properties. Accordingly, sportswear designers experiment with variable fiber cross-sectional shape, shape factor and specific surface area of fiber, yarn variables like twist, linear density, structure and packing coefficient and fabric variables like loop length and porosity, varying knit structures like plated, elastene fabrics and those designed with bio mimic concepts to design sportswear intended for performance sports to keep the wearer comfortable with dry sensation next to skin.

Undoubtedly, the role of fibers, yarns and fabric structure in engineering textile structures suitable for sportswear cannot be undermined. The following section will discuss the role of fibers, yarns and fabric variables and their selection criteria for sportswear design and development.

4.1 Fiber variables and their influence on thermo-physiological comfort aspects

A combination of natural and synthetic fibers is an optimal solution when designing clothing for next to skin and sportswear applications. However no single fiber or different fiber blends can ensure ideal clothing suitable for varied applications. The right type of fiber needs to be in the right place according to the fabric's end use. Any wrong selection of fiber combinations may lead to thermal and wetness discomfort to the wearer if water absorption and liquid transfer properties of the selected fibers are not according to level of sweat generated.

The primary requirements of effective liquid transmission, better wick ability and faster drying in sportswear can be achieved by incorporation of varying fiber profiles like tetra channel, hexa channel, five-leaf, trilobal and triangular cross-sections that offer enlarged surface area for transmission of liquid sweat compared to their circular counterparts (**Figure 1a** and **b**).

Coolmax is modified polyester fiber developed by Dupont. The fiber resembles double scallop with four channels having 20% more surface area than conventional polyester fiber therefore offering better wicking, moisture vapor permeability and water spreading over greater area in fabric.

4 DG fiber is speciality fiber with eight-legged cross section made of polyester and other polymers and large surface area/volume and bulk compared to round fibers. The fiber is capable of moving, storing and trapping the fluids owing to the unique grooved shape. Accordingly, fibers of varying cross sections are finding applications in sportswear owing to their effectiveness in heat, moisture and liquid transmission through fabrics.

Incorporation of non-circular fiber profile are characterized by increase in fiber's shape factor which influences the fiber capillary spaces, inter yarn pore spaces, packing density, specific surface area and in turn the thermo-physiological properties of fabrics.

Fibers with greater specific surface area possess good moisture absorption and release properties. The micro grooves present on fiber surface enhance capillary absorbency, cause siphoning of moisture which can thus be dissipated by spreading over fiber surface. **Figure 1b** shows the different fiber cross-sections generally used in sportswear.

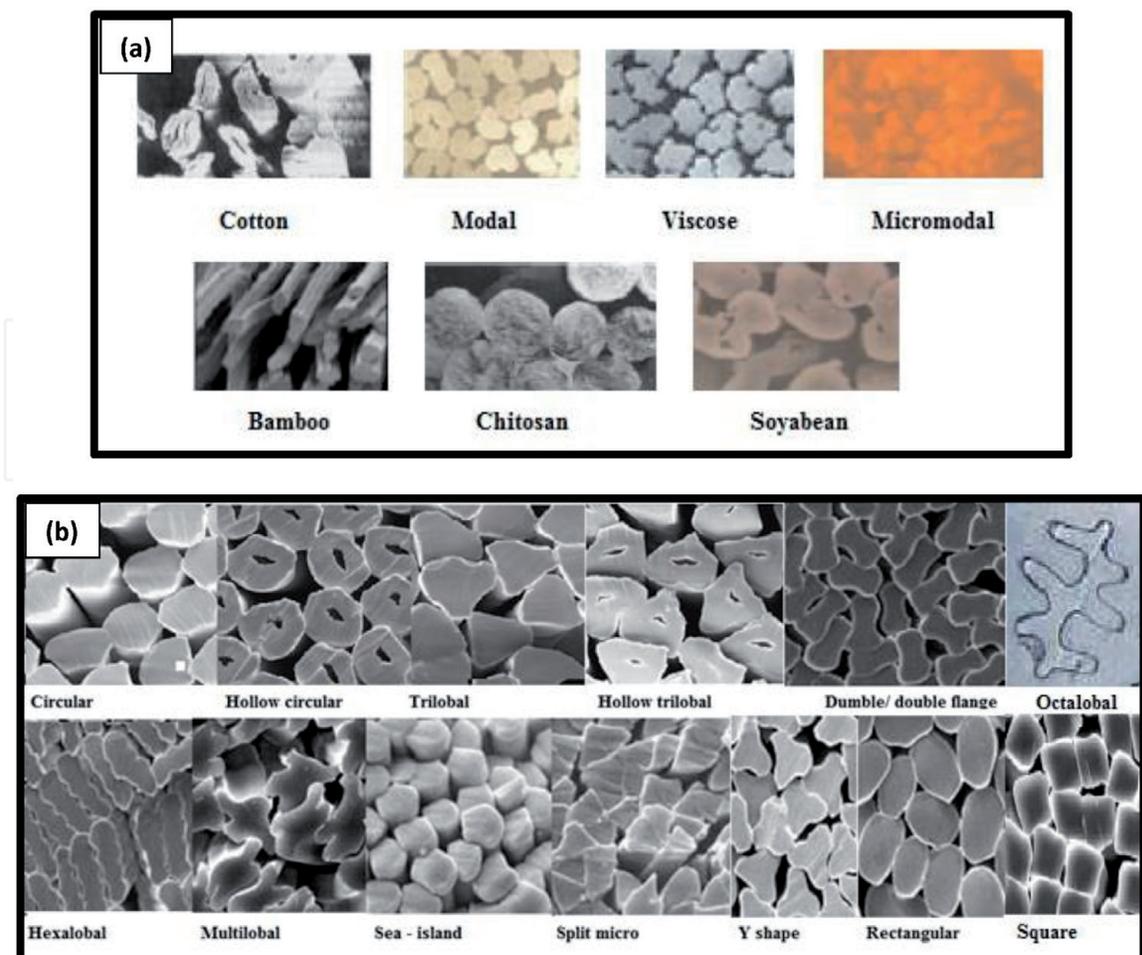


Figure 1.
 (a) Different fibers for sportswear, (b) fibers of varying cross sections.

Moisture transmission properties of individual components can be drastically improved by blending two or more fibers into single yarns. Polyester and cotton fibers in blended form are increasingly being used for specialized yarn production to achieve good wicking and low absorbency.

Wicking and thermal resistance can further be improved by creation of hollow and microporous yarn core by combination of different fibers such as cotton and PVA fibers (**Figure 2a**).

Welkey is fiber with hollow core and body of fiber has proliferation of small holes. Thermal resistance increases as a result of increased number of air spaces inside fibers. Wicking of sweat next to skin is possible by capillary action caused by small holes forming proliferations in fiber body. The fiber can thus be effectively utilized for designing winter wear sportswear to obtain efficient moisture management along with rapid sweat dissipation.

Bicomponent fiber is classified based on fiber cross-section into side-by-side, sheath core, islands in the sea, segmented pie cross-section. Matrix of one polymer contains another polymer and micro denier fibers can be generated by this type of bi component structure. Polyester, polypropylene, nylon forms the island in the structure.

Bi-component filament yarn, *Naiva* developed by combination of 55% Naiva (Eval/ Nylon) yarn and 45% nylon microfiber is used for development of light weight, soft and moisture absorbing Naiva fabric suitable for mountaineering and other active sportswear. The extraordinary thermal and moisture management properties of Naiva fabric may be attributed to micro loops on the surface of Naiva fabric (**Figure 2b**) as a result of high thermal shrinkage property of yarn.

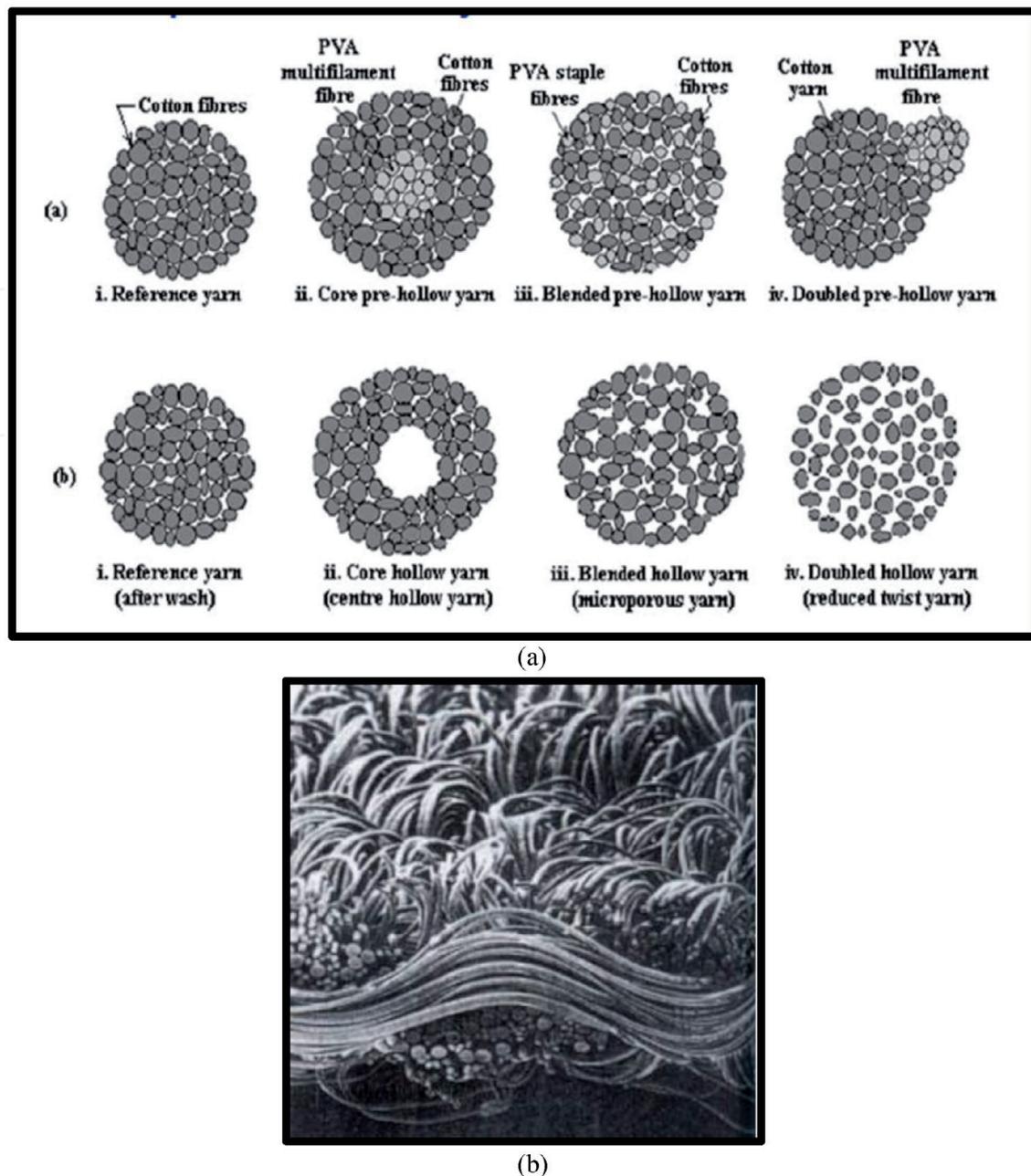


Figure 2.
 (a) Core hollow yarn composed of cotton & PVA fibers. (b) Micro loops on surface of Naiva Fabric.

Eval, one of the components of bi component yarn is the copolymer resin of ethylene vinyl-alcohol [1–3].

Several researchers have explored the possibilities of combining different commodity and speciality fibers to engineer a textile structure suitable for sportswear with desirable thermal and moisture management properties.

Gurudatt et al. [5] studied the absorption and drying behavior of textile using cotton, polyester of regular cross section, polyethylene glycol modified polyester and scalloped oval cross-section fiber. It was suggested that absorption capacity of polyester enhances by cross-section and polymer modification. Knitted fabrics using scalloped oval cross section had higher absorption rate compared to regular polyester fiber.

Das et al. [6] studied the effect of fiber cross-sectional shape on moisture transmission properties of the fabrics and suggested that wicking rate through fabrics increased while water vapor permeability reduced as the fiber shape factor increased.

Matsudaira and Kondo [7] reported that more water could be absorbed by polyester fibers by making grooved or non-grooved hollow in fiber due to increase in space ratio and surface area of fiber in their studies on moisture transport properties of fabrics having different ratio of space to polymer in fiber cross-section.

Su et al. [8] developed composite knitted fabrics by blending profiled polyester fibers and cotton fibers. Fabrics with decreasing cotton content showed higher diffusion rate and drying rate. Worst water absorption ability was shown by fabrics made of profiled polyester alone. They suggested that moisture absorption and release of fabrics could be improved by making fabrics from core and cover yarns of polyester profile filament, profile polyester spun and cotton in different blend ratios.

Troynikov and Wardiningsih [9] suggested that blending wool fiber with polyester and regenerated bamboo fiber, produced fabrics with better moisture management properties than fabrics without blending.

Fangueiro et al. [10] studied the wicking and drying ability of knitted fabrics produced from blends of wool- coolmax and wool- fine cool. It was reported that fabrics with coolmax fibers could transport perspiration quickly from the skin to environment and showed the best capillarity performance, fine cool fabrics had higher drying rates whereas wool fiber-based fabrics showed low water absorption but good drying rate.

Oner et al. [11] observed higher overall moisture management capacity values for polyester fabrics compared to cellulose based fabrics and suggested that cotton fabrics caused wetness to be felt more than other fabrics.

Long [12] stated that liquid water transfer from the back to the face layer depends upon the water absorption of the fiber materials of the two layers and to a greater extent their difference.

Adams and Rebenfeld [13] observed that polyester fabrics showed better liquid water diffusion due to fast capillary action as the contact angle of polyester and water is small compared to wool. Highly hygroscopic fibers like wool took longer to reach equilibrium during process of water diffusion compared to less hygroscopic fibers like polyester.

Supuren et al. [14] investigated the moisture management properties of the double face fabrics and suggested that polypropylene (back) and cotton (face) fabric had better moisture management property.

Mehrtens & Mcalister [15] reported low wick ability for nylon fabrics when compared to cotton and orlon fabrics and suggested combination of lower fabric weight and thickness led to better comfort in their studies on knitted sport shirts for hot and humid conditions.

Ozturk et al. [16] studied the influence of fiber type on wicking properties of cotton- acrylic yarns and fabrics and suggested that wicking ability of yarns and fabrics increased with the increase in acrylic content in the blends.

The exhaustive reported research emphasizes that the fiber types owing to difference in their chemical nature and surface geometry have strong influence on heat, moisture, liquid transfer and moisture management properties of textiles.

4.2 Yarn variables and their influence on thermo-physiological comfort aspects

The yarn variables namely twist level, linear density, spinning system and yarn types play a crucial role in influencing the moisture vapor and liquid moisture transmission and in turn the thermo-physiological comfort aspects of sports textiles. The variation in any of these yarn variables influence the yarn structure which in turn depends on fiber geometry. Distribution of fibers in yarn dictates thermal as well as moisture transfer properties of fabrics.

Yarn structure is not rigid and capillary flow may produce lateral stress, which affects capillary sizes during liquid rise. Disruption of the continuity, length and orientation of the capillaries occurs due to changing packing density throughout yarn structure. Heterogeneity of pore size, shape and orientation affects the penetration of liquid into the yarn structure and hence its liquid retention properties. Likewise, number of filaments, yarn tension and twist significantly affect the yarn wicking performance by influencing the way in which individual filaments can pack in the yarn thus determining the amount of void spaces between filaments.

Moisture transfer is affected by degree of yarn twist, higher twist yarns improve capillary effect in moisture transfer as they are compact and provide less air volume. Lower twist generally results in reduced water transport through fabrics due to reduction in number and continuity of inter fiber capillaries. Twist in the yarn also affects the size of capillaries due to helical path of fibers in the yarn. More liquid on surface of twisted yarn is retained due to rough surface profile of these yarns compared to filament yarns.

Awadesh Kumar and Ramratan [17] studied the moisture management properties of different knit structures composed of micro polyester, texturized polyester and polyester –spandex blend and concluded that micro polyester fiber fabrics exhibited better liquid transmission properties compared to their counterparts owing to more capillary channels.

Linear density of constituent yarns affects the radial spread of water in fabrics. Fast liquid flow through inter yarn spaces in fine yarns is possible due to reduced capillary radius and low water retention of finer count yarns.

The yarns produced on different spinning system play a crucial role in dictating thermo-physiological properties of textiles intended for varied applications. The difference in the yarn structure and packing density of yarns produced on different spinning systems account for different thermal, moisture and liquid transfer properties of fabrics made from these yarns. Physical features of yarns and fabrics produced from these yarns are influenced by the type of yarn production (ring-spun, compact, open end) and in turn affect the performance properties of fabric.

A variety of yarns like ring, rotor, friction, vortex and compact spun yarns are used for varied applications in sports textiles. Dimensions and structure of inter yarn and intra yarn pores, pore size and their distribution along fabrics are influenced by density and structure of yarn.

Ring and rotor spun yarns vary widely in their structure which contributes to the entirely different properties of the two yarns. Ring-spun yarn has an ideal cylindrical helical structure with same number of turns per unit length in each helix, uniform specific volume and maximum packing density in the outermost zone of the yarn cross-section. Rotor spun yarn has a bipartite structure with an inner core which forms the bulk of the yarn and an outer zone of wrapper fibers occurring irregularly along the core length. Rotor yarn shows maximum packing density in first zone from core. Core part of rotor yarn is relatively dense structure; sheath part is less dense structure with belly-bands (**Figure 3**).

Yarn types can significantly influence the performance properties of textiles by affecting the fabric's bulk properties. Yarn hairiness and roughness can bring about changes in thermal properties of fabrics by entrapment of still air layer. Likewise, the moisture and liquid transfer properties of textiles are significantly affected by yarn types owing to difference in yarn roughness and arrangement of fibers in yarns. Increase in yarn roughness results in reduced rate of water transport through fabrics due to increase in effective advancing contact angle of water on yarn. Yarns with more random fiber arrangement can retard the liquid transfer by wicking as a result of disruption in continuity of capillaries formed by fibers. Wicking of yarns and fabrics is affected by difference in yarn surface roughness. Rough yarns are

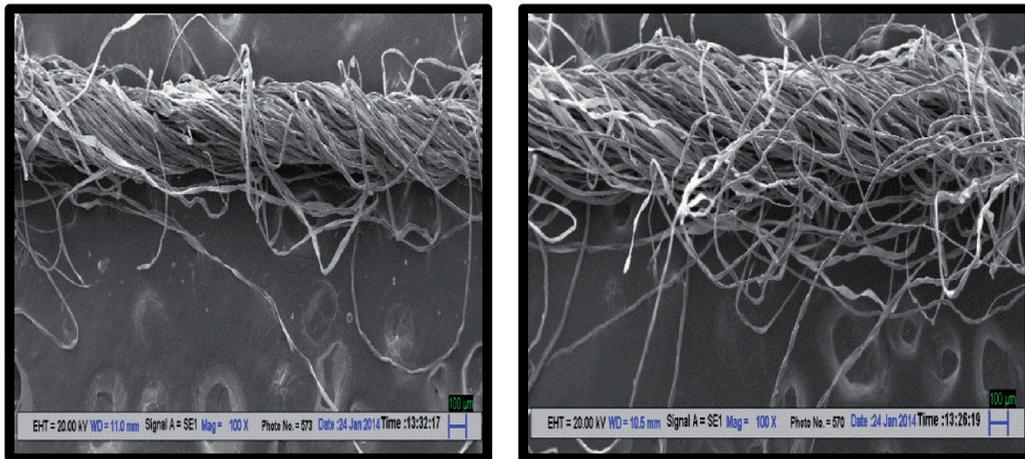


Figure 3.
SEM images of ring & rotor spun yarns.

formed by wool fibers with high apparent contact angle owing to random distribution of fibers in the yarns and the natural crimp. Yarns made of synthetic fibers have smooth surfaces and are well aligned.

Water transfer by capillary process is thus affected by two factors:

- Increase in yarn roughness causes an increase in effective advancing contact angle of water on yarn
- Random fiber arrangement decreases the continuity of capillaries formed by fibers in yarn

The following section reviews the studies undertaken and reported to determine the effect of various yarn variables on thermo-physiological aspects of textiles.

Y Jhanji et al. [18] studied the moisture management properties of polyester-cotton plated fabrics of ring vis a vis rotor yarns. They observed that ring yarn fabrics exhibited higher moisture vapor transmission rate, trans planar wicking, lower wetting time and higher one-way transport capacity as compared to rotor yarn fabrics, making the former suitable where body needs to dissipate sweat both in vapor and liquid forms, with respect to fabrics using combination of rotor-spun cotton yarns, which show higher absorbent capacity and would be slow drying with poor one way transport capacity. They concluded that yarn spinning system plays an important role in influencing moisture management properties of fabrics intended for next to skin applications.

Ansary [19] studied the influence of number of filaments on air permeability of polyester woven fabrics and reported a decrease in air permeability with increase in the number of filaments in the cross section of filling yarns.

Li and Joo [20] compared nano-scale filament, micro filament and normal filament knitted fabrics for their liquid transfer properties and concluded that nano-scale filament fabrics showed low porosity, high aerial density and increased absorption capacity and absorption rate. Better water absorption ability of nano scale filament fabrics compared to micro filament fabrics was attributed to smaller pore size of nano scale filaments compared to micro filaments.

Das et al. [21] varied the denier per filament for polypropylene knitted fabric to assess its influence on thermo-physiological comfort properties and observed that water uptake and wicking increases with increase in the number of filaments.

Behera et al. [22] compared the comfort properties of ring, rotor and friction spun yarn fabrics and suggested that ring and rotor spun yarns were comparable in

thermal comfort aspects, friction spun yarn being the most suitable. They pointed out that in the normal wear conditions and in the absence of perspiration, rotor spun yarn would be superior to ring-spun yarns.

Kumar et al. [23] compared ring, rotor and vortex yarn knitted fabrics and observed that ring yarn knitted fabrics showed good knitting performance and smooth feel, however abrasion resistance of rotor and vortex spun yarn fabrics were higher than ring spun yarn fabrics.

Erdumlu and Saricam [24] studied the wicking and drying properties of vortex spun yarns and knitted fabrics in comparison with ring-spun yarns and fabrics. They observed that yarn type significantly affected the yarn wicking, fabric wicking and water absorbency. Vortex spun yarn owing to crimped yarn axis and tight wrappings along yarn length had lower yarn and fabric wicking values than ring-spun yarn fabrics. Fabrics knitted from ring-spun yarns wicked and absorbed water more evenly than fabrics knitted from vortex spun yarns.

Singh and Nigam [25] compared carded, combed and compact spun yarn woven fabrics for their comfort performance and reported that carded weft yarn-based fabric samples showed higher resistance against air drag than combed and compact weft filled fabric samples. Compact weft yarn fabrics showed high water vapor permeability and were reported to be suitable for summer wear shirting. Carded yarn woven fabrics showed high thermal insulation and were.

Sengupta and Murthy [26] reported that open- end spun yarns showed lesser wicking time for any given vertical weight compared to ring- spun yarn fabrics. They observed that owing to dense core and less dense skin of open-end yarns it showed differential dyeing behavior in core and skin with dye wicking to greater height in the core than in surrounding sheath fibers.

Chattopadhyay and Chauhan [27] compared ring and compact yarns for their wicking performance and suggested that ring yarns showed faster wicking compared to compact yarns as evident from higher equilibrium heights for ring yarns. They explained the lower wicking of compact yarn due to less average capillary size of compact yarn compared to ring yarn owing to higher packing coefficient of compact yarn.

4.3 Fabric variables and their influence on thermo-physiological comfort aspects

The thermo-physiological properties of textile materials particularly sportswear depend on constructional variables and bulk properties of fabrics. Fabric structure, thickness, cover factor, aerial density, bulk density, fabric porosity and finishing treatments affect the thermal and moisture management properties and hence determine the comfort properties of fabrics.

Woven and knitted fabrics are generally used for varied applications like inner wears, outerwear, work wear and sportswear. Knitted fabrics owing to lower cover factor have more pores in their structure and the porous structure ensures good air, moisture and heat transfer properties and show better liquid transmission properties than woven fabrics. The difference in basic structures of textile materials account for variation in amount of water absorbed by different fabric constructions. The structural differences are related to fiber arrangement in yarn thereby affecting yarn roughness factor $\cos \theta$ and size and continuity of capillaries. Random fiber arrangement leads to high contact angle; while lower contact angle associated with faster movement of water in yarns and fabrics is attributed to high degree of fiber alignment.

The different fabric structures used for sportswear vary in their bulk properties such as fabric tightness, porosity, aerial density and thickness that in turn dictate the heat, moisture and liquid transfer through the fabrics. Availability of inter yarn

spaces for heat transmission, passage of air and moisture diffusion depend on the fabric's tightness factor. Thus, the bulk properties of fabric structures are crucial for optimum air, heat and moisture transmission through sportswear.

Several researchers have attempted to engineer different knit structures and compared the structures in terms of their comfort and performance properties intended for sportswear and other functional textiles. Innovative knit structures like plated fabrics, moisture management fabrics with different combinations of yarns in alternating courses, multilayered fabrics and fabrics mimicking the biometrics of plant structure have been developed for providing effective thermal and moisture management properties and sense of well-being to the wearer.

Structured or engineered fabrics are used in application areas relevant to commercial interest. Class of structured fabrics is moisture management fabrics; utilizing two or more fiber types in layered structures rendering two sides of fabrics distinctly different in character. Each side of fabric has the ability to exhibit different performance characteristics and thermo-physiological properties. Light weight two sided fabrics finding applications in varied areas are produced by plated knitted technique.

Both hydrophobic and hydrophilic yarns can be fed to single set of knitting needles and two separate yarns thus pass through each single needle of the set appearing distinctly on face and back sides of fabrics. Careful control of feed and positioning of two yarns is important to position distinct yarns in the two layers.

Plated knit structure is a double layered construction characterized by distinct face and back layers. The two layers are composed of different materials and accordingly serve different roles in providing wearer comfort.

One layer of plated fabric is the inner layer which is in direct contact with skin and serves the role of quick removal and transportation of sweat from body in vapor and liquid form. This layer serves as a separation layer and is composed of conductive and diffusive yarns generally characterized by low water absorption properties.

Another layer of plated fabric is the outer layer which is not in direct contact with the skin and prevents humidity build up near skin and vaporizes it to environment. This layer serves as absorptive layer and is composed of hydrophilic fibers and governs the liquid spreading and drying ability of fabrics. **Figure 4** shows the schematics of face and back layers of plated fabric.

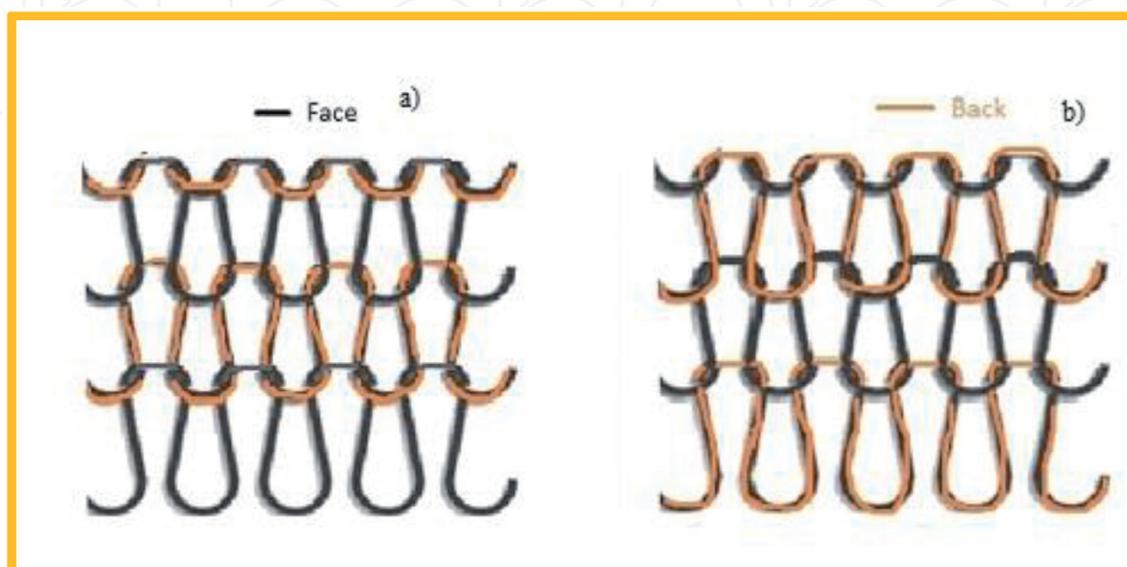


Figure 4.
Schematics of plated fabric (a) face and (b) back layer.

Selection of fiber and yarn combinations in the two layers can have a great bearing on the comfort properties, performance, esthetic appeal and end use of the knit structures.

Fibers of different chemical nature and thus different water absorbing properties can be used in different combinations to appear in face and back layers of plated fabrics.

Double layered knitted fabrics can be divided into following four types based on different fiber combinations and difference in water absorption properties of different fibers used in the two layers.

4.3.1 Double layered fabrics with hydrophobic fibers in face and back layer

The fabric has hydrophobic fiber in both face and back layers as shown in **Figure 5a**.

Liquid sweat next to skin cannot be absorbed by inner layer owing to its hydrophobicity and the only means by which sweat can be removed from skin is water vapor diffusion through pores within fabric. The diffused water vapor will evaporate slowly from the face layer in turn causing thermal and wetness discomfort to the wearer.

4.3.2 Double layered fabrics with hydrophilic fiber in back and hydrophobic fiber in face layer

The fabric has hydrophilic fiber in back/next to skin layer and hydrophobic fiber in face layer as shown in **Figure 5b**.

Liquid sweat next to skin can be absorbed by the back hydrophilic layer but the transfer of sweat to the face layer is restricted owing to hydrophobicity of the face layer. Thermal insulation of fabric decreases and fabric gives sensation of wetness and coolness as the pores in the inner layer are filled with water, removing the static air from the pores.

4.3.3 Double layered fabric with hydrophilic fibers in face and back layers

Figure 5c shows the fabric with hydrophilic fiber in face as well as back layers.

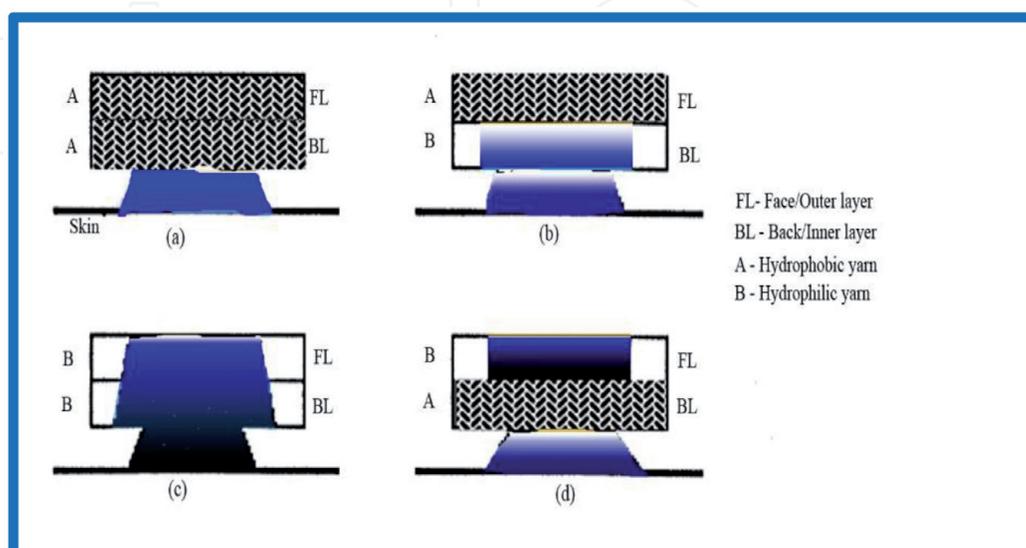


Figure 5. Water transfer from skin to different fabric layers. (a) Hydrophobic yarns in inner & outer layer, (b) Hydrophilic yarn in inner & hydrophobic yarn in outer layer, (c) Hydrophilic yarn in inner & outer layers, (d) Hydrophobic yarn in inner & hydrophilic yarn in outer layer.

Sweat from skin is picked up by hydrophilic fibers of back layer resulting in moisture accumulation and poor transfer to face layer. Water remains in the back layer and evaporation rate will be small owing to smaller wet area. The fabric will feel cool and wet to the wearer.

4.3.4 Double layered fabric with hydrophobic fiber in back and hydrophilic fiber in the face layer

Figure 5d shows the fabric with hydrophobic fiber in the back and hydrophilic fiber in the face layer. The back hydrophobic layer without absorbing the sweat itself transfers it to the face layer by means of capillary wicking. Face layer owing to hydrophilic fibers has good water absorption property and hence enables quick evaporation of sweat to environment by providing larger wet area.

Based on classification of double layered fabrics, Lord [28] indicated that that structure (d) with hydrophobic fiber in the back and hydrophilic fiber in the face layer would be most effective in maintaining dry skin micro climate by rapid liquid transfer to face layer. Additionally, several other researchers have unanimously recommended the use of hydrophobic fibers in next to skin and hydrophilic fibers in the face layer to achieve desirable moisture management and comfort properties in plated fabrics.

Plated fabrics designed with contrastingly different fiber and yarns exhibit the push- pull effect. Layer of hydrophobic fibers repel the perspiration next to skin and pushes or wicks it into outer layer of hydrophilic fibers which absorb or pulls away the moisture. Structured arrangement of hydrophobic and hydrophilic fibers in the two layers of plated fabrics and large difference in humidity between inner layer and ambient environment causes moisture movement from skin to outer atmosphere thus making the structures preferred choice for sportswear.

The structures are increasingly gaining popularity in apparels, next to skin applications, active wear and leisure sportswear owing to freedom in selection of contrastingly different constituents in the two layers. Therefore, the functional clothing intended for such applications are often specially engineered or structured such that the fabrics are normally two sided and are produced from a minimum of two yarns of different fiber content or characteristics.

Toda developed multi layered knitted structures composed of non-hygroscopic fibers. The structure was characterized by smaller inter fiber spaces in the face layer than in back layer by careful selection of fiber fineness, knitted structure and yarn type in face and back layers.

Yamini Jhanji et al. [29] investigated the effect of fiber type and yarn linear density on the thermal properties such as thermal resistance, thermal conductivity and thermal absorptivity along with air permeability and moisture vapor transmission rate of single jersey plated fabrics. They suggested that plated fabrics with nylon in the next to skin layer seemed suitable choice for warm conditions as these fabrics would feel cooler on initial skin contact owing to high thermal absorptivity and were permeable to passage of air and moisture vapor. Fabrics knitted with yarns of high linear density were found to be unsuitable in warm conditions owing to higher value of thermal resistance and lower values of air permeability and moisture vapor transmission rate.

Jhanji et al. [30] compared the moisture management properties of plated fabrics with altering hydrophilic and hydrophobic fibers in top and bottom layers and different types of hydrophobic fibers in top layers. They concluded that fabrics knitted with hydrophobic fibers (polypropylene, polyester) in top layers were suitable for next-to-skin applications as they were classified as moisture management fabrics owing to high values of accumulative one-way transport index and bottom

spreading speed. It was further suggested that fabric knitted with nylon in top layer was classified as water penetration fabric due to poor liquid transfer properties. Fabrics knitted with cotton in top layer irrespective of the hydrophobic fiber in bottom layer were poor in moisture management properties.

Ghosh and Kaur [31] studied the effect of tightness factor on liquid transport properties of plain knitted fabrics and observed that with increase in tightness factor, fabrics showed higher wicking and lower water absorbency. They suggested that higher tightness factor resulted in less tortuosity thus providing less complicated path for liquid flow and offering less resistance to fluid flow compared to fabrics knitted with lower tightness factor.

Suganthi and Senthilkumar [32] studied moisture management properties of double layered fabrics varying the fiber types in inner and outer layers and observed that bi layered fabrics with micro fiber polyester in inner and modal in outer layer was the preferred choice for active sportswear owing to fabric's better moisture management properties.

The published literature suggests that fabric structures engineered by strategic combination of hydrophilic and hydrophobic fibers, speciality fibers and yarns exhibit variations in their bulk, physical and comfort characteristics thereby influencing thermal and mass transport properties of textiles. The fabric structure and in turn the fabric properties determine the suitability of textiles for sportswear applications. Having discussed, the significance of fiber, yarn and fabric variables on functional aspects of sportswear in the previous section, it becomes necessary to highlight the key trends and innovations in sportswear which serve to enhance the performance as well as esthetic attributes of the sportswear. The designing aspects and innovative approaches employed to render smart functionality to sportswear will be covered in details in the following sections of the chapter.

5. Key trends in sportswear design and development

Key trends in sportswear design and development encompasses performance and esthetic evolution of sportswear from next to skin to exterior or outer wear.

The inception of new functional and high-performance fibers and waterproof and breathable materials like polypropylene, polyester, polyamide in micro fine denier and Goretex respectively led to innovations in first layer sportswear such as performance underwear. The functional properties like wicking, fast drying, anti-odor and UV blocking have been considerably enhanced by inclusion of new, innovative fibers. However, the raw material selection has not brought about radical changes in design aspects of the first layer.

5.1 Designing sportswear as first layer garments with enhanced functionality and unconventional styling

The first layer garments have undergone a major transformation with more emphasis on design and development of all-in-one suits in competition swimming and running, winter sport wear and athletics.

Furthermore, sportswear manufacturers are exploring the avenues for creating garments offering multiple functionalities in a single layer as per specific requirements of wearer's body parts.

The first layer sportswear is particularly popular among runners and top level athletes who seek comfort, unhindered bodily movement, light weight, fast drying and stretch ability in their attires. Apart from functional aspects, first layer sportswear have witnessed huge esthetic transformation with emergence of racier styles

featuring attractive and variable designs, funky colors, quirky prints, patterns and strategic placement of trimming as means of surface ornamentation. The sports person and fitness freaks who once merely considered the performance aspects of their clothing, no longer follow a taciturn approach to doff a stylish, funky sportswear that can render psychological well-being to wearer and visual delight to viewers.

Accordingly, designers are fostered to include innovative design concepts such as elaborate patchwork, asymmetrical styling and unconventional placement of trimmings, notions and labels in their sportswear design collections with due consideration to the changing preferences of sportspersons and consumers.

The functional aspects of performance under wears are enhanced by incorporation of innovative technologies like application of moisture management, UV protective, bacteriostatic finishes, controlled release of chemicals and other auxiliaries via microencapsulation. Accordingly, the underwear exhibit exceptionally superior moisture management properties, thermal and UV protection, antimicrobial and antistatic properties. Apart from functional attributes, the performance underwear have evolved significantly with vibrant fabric colors, contrasting trimming and off-center patterns widely used in their designing.

Introduction of asymmetrical design concepts like placing the closures along the side seam serve both esthetic and functional aspects by rendering unorthodox fashion appeal, layering and enhanced wearer agility. The trendy styles are thus becoming asset for youth oriented sportswear.

The first and second skin sportswear segment once considered a dowdy category, has emerged as top notch sportswear segment bringing new dynamics to sportswear market with all the innovative design concepts enjoying consumer acceptance.

5.2 All in one suits

The classic example of all in one suit is the body-covering Speedo swimwear intended for competition swimming introduced during Olympics.

The swimwear design fostered the concept of bio mimetics in sportswear designed later as the former closely mimicked the sharkskin as far as design orientation was concerned.

The success story of all-in-one swim suits paved the way for designing athletic sportswear, speed skating and cross country skiing suits. Nike, a popular sportswear brand was trailblazer in designing an elaborate, paneled speed skating suits comprising of seven different fabric types for cyclists. The novel suit with patchwork was designed to enhance the cyclist's performance, protection level and comfort in spite of the unfavorable ambient environment and excruciating conditions which cyclists generally encounter. The high tech suits are the state of the art suits offering multiple functionalities such as elasticity, compression, thermal insulation, protection against external elements and aerodynamics. The patch work design unique to high-end cycling sportswear has been adopted in second skin and first layer garment design as well.

5.3 Designing smartly via incorporation of sensors and electronic components

Another design perspective in sportswear segment envisages the incorporation of smart features via sensors and other electronic components that are comparable to high tech trimmings. A microphone with its associated embroidered control buttons on a garment sleeve or collar renders graphic yet functional embellishment to the clothing. The elimination of wind and rain flaps by inclusion of water tight zippers for medium level performance outerwear, switching to leaner and pared styles

of trims and notions like printed and embroidered labels and motifs, drawstrings, velcro, snap closures and mesh lining for pockets to offer storage and ventilation both are some approaches to enhance the functionality and esthetic appeal without adding any additional bulk to the sportswear.

The sportswear designers are thus fascinated by concept of stealth design that implies less detailing, fewer accessories yet not at tradeoff with functional and smart features.

5.4 Design approaches to render breathability and waterproofing to sportswear

Waterproofing and breathability becomes all the more crucial while designing sportswear intended for outdoor sports where sports person is doomed to be exposed to humid, rainy conditions.

The technologies generally employed for development of waterproof breathable sportswear include:

- Development of high density fabric
- Application of polymeric coating
- Film lamination.

Development of High density fabric - The densely woven fabrics consisting of cotton or synthetic microfilament yarns with individual filament diameter of less than 10 micron and produced with high cover factor exhibit water proofing and breathability. The high cover factor of fabrics reduces the inter yarn spaces thereby preventing liquid penetration through fabric structure. The fabric on exposure to liquid causes cotton fibers to swell transversely reducing the pore size in the fabric structure. The dimensions of pore are smaller than water droplet thus effectively preventing water penetration however the pores allow the transmission of water vapor molecules (insensible perspiration) on account of smaller size of vapor molecules compared to water droplets thereby rendering breathability to the fabrics. The classic example of water proof breathable fabric is VENTILE, a high density oxford woven cotton fabric that effectively prevents the penetration of fluid but is permeable to passage of water vapor through the clothing.

Coated fabrics - Fabrics intended for sportswear can be imparted water proofing and breathability by application of polymeric coating either on one or both fabric surfaces. Polyurethane is the most commonly used coating for imparting water proofing to textiles. Micro-porous and hydrophilic membranes can be used for development of coated textiles. The micro-porous membrane features a coating containing very fine inter connected channels of the dimensions smaller than the finest raindrop. However, the size of channels is larger than that of water vapor molecules enabling water vapor passage through the air-permeable channels. Although, the hydrophilic membrane exhibit similar structure as that of micro-porous membrane, however, the mechanism of water vapor transmission in former is via adsorption-diffusion and de-sorption in contrast to passage of water vapor molecules through the air-permeable channels in the latter.

Lamination involves bonding a waterproof and breathable film to textile substrate. Thin polymeric membranes of maximum thickness up to 10 micron when bonded with base fabrics offer water proofing and breathability to textile substrate. Micro-porous membrane of poly-tetra fluoro ethylene (PTFE), poly-vinylidene fluoride PVDF and hydrophilic membrane composed of poly ethylene oxide are utilized for development of laminated water proof textiles for sports applications.

The ingress of water through seams in a water proof garment needs to be prevented through seam sealing. Apart from waterproofing, the laminated garments should be lightweight, flexible and comfortable to wearer. Thus, thinner strips, elasticized tapes and improved glues are increasingly being used for designing bulk free laminated sportswear. The traditional three ply composite construction comprising of fabric, film and mesh lining have undergone major transformation by elimination of mesh linings and addition of silicone touch finish to films imparting cleaner finishing and convenient doffing of the clothing. The overall freedom of wearer movement is thus ensured as a result of reduced friction within garment layers.

The sportswear designers prefer to do away with seams as they are a major source of friction, added fabric layers and bulk. Thus, designers prefer seamless knitting or heat sealing for reduction and elimination of seams to achieve a clean, compact performance wear.

The three layer sportswear are generally preferred for outdoor activities like hiking and cycling owing to their ability to provide protection against external elements (extreme cold or humidity) along with basic sportswear requirement of being lightweight, breathable and comfortable.

Each layer of a three layered assembly is designed to serve a specific function. The first, next to skin layer is designed with hydrophobic fibers to wick away sweat from skin to the outer layers, thereby rendering dry feel next to skin. Additionally, the innermost layer offers thermal protection to wearer in cold ambient conditions.

Second layer garments generally composed of fleece, assist in keeping the wearer warm and dry by drawing sweat from skin to the outer layer. The modifications in second layer are targeted to achieve high warmth to weight ratio without compromising the thermal insulation of clothing. However, the traditional three layer protective clothing assemblies are being rapidly replaced by advanced composite textile structures referred to as soft shell clothing designed by bonding multiple knits and fleece layers together.

The latter offers agility to wearer, protection against adverse environmental conditions with an additional advantage of being light weight and compact.

The second layer is further improvised to impart multiple functionalities such as warmth retention and insulation, water resistance, elasticity and wind protection. Therefore, sportswear has been witnessing a transition from complete water proofing by hard shell to water resistance by soft shell.

There are three approaches to design soft shell with augmented thermal insulation and wind protection. The first approach involves the utilization of windproof shell as a separate clothing entity while the second involves bonding fleece to wind blocking membrane. The membrane laminated sportswear thus offer thermal insulation along with water proofing and breathability. A new range of laminates designed with wind defender type membranes namely Gore – Tex Windstopper, Symptex Windmaster underscore protection against wind over water proofing, are being specifically developed for windy climatic conditions (**Figure 6**).

Adequate warmth and wind protection can also be achieved by third approach wherein fleece is bonded to tightly woven fabric or knitted structure.

Moreover, the comfort level, warmth and protection to wearer can further be provided by four layer system comprising of four garments - first layer, fleece, soft shell and hard shell.

Soft shells comprising of fleece and treated with water repellent surface finish are ideal candidates for outdoor activities as they primarily focus on enhanced thermal insulation, elasticity and abrasion resistance. The jackets have evolved radically

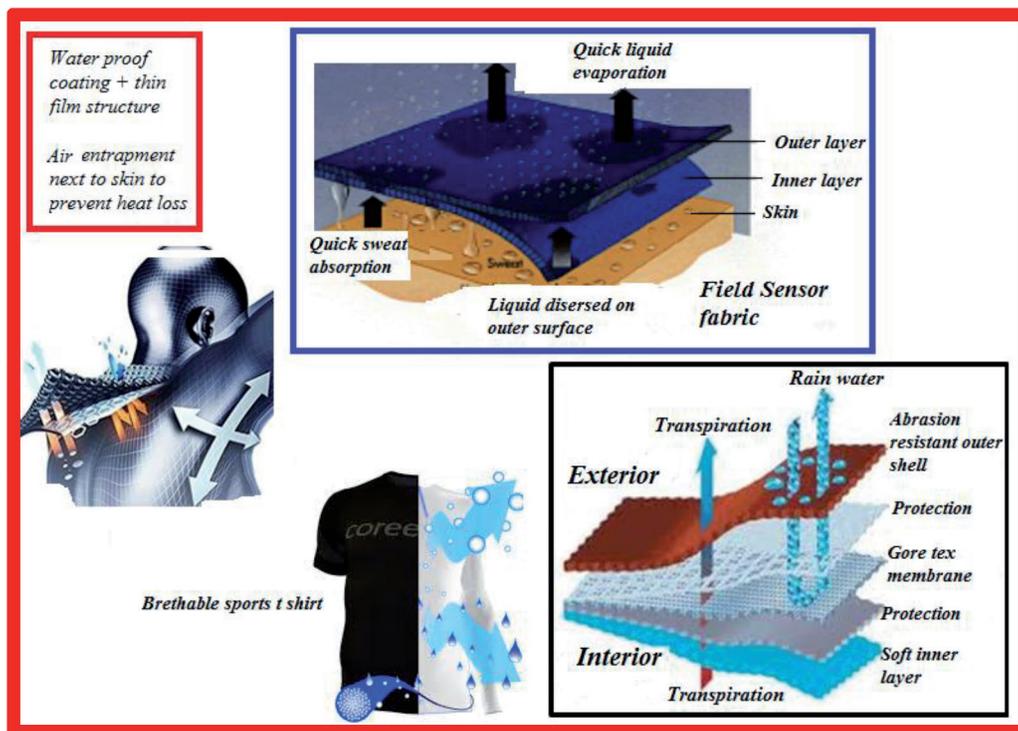


Figure 6.
Water proof & breathable sports wear.

as far as design and style elements are concerned and are increasingly being designed devoid of multiple drawstrings, elasticized hems or double storm flaps thereby eliminating cumbersome and bulky garment features. A closer-fitting, bulk free silhouette for better mobility, warmth retention and comfort to wearer has thus become synonymous to performance outerwear. The designing of hard shell jacket is also not aloof of the close fitting approach and thus designers have been striving to design leaner, fitted hard shell attires taking design inspirations from soft shells.

5.5 Design approaches for enhanced thermal insulation of sportswear

Other approaches for designing outdoor, winter sportswear are based on fundamental concept of exploiting the good insulation properties of still air layer and thus engineering textile structures with an ability to trap large volumes of still air. The entrapped air layer being good thermal insulator can provide enhanced thermal insulation to clothing incorporating hollow fibers, three dimensional spacer fabrics and alveolar or nodular raised knit structures. Hollow fibers on account of their light weight and improved thermal regulation outshines conventional fibers and are considered ideal for all such applications where high thermal resistance is sought for.

Accordingly, knitted structures like pique, honeycomb or ribbed raised textures are generally used for designing sportswear intended for winters. The honeycomb knits in conjunction with raised fabric in next to skin layer offers effective thermal insulation and are suitable for cold weather clothing and sportswear. Likewise, the structure of fleece can be modified for enhanced warmth by trimming the piles and creation of three dimensional grid thereby increasing the air entrapment next to skin.

The high performance thermo regulation along with light weight and wearer comfort can be engineered into sports apparels and accessories via three dimensional knit structures, spacer fabrics.

5.6 Nature as source of inspiration for sportswear designers

Nature is a big source of inspiration for human beings and capturing nature's beauty and functionality by biomimetic is a concept frequently explored in functional clothing particularly sportswear and protective clothing.

Speedo, a sportswear manufacturing company developed one of its own kinds of Fast skin biomimetic swimsuit taking inspiration from shark skin (Figure 7). The denticles of shark's skin were imitated on the fabric to impart super stretch property and thus the performance of swimmer donning the swimsuit could be considerably enhanced by shape retention, muscle compression and reduced drag coefficient.

Inotek® fabric based on "Pine cone effect" is quite popular among sportswear designers and manufacturers owing to exceptionally excellent thermal regulation and moisture management properties exhibited by the fabric. Pine cones comprises of two layers of stiff fibers that are oriented in different directions (Figure 7). The cones tend to close as the humidity increases to prevent moisture from getting in while they open up releasing their seeds and falling to the ground as a response to decreasing humidity. Likewise, the Pine Cone Effect based on reaction of plants to humidity is explored for designing fabrics that can respond to changing humidity conditions. The textiles based on biomimetic concept are composed of layer of thin wool spikes that open up on encountering increased humidity as a result of sweating by wearer. However, as the sweat evaporates and humidity drops down, the spikes on the fabric closes again in response to changing humidity.

The designers of long jump suit named SKYNFEEL exclusively designed for professional athletes might have been enticed by the salient characteristics of fauna to exhibit unhindered flights with their wings. The suit is designed with laterally

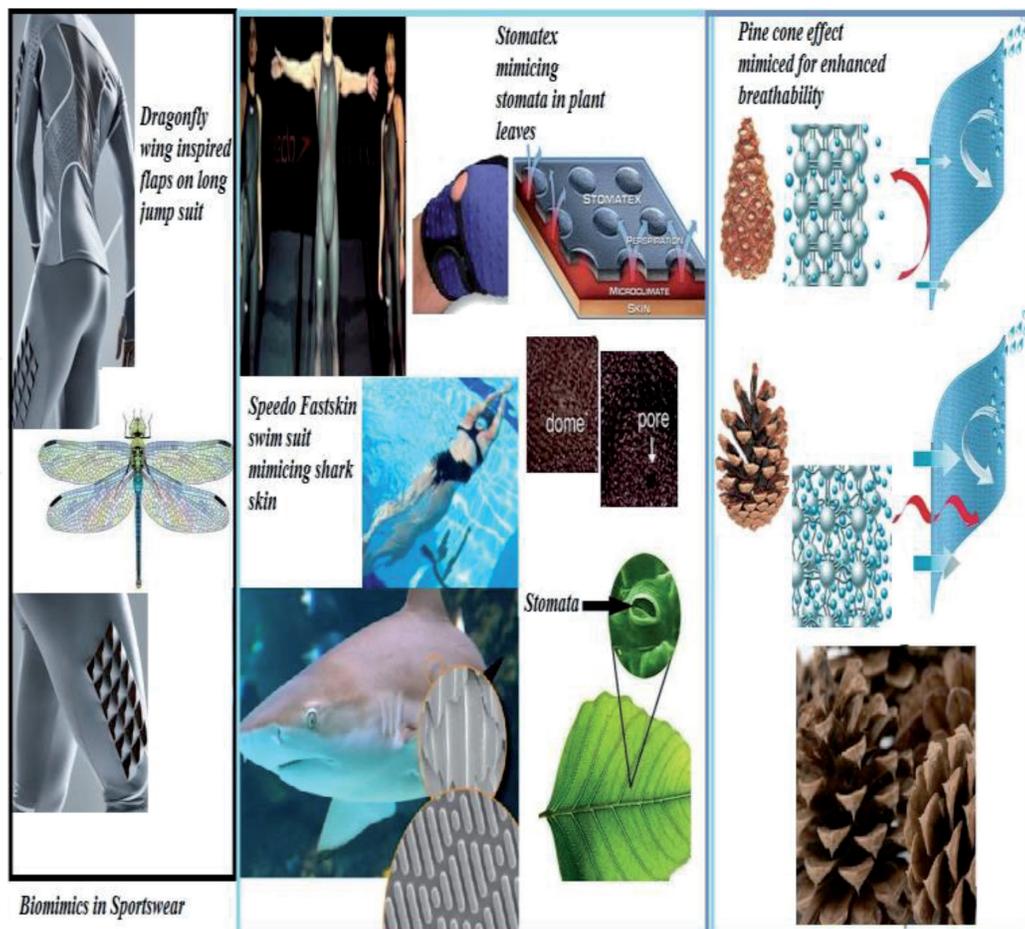


Figure 7.
Biomimetic principles for sportswear designing.

positioned flaps much like the wings of dragonfly. The dragon fly wing inspired flaps feature geometric lased cut panels that enhance the athlete's elevation during jumping via closing and opening up as per athlete's movement. The flaps remain closed during run-up however they open up as the wearer is preparing for jump. The opening of panels leads to creation of air pockets thereby resulting in aerodynamic effect. Consequently, the jumper's performance is enhanced due to his ability to suspend in air for longer duration and gaining distance while jumping.

Stomatex®, another smart fabric designed using the biomimetic principles finds application in compression athletic wear for enhanced performance and recovery. The salient feature of fabric is dome and pore mimicking the stomata (tiny pores) on the plant's leaves responsible for respiration and gaseous exchange in plants (**Figure 7**). The phenomenon of opening of stomata in daylight and closure at night is attempted to be recreated by the way of opening and closing of pores present on domes embossed in the outer knitted layer of fabric. The sportswear utilizing aforesaid fabric is generally designed in close-fitting silhouette to be able to react to wearer's bodily movements. During static conditions, the energy consumption by sports person is reduced and thus wearer comfort is ensured by release of excess heat and moisture rising into the domes and ultimately released via the pore. As the wearer is actively involved in some physical activity, the flexing and movement of domes (and pores) enables passage of cooler air into clothing and escape of heat and moisture to outer environment.

6. Innovative approaches for sportswear design and development

The sportswear industry is taken by storm by path breaking innovations as far as procurement of raw materials like high performance and specialty fibers, yarns and engineering of fabric structures like double layered, elastane and breathable fabrics are concerned. Furthermore, smart functionalities like antimicrobial, antistatic, anti-odor properties, monitoring sportsperson's physiological parameters, incorporation of smart materials like phase change materials and shape memory polymers, wearable sensors, tracking performance record of sportsperson and incorporation of smart technologies like smart coatings, nano technology and wearable electronics are engineered into sportswear (**Figures 8 and 9**).

6.1 Innovative raw materials for sportswear

The fibers suitable for sportswear have already been discussed in the previous section. However, the innovations in sportswear cannot be conscripted without the mention of high performance fibers and their role in improving the moisture transmission properties of sportswear. The utilization of high performance fibers such as Coolmax®, Thermolite®, Thermocool® in performance and active wear results in increased surface area, better wicking and moisture management and in turn dry, cooler microclimate to wearer. Thermolite® is particularly suitable for cold weather sportswear due to fabric's exceptionally high thermal insulation and moisture transmission properties. Winter sportswear comprising hollow core fibers possess the ability to trap higher volumes of static air and thus provide enhanced warmth and wearer comfort without any additional weight or bulk unlike conventional fleece fabrics. The clothing is thus gaining popularity among sports persons indulging in outdoor, winter sports like ice skating, mountaineering etc.

Dryarn, an innovative sustainable fiber from Aquafil is recyclable polypropylene microfiber and a preferred choice for developing sportswear fabrics that are sustainable, soft, anti-bacterial, light weight, quick drying, comfortable and exhibits high thermoregulatory capacity.

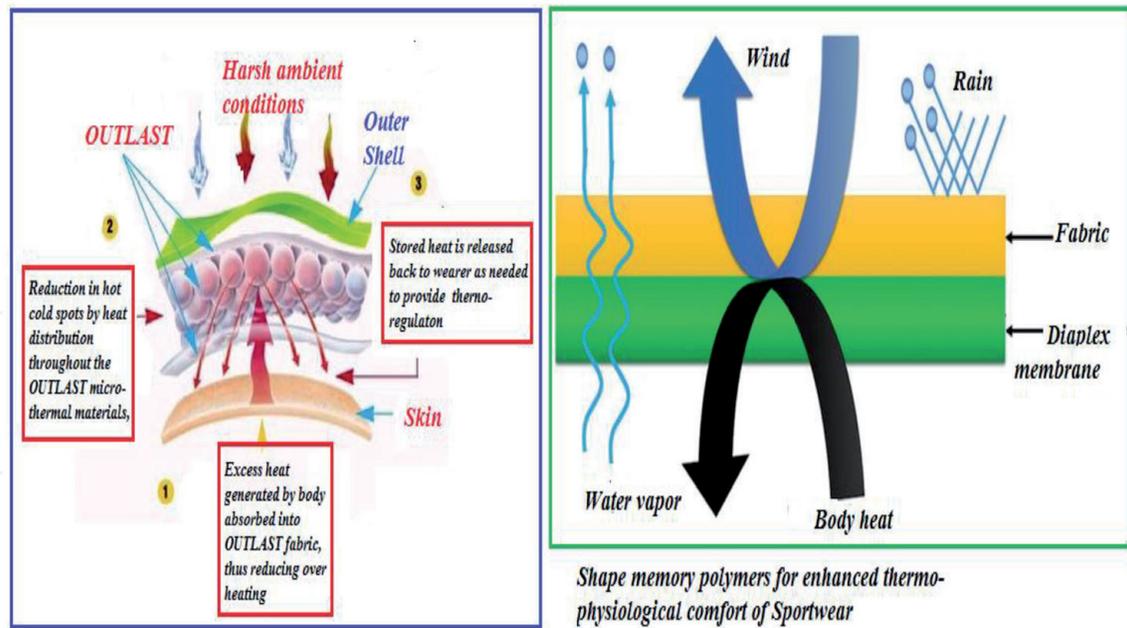


Figure 8.
 Phase change materials & shape memory polymers for sportswear.

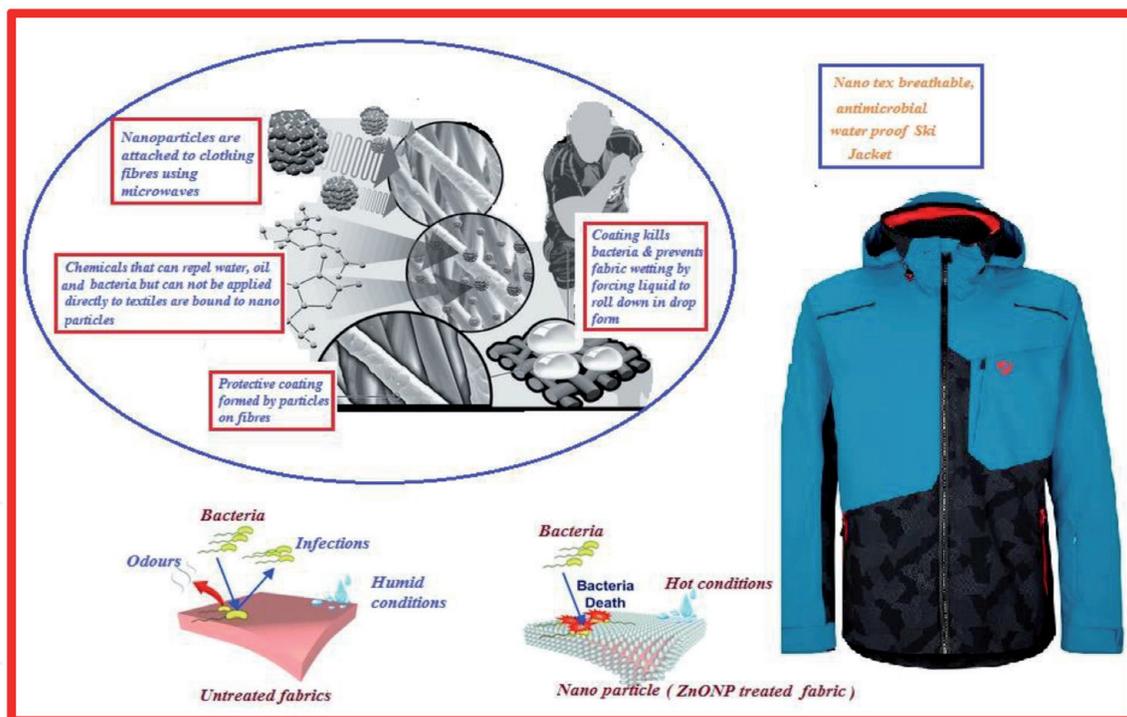


Figure 9.
 Nano technology for antimicrobial sportswear.

Sportwool®, a two layered moisture management fabric featuring wool on the inner side and synthetic fiber on the outer side and Field sensor TM® with brushed inner side are other options for winter sportswear.

Field Sensor, high performance fabric from Toray is a multilayered structure suitable for varied sports applications. The excellent moisture management properties and wick ability for rapid liquid transmission from next to skin to outer layer can be attributed to the fabric's specially engineered structure with distinct inner and outer layers composed of coarser denier yarn and fine denier hydrophobic polyester yarn in a mesh construction respectively.

Additionally, thermo regulating materials like phase change or latent heat storage materials capable of sensing varying ambient conditions and responding by changing their phase are increasingly finding application in sportswear where sportsperson is exposed to prolonged, drastic environmental conditions. Outlast technology is involved in development of microencapsulated PCM coated fabric intended for sportswear and other smart textile applications. The sportswear developed with PCM treated fabrics provides thermal balance and maintain constant body temperature to wearer by absorbing excess body heat at elevated temperatures due to metabolic heat production and releasing it as the temperature drops down during cooling.

The potential of shape memory polymers to obtain effective thermal and moisture management properties was first explored in sailor suit designed for Swedish sailors. The suit based on membrane technology employed waterproof, windproof and breathable Diaplex membrane. The smart membrane can sense the changing ambient conditions and respond by changing its shape, memorizing the original shape and returning to the original, memorized shape accordingly. The membrane undergoes Micro-Brownian motion as it senses elevated temperature thereby creating micro-pores for heat and moisture transmission through the membrane (**Figure 8**).

6.2 Innovative wearable sensors and AI based technologies for sportswear

The concept of sportswear design and development has been drastically changing with sportsperson anticipating technological features in their attire apart from basic requirements of functionality and comfort. It thus becomes mandate for sportswear designers and manufacturers to conform to the expectations of their consumers and come up with technology laced sportswear that can serve best of both worlds by offering comfort, protection and other functional attributes along with serving as a personal trainer, activity tracker and can monitor physiological parameters of the sports persons (**Figure 10**). The new generation of sportswear exhibits such smart features which would be considered fantasy a decade ago. The myriad of innovations in sportswear as far as incorporation of smart features are concerned will be discussed in detail in this section of the chapter. **Figure 10** show the technology laced smart sportswear for performance & health monitoring. An innovation in athletic wear is development of Skin® 400 compression athletic wear series. The athletic wear is composed of elastane warp knitted fabric that can foster oxygen delivery to athlete's active muscles via dynamic gradient compression.

Smart sportswear like fitness pants feature built-in haptic vibrations and signal the wearer to be agile or hold position as per pulse generated at the stress prone zones like hips, knees and ankles. The smart pants can be synched to wearer's phone via bluetooth and provides additional feedback through the companion app.

Ambiotex's smart shirt intended for athletes is designed with integrated sensors and clip-on box for recording athlete's data pertaining to heart rate variability, threshold, fitness and stress levels.

Sabine Seymour's smart bra is designed with an integrated invisible biometric sensors and can be effectively worn to track heart rate and workout routines during sporting, gyming activities.

Compression sleeve by Komodo technologies is beneficial for sportspersons and heart patients as the sleeve is capable of monitoring heart rate activity via electrocardiogram (ECG) technology. The sensors integrated in the sleeve can monitor wearer's body temperature, sleeping patterns, workout intensity, air quality and UV rays.



Figure 10.
Technology laced smart sportswear for performance & health monitoring.

A smart shirt laced with blue tooth smart sensor can be paired with fitness apps like Map My Run, Run Keeper and Strava to capture the real time data and monitor physical activity and physiological parameters of sportspersons such as intensity and recovery; consumed calories fatigue level and sleep patterns.

Athos deals in range of training clothes intended for gym goers. The ensemble is designed with micro-EMG sensors that can detect muscle movement and in turn transfer the workout data such as sports person's muscle effort, heart rate and breathing to a smartphone. The app serves as a personal trainer for fitness freaks by providing insights on correct exercise protocol and injury avoidance.

Hexo skin smart sportswear are designed with embedded textile sensors for monitoring cardiac, respiratory phenomenon, physical training, sleep patterns, and mundane activities of an individual involved in rigorous sports. The visualization, reporting and analysis of data becomes very convenient with Hexo skin as the smart clothing is equipped with an accelerometer to quantify body movements, track heart rate to be viewed in real time. Furthermore, it prevents the sports person from over training by determining lung capacity for each activities performed and measurement of stress and training fatigue.

Boltt, a sports tech-brand pioneer in design and development of consumer-centric health and fitness clothing and smart shoes laced with stride sensors and activity tracker. The real-time audio feedback and customized workout suggestions generated by the brand's advanced artificial intelligence (AI) ecosystem can provide customized health and fitness coaching to wearers.

An on demand inflatable- deflate able textile tubing network in a jacket developed by Sympatex can provide the extra warmth to wearer when inflated while the jacket can be deflated to release the air held inside the tubes into the environment as it senses an elevation in body temperature ow wearer's activity level.

A Cyberia survival suit intended for arctic environment serves as a personal GPS and monitors the wearer's physical conditions. The suit derives its sensing and monitoring capabilities from an array of sensors and connecting electrodes embroidered onto textile substrate.

Qardio Core, an ECG monitor is a hardware fitness tracker capable of providing continuous medical grade data by incorporated sensors in the tracker. The smart tracker is designed for people indulging in active lifestyles but with a family history of chronic diseases. The doctors can analyze the obtained data from sensors to monitor the health record and can act instantly in event of any abnormal data.

Wearable X, pioneer in bringing design and technology together, launched smart yoga wear incorporating haptic feedback. Posture monitoring and vibrational reaction by smart garment assists in guided yoga.

Vitali smart bra is another state-of-the-art smart sport wear designed for fitness freak females. The bra is equipped with sensors to track heart and breathing rates. The stress levels of women can be monitored via data collected from sensors thereby sending reminder to wearer to take deep breath on detection of high stress levels.

Exercise routine for elderly people can be managed by smart knitted cardigan designed by Dutch designer Pauline van Dongen. The ordinary looking cardigan is equipped with four stretch sensors comprising conductive yarns and can transmit the information to an app for generating feedback. The obtained feedback serves as a guide for physiotherapist to suggest the best exercising options as per age and physical stamina of the wearer.

7. Conclusions

Sportswear constitutes an integral part of technical textiles and encases great potential as far as technological and design innovations are concerned. The sports textiles have witnessed tremendous evolution and that too at a much faster pace compared to ready to wear segment. The sports clothing is no longer restricted to sportsperson involved in performance sports or strenuous physical activities. However, there has been a surge for sports apparels and accessories among health conscious, fitness freak and gym enthusiasts. Accordingly, the sportswear industry has witnessed revolutionary advancements in development of different sportswear categories like active wear, leisurewear and athleisure to fulfill the requirements of sportsperson as well as health-conscious millennials. The basic and functional requirements of comfort, breathability, light weight, anti-static and anti-odor properties can be engineered into sportswear by optimum selection of fibers, yarns, fabrics and garments' designing aspects.

Sportswear has emerged as one of the most promising and technologically driven segments of technical textiles with massive innovations and advancements involved in design and development of sport specific attires.

The basic requirements of sportswear vary as per the sportsperson's level of physical activity, the specific nature of sport and the ambient conditions to which the sportsperson is exposed. The technological and ergonomic aspects for designing under water diving suit will be contrastingly different from those incorporated in designing clothing for a golfer. Thus, a lot of brain storming and research is involved in designing a clothing that meets the specific requirement of sports along with providing comfort, dexterity, agility to wearer, breathability, moisture management, light weight, antimicrobial and anti-odor properties. The correct selection of fibers, yarns and fabric variables for sportswear is of paramount importance to engineer the desired properties in the sport clothing.

Apart from functional requirements, a lot of emphasis is being laid on esthetic aspects as well considering increasing number of females involved in yoga, gyming and other sporting activities who give precedence to silhouette, colors and other design details of sportswear. Accordingly, the technological as well as ergonomic advancements in sportswear design and development have opened new avenues for researchers to explore the field further.

8. Future scope in design and development of sportswear

The field is promising and innovative with several avenues as far as research and development, pioneering new technologies and trailblazing concepts are concerned. Furthermore, the role of technology, bio mimics, fashion and mediation of interdisciplinary fields like wearable electronics, bio medical avenues have brought about a major transformation in design and development of smart sportswear thereby enhancing functionality and esthetics of sportswear. Apart from functional and esthetic appreciation of sportswear, the need of the hour is switching over to sustainable practices in sportswear supply chain. Consequently, the sportswear designers and manufacturers understanding their social and economic responsibilities should commit to sustainable practices for design and development of sportswear.

It can thus be recapitulated that the future belongs to smart sportswear spanning from ethical, to technology laced wearable electronics to camouflage clothing to convertible, modular sports ensembles which not merely serves as clothing for wearer but can be multifunctional entities with an ability to be transformed into a travel bag or a sleeping bag as per the sportsperson's convenience and requirements.

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