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A Review: Development of Sports Textiles with Enhanced Comfort Properties for Thermal and Moisture Transport

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A B S T R A C T

In the realm of sports, the importance of sports textiles takes centre stage, ensuring athletes experience optimal comfort and peak performance. This intricate field prioritizes effective thermoregulation (heat management) and efficient moisture transport (sweat wicking) to achieve the utmost comfort. The ideal base layers excel in conducting heat, handling moisture effectively, and providing a pleasant feel against the skin. The key lies in the interplay of fabric structure, fibres, and design, intricately influencing how moisture is wicked away and heat is dissipated. Synthetic fibres, known for their quick-drying capabilities compared to natural cotton, often take the spotlight. Introducing a blend of different fibres can further enhance moisture management. While compression garments offer benefits, they may pose challenges to comfort by covering more skin and hindering heat transfer. This aims to understand how fit and coverage impact comfort in various environments, ultimately guiding apparel recommendations for athletes and active individuals.

Keywords: Thermoregulation, Moisture Transport, Synthetic fibres

1. Introduction

Thermoregulation involves the regulation of the body's core temperature. When engaging in physical activity in warm environments, the primary mechanism for thermoregulation is the evaporation of sweat. The body aims to attain a thermal steady state by effectively balancing the production of metabolic heat with heat loss [1]. Effective thermoregulation holds significant importance for endurance athletes, especially when participating in competitions set in hot and humid environments. In such conditions, the body's natural ability to regulate temperature is compromised, elevating the risk of heat-related illnesses, and adversely affecting performance. Scientific literature has extensively explored various methods aimed at improving body cooling to address these challenges [2]. Comfort is divided into three main aspects: psychological/ergonomic, physical (sensorial/tactile), and physiological. Psychological/ergonomic comfort involves how something looks, its design, colour, fit, and how easy it is to move in. Physical comfort relates to how something feels, including its texture (smooth, rough, soft), temperature (warm or cool), breathability, moisture (wetness, stickiness), and pressure (light or heavy sensations). This division helps us understand and address different aspects of comfort in a more detailed way. The physiological comfort finally refers to the body thermoregulation [3]. In the realm of sports textiles, the term "performance" has gained significant importance, focusing on factors such as moisture management, temperature regulation, stretch, lightweight properties, wind and water resistance, and a low-friction surface [4].

The fabric used for sports base layers is in direct contact with the athlete's skin, significantly impacting their critical performance by enhancing thermo-physiological comfort. An ideal base layer, worn closest to the skin, should possess the following qualities: effective thermal conductivity, efficient moisture management, and favourable tactile properties. The fabric structures and fibres utilized in creating these base fabrics should be soft and smooth, with the overall assembly designed to efficiently move moisture away from the skin. This ensures both wearer comfort and unrestricted body movement during physical activity [5]. Thermal comfort refers to the equilibrium between the total heat gained and lost in the microclimate around the wearer's skin when textiles are present. The complexity of thermoregulation in textiles involves various mechanisms of heat exchange, including conduction, convection, radiation, and moisture evaporation [6].

2.1. Sports Textile

The human body strives to maintain its core temperature at 37±1ºC, employing four modes of heat transfer: conduction, convection, radiation, and evaporation. During sports activities, approximately 80% of energy is converted into heat, and in hot conditions where the air temperature surpasses the body core temperature, heat loss occurs through evaporation to regulate the body temperature. The amount of heat loss relies on the rate of sweat evaporation, which, in turn, is influenced by atmospheric conditions **[**7]. In warmer regions, the sweat rate can elevate to as much as 2.5L/h due to heightened metabolic activities in active sportswear, leading to increased convective and radiative heat loads. Researchers have identified that fabrics

with superior moisture absorption enhance player performance. Fabrics create a microclimate between the body and the atmosphere, acting as conduits for heat and vapor transfer between the skin and the environment **[**8]. Sportswear possesses both functional and aesthetic requirements, each crucial in determining its performance and consumer acceptance. Aesthetic considerations encompass characteristics such as softness, surface texture, handle, luster, and color, while functional requirements include being lightweight, offering low fluid resistance, high tenacity, stretch-ability, thermal regulation, UV protection, vapor permeability, and effective sweat absorption and release. The thermo-physiological comfort aspect of sportswear is vital for the well-being of athletes without compromising performance. Engineering materials with superior moisture vapor and liquid moisture transmission capabilities establish a dry microclimate for wearers engaged in vigorous physical activity in hot and humid conditions. Fabrics designed for activewear must carefully consider geometry, packing density, and the structure of component fibers to efficiently dissipate heat and moisture. Sportswear with excellent moisture management often involves specific fibers, yarns, and fabric structures. Designers experiment with various factors like fiber cross-sectional shapes, shape factors, specific surface areas, yarn variables (twist, linear density, structure, packing coefficient), fabric variables (loop length, porosity), and different knit structures like plated and elastane fabrics, as well as those inspired by bio-mimic concepts. Recent advancements in functional polymers, fibers, yarns, fabrics, and production techniques have spurred research into the design of active sportswear to meet consumer requirements. The performance characteristics of sportswear are influenced by factors such as fiber structure, inter-fiber interaction, yarn/fabric structure, and chemical treatments applied during development. The introduction of synthetic fibers has further expanded possibilities in creating active sportswear with enhanced thermal performance and moisture management properties. The choice of raw materials significantly impacts the properties of sportswear, presenting a challenge in the sports textiles market [9,10].

2.2. Clothing Physiology And Comfort

Achieving comfort is a crucial factor in evaluating the quality of individual garments and plays a significant role in clothing selection. The comfort experienced while wearing clothes is a subjective response influenced by various factors. For optimal comfort, the textile material used in the garment should exhibit good porosity, allowing the diffusion of water vapor through pores when the body is in motion. In cold conditions, clothing should provide effective thermal insulation, along with high moisture permeability and adequate ventilation to ensure optimal thermoregulation of the human body. This involves maintaining the body in thermal equilibrium, where the energy generated by metabolism is equal to the energy gained from the environment, resulting in the loss of the body's thermal energy. The outcome of a balanced interaction between the human body, air, and clothing is manifested in the comfort experienced by individuals wearing the garments **[**11].

Hence, the criteria that both clothing and sportswear need to fulfill are derived from the following considerations:

- Physiological Function: Aimed at ensuring the wearer's thermal equilibrium.
- Skin Sensory Comfort: Focus on providing comfort to the wearer's skin.
- Ergonomic Function: Emphasis on maintaining ergonomic comfort in clothing.
- Aesthetic Function: Requirement for clothing to align with fashion standards, encompassing aspects such as color, cut, and design.

Essential Four Types for Clothing Comforts are

- Thermo-Physiological Comfort

Thermo-physiological comfort occurs when a person is in thermal equilibrium, meaning the rate of heat loss matches the rate of heat generated by the body due to metabolic activity. Inadequate heat loss leads to a feeling of heat and humidity, causing heat stress, while excessive heat loss results in a sensation of cold. Hence, textiles need to be designed to facilitate optimal water vapor transmission while maintaining the necessary thermal insulation [12].

- Sensorial/Tactile Comfort

Sensorial comfort is not directly linked to temperature balance but is primarily associated with the sensation experienced by an individual when clothing is worn against the skin. The main contributors to sensorial discomfort are the feelings of wetness and clinginess, particularly in situations of excessive sweating. When low moisture transport leads to skin wetness, an uncomfortable sensation arises as the clothing adheres to the body [12].

- Mobility

In active sports involving diverse physical activities, significant movements of various body parts occur. Consequently, sportswear needs to ensure an adequate level of mobility, enabling wearers to engage in their activities seamlessly without hindrance. Excessively voluminous, heavy, or rigid fabrics are unsuitable for active sports applications, as they impede both the fabric's flexibility and the individual's freedom of movement [12].

- Psychological Comfort

Psychological comfort refers to the wearer's perception that they are appropriately dressed. This aspect is primarily associated with aesthetic appeal, considering style and fashion. While it does not actively contribute to functional performance, individuals, ranging from top-level professional athletes to amateurs, generally value psychological comfort in addition to the three functional comforts [12].

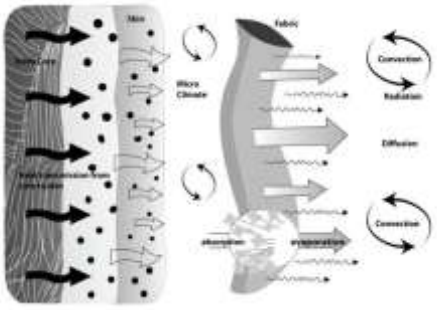

Fig. 1 - The transmission of heat and moisture vapor from the human body to the environment through fabrics **[12].**

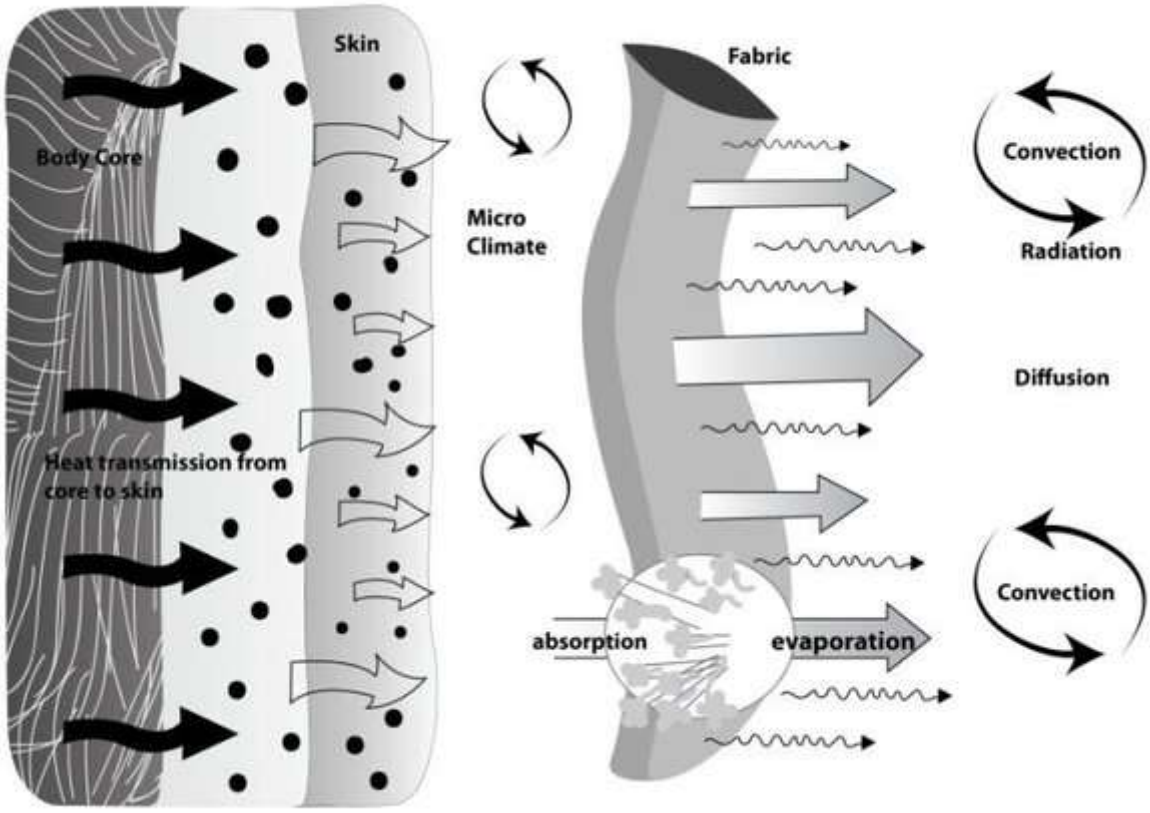

Table 1 - Functional Requirements For Sportswear According To A Specific Sport [14]

Sportswear	Fibers	Functional Requirements
Shirts And Track Suits (Running, Volleyball, Tennis, Basketball, Football, Golf, Rugby, Etc.)	Cotton, Polyester, Nylon, Spandex, Polypropylene	Sweat Absorption, Rapid Drying, And Cooling Features, UV Protection, Odor Resistance
Wind Breakers	Nylon, Polyester, Gore-Tex, Microfiber	Permeability To Moisture Vapor, Waterproofing, Moisture Vapor Permeability, Waterproofing.
Swimwear, Tri Suits	Nylon, Spandex, Lycra, Polyamide	Resistance To Chlorine and Sunlight, Quick Drying, Colorfastness
Rainwear	PU, PVC, EPTFE, DWR, Neoprene, Nylon Ripstop	Waterproofing, Durability, Quick Drying

3.1. Factors Affecting Thermal Comfort Properties

Thermal comfort, tactile comfort, and psychological comfort represent three crucial facets of human clothing, typically linked to the regulation of heat, liquid moisture, and air transportation through textile materials. The objective is to maintain the wearer's dryness while ensuring a constant body temperature of 37±1ºC **[**11]. Considering the T-shirt's structure, sweat concentration varies across different body areas. The sides exhibit lower moisture compared to the central part, suggesting the need for innovative fabric and design placement. When wearing a regular-fit T-shirt, the upper regions, in direct contact with the body, experience higher sweat concentration, particularly in the upper and mid-back areas. Notably, the posterior torso, specifically around the spine, exhibits the highest sweat accumulation. Sweating pattern measurement techniques were conducted in controlled laboratory settings by trained personnel, utilizing expensive equipment and intricate sampling procedures. In the contemporary era, groundbreaking wearable sensors based on skin have emerged, offering a continuous and portable means to assess dynamic sweating **[**12]. Sweat Rate between the right and left sides of the body were noted across various body regions. In the older group, the right posterior lower arm exhibited significantly higher Sweat rate compared to the left during both rest and exercise. Among the young group at rest, the right shoulder, side, and lateral upper leg showed significantly higher sweat rate than the left side. During exercise in the young group, this difference was evident at the anterior and posterior lower arm and the lateral lower leg. After corrections, right-to-left differences were only noticeable at the posterior lower arm in the young group during the exercise period. During passive heating (rest), younger individuals exhibited higher sweat rates at all body regions, with significance noted mainly at the torso and all regions at the legs and feet. In the exercise period, young individuals demonstrated significantly higher sweat rate than the older group, particularly at the lateral ankle and the feet, during the exercise period were significantly higher than rest at all body regions in both age groups **[**15]. The thermal insulation of clothing decreases because of perspiration, with a reduction ranging from 2% to 8%. This decline is attributed to the accumulation of water within the clothing, potentially leading to the "after chill" effect for wearers following intense exercise. The sensorial or tactile comfort of sportswear on the skin is influenced by factors such as surface friction, roughness, and softness. Given that the skin is the body's largest organ and more susceptible to injury during sports activities, issues like chafing become prevalent. Chafing occurs due to the mechanical rubbing of the skin against clothing or other skin areas. Additionally, skin abrasion, involving the removal of skin cells during rubbing against external surfaces like synthetic turf, poses another risk of skin injury in active sports [13].

3.2. Factors Affecting Moisture Comfort Properties

The process through which moisture is conveyed in textiles mirrors the capillary action involved in liquid wicking. Capillary action within a porous material is influenced by two fundamental properties: the diameter of the pore and the surface energy of the material. Smaller pore diameters or higher surface energy of the material enhance capillary action. In the structure of textiles, the spaces formed between fibers in yarn create effective capillaries. The incorporation of micro-size fibers contributes to the formation of narrow capillaries, facilitating efficient moisture transport. The surface energy of textile material is predominantly influenced by the chemical composition of the fiber-forming polymer, coupled with the surface texture of the fabric.

Effectively managing moisture in textiles during intense physical activities poses a significant challenge that must be addressed to ensure comprehensive comfort for athletes [16].

Fabrics create a microclimate between the body and the atmosphere, serving as a conduit for heat and vapor exchange between the skin and the environment. Moisture transmission through the fabric primarily involves three processes: diffusion of moisture, sorption-desorption, and forced convection through moving air near the skin. In hot and humid conditions, it is crucial for clothing to swiftly absorb moisture and efficiently transport it through the fabric to the environment, employing wetting and wicking actions for the player's comfort. Wetting action initiates the spread of fluid on textiles, replacing the fiber-air interface in the fabric. Wicking action, determined by surface tension, effective capillary pathways, and pore distribution on fibers, involves molecular attraction between fibers and liquid at the fabric surface. The physical comfort of the body is closely tied to skin temperature and moisture content in the environment, both significantly influenced by the level of physical exertion. The type of fabric plays a vital role in regulating skin moisture.

Primarily, the comfort aspect of clothing is influenced by the wetness or drying of the fabric and the thermal conditions within that specific micro-climate. Consequently, sports garments worn close to the skin should exhibit effective sweat absorption, transmission, and desorption properties. In terms of moisture management, certain textile manufacturers advocate for absorbent fibers like cotton or viscose, emphasizing their ability to readily absorb liquid moisture. On the other hand, some argue that fibers for sports applications should not absorb moisture but instead enable rapid wicking through capillary action. In this context, synthetic fibers are often favored over natural fibers such as cotton, ramie, and flax, as they do not retain moisture, keeping the garment dry and lighter in wet conditions. Additionally, wet synthetic fibers tend to dry faster due to their lower liquid absorbency [13]**.**

3.3. Natural And Synthetic Textile

Sports clothing incorporates various fabrics, ranging from natural fibers derived from plants and animals (e.g., cotton, wool) to synthetic fibers produced through chemical synthesis (e.g., polyester, nylon). Each fabric possesses unique strengths and limitations concerning thermoregulation and comfort, influenced by its inherent material properties. Sportswear encompasses a variety of commercially available fabrics, including woven, knitted, and nonwoven types. These fabrics exhibit distinct structural characteristics such as entrapped air, pore shape and size, bulk, and surface properties, all of which can impact their heat and moisture transmission characteristics. Knitted fabrics are typically preferred for sportswear due to their superior elasticity and stretch compared to woven fabrics. This quality ensures unrestricted freedom of movement and facilitates the efficient transmission of body vapor to the next layer in the clothing system. With ongoing developments in fabric construction and the introduction of novel fabric and yarn combinations,

knitted fabrics are increasingly regarded as the optimal choice for the base of active sportswear. Knitted garments, often worn directly against the skin, merit special attention. However, a common challenge in both woven and knitted fabrics is their tendency to adhere to the athlete's body due to sweat, causing discomfort during activities like running. The term "sportswear" encompasses garments specifically designed for sports activities. To enhance athlete performance, sportswear must excel in body thermoregulation and moisture management, aspects heavily influenced by the selection of fibrous materials and structures [17,18].

Natural textile materials, including cotton and wool, are generally known for their softness, smooth texture, and breathability. They excel in absorbing and wicking away moisture, contributing to the dryness and comfort of athletes. However, these materials may have lower durability and water resistance compared to synthetic counterparts.

Synthetic textile materials, such as polyester, nylon, and spandex, offer increased durability and water resistance. They can be engineered to possess specific performance attributes like moisture-wicking, breathability, and thermal regulation. Polyester blends are particularly noteworthy for their effective moisture-wicking capabilities, efficiently drawing sweat away from the body during physical activity. Nylon, known for its durability, enhances fabric strength for prolonged use in high-performance sportswear. Spandex or elastane contributes essential stretch and flexibility, allowing unrestricted movement for athletes [19]. Nylon, another commonly utilized synthetic material in sports clothing, exhibits superior moisture absorption and enhanced wicking capabilities compared to polyester. Nylon tends to have a slower drying rate **[**20].

The choice of synthetic fibers in sports textiles depends on the intended use. For instance, a base layer designed for cold weather may incorporate synthetic fibers with excellent thermal insulation properties, such as polyester. Conversely, a running shirt crafted for hot weather is likely to be made from a synthetic fiber with superior wicking properties, like microfiber polyester.

3.4. Fibers Used For Sportswear.

3.4.1. Cotton

Cotton, a naturally occurring cellulosic fiber derived from the biological species Gossypium within the Malvaceae family, possesses remarkable comfort qualities. However, the increased absorption and retention of moisture within cotton fibers have resulted in a noticeable decline in their use for manufacturing sportswear. This has impacted athlete comfort as, although cotton provides outstanding comfort when dry, it becomes heavier and stickier after absorbing sweat, causing increased discomfort for the wearer **[**21]. In recent years, there has been a decline in the use of cotton fibers for sportswear production primarily due to their heightened absorption and retention of moisture. While cotton exhibits excellent comfort properties in dry conditions, the discomfort arises when cotton garments become wet or damp during physical activity, causing them to become heavy and sticky. A potential solution lies in incorporating a combination of cotton with synthetic fibers, favoring blends with a higher proportion of cotton fibers. Alternatively, water-repellent treatments can be applied to cotton to mitigate its water absorption, enhancing the overall comfort of the textile fabric [22].

3.4.2. Wool

Fine wool fibers, such as merino wool, are commonly utilized in running apparel and cycling wear. Merino wool fibers exhibit hydrophilic properties, exceptional wicking capabilities, rapid drying, and contribute to the maintenance of the body's natural cooling system. These fibers possess excellent absorption properties, supporting the body's natural thermoregulatory system across various climatic conditions. Despite wool's relatively lower strength, it boasts good durability and intermittent elongation, with up to 50% in the wet state and 30% in the dry state. Conventional wool fibers typically range from 35 to 350 mm in length, depending on the type, while Merino wool fibers have a length ranging from 60 to 110 mm. Additionally, these fibers display favorable air and water vapor permeability, odor control, environmental acceptability, and renewability [23].Cycling and running apparel often incorporate wool and other fine wool fibers due to their hydrophilic nature, excellent wicking capabilities, quick-drying properties, and ability to support the body's natural cooling system. Fine merino wool fibers, renowned for their remarkable absorption qualities, play a crucial role in maintaining the body's natural thermoregulatory system across various environmental conditions **[**24].

3.4.3. Polyester

The predominant material used in sportswear is polyester knitted fabrics, a synthetic fiber produced through polycondensation reactions involving monoethylene glycol and PTA (Pure Terephthalic Acid). For PET polymer, two favored processes are esterification and transesterification. The manufacturing of polyester fiber and filament commonly employs continuous polymerization and melt spinning. PET fibers exhibit a density of 1.38 g/cm3, impressive mechanical properties, and versatility for various textile applications. Polyester fibers can be produced in different cross-sections, such as round, hollow round, trilobal, hollow trilobal, and bicomponent. Additionally, polyester showcases exceptional thermal stability or heat resistance. The unique cross-sectional features of fibers and filaments play a significant role in moisture transportation phenomena, contributing to enhanced athlete comfort [25].

3.4.4. Elastane

Elastane fibers, known for their elastic elongation and remarkable ability to recover their original shape after stretching, can be stretched at least three times their length and return to their initial length once the load is released. Among elastane fibers, the most significant types are elastane and elastodiene fibers. The well-known elastane fiber, often recognized by the trade name Lycra (DuPont), is categorized under the general name Elastane in German-speaking areas and as Spandex in English. These fibers can stretch up to 700% with an elastic recovery of 95%. The key property of elastane fibers or filaments is their high tensile elasticity, with breaking elongation values ranging between 300 and 700%, and an elastic recovery reaching 95%. Elastane filaments are seldom used independently and are more commonly incorporated into yarns twisted with natural or other man-made fibers **[**26].

3.4.5. Lycra

Lycra, a long-chain synthetic polymer fiber containing 85% segmented polyurethane, is widely utilized in floor gymnastics, active sportswear, and swimwear due to its ease of wear and comfort. The stretch recovery feature of Lycra adds value to sports fabrics used in gymnastics and swimming, particularly in situations where the flexing and stretching of the body's skin are unavoidable [27].

3.4.6. Hollow fiber

A hollow fiber refers to a filament or staple fiber containing one or more axially implanted hollow (air) cores, developed to mimic the lumen structure found in cotton fibers. While technological advancements enable the creation of hollow fibers from practically all synthetic fibers, polyester and polyamide hollow fibers are most used in athletic apparel. These fibers may feature a trilobal, square, hexalobal, or circular cross-section. In addition to exhibiting superior bending and torsional (twisting) capabilities compared to regular fibers, hollow fibers offer enhanced heat insulation. They are frequently employed in the production of clothing with thermal protection qualities and for various winter sports apparel. The lightweight nature of these fibers is attributed to the voids present in their structure **[**28]. The fiber known by the trade name Thermolite is highly favored in the manufacturing of winter sportswear. This polyester fiber effectively "captures" air within its cavities, delivering warmth and comfort. Thanks to the hollow fibers and their substantially increased specific surface area, sweat can evaporate rapidly. This feature contributes to the textile fabric made from these fibers drying up to 50% faster than cotton textiles **[**29].

3.4.7. Microfiber

Microfibers, manufactured fibers characterized by high linear densities typically less than 0.4 dtex and available in polyester and nylon, offer a soft feel, high strength, and durability. These microfibers are water-repellent and possess good air permeability, collectively contributing to the development of comfort features. The elevated fineness of microfibers results in increased porosity, enhancing the textile material's capability to expel water vapor and regulate temperature effectively [30]**.** Microfibers are predominantly found in polyester and polyamide fibers, although they can also be composed of acrylic, polypropylene, and cellulose. In addition to their high aesthetic appeal, microfibers offer specific properties to textile materials, depending on the manufacturing technology employed. These properties include water repellency and impermeability, coupled with excellent air permeability, resulting in enhanced comfort compared to standard fiber types and superior mechanical characteristics [31].

3.5. Recent Development Fibers For Sports Application

Cooling textiles are specialized fabrics designed to regulate body temperature and enhance comfort. They fall into two categories: passive, which operate without external power and are energy-efficient, and active, offering precise temperature control but with higher costs. Despite the growing demand, challenges persist in manufacturing truly wearable cooling textiles. This review systematically explores current trends in cooling technologies, addressing materials, design, fabrication, and applications. It discusses various cooling methods, both passive and active, and highlights challenges and future perspectives to encourage further research in this emerging field [32].

3.5.1. Phase Change Material

Thermoregulated fibers enhance comfort by absorbing or releasing heat, helping maintain skin temperature within a narrow range. These fibers contain phase-change materials (PCMs) that undergo a physical state change when heated or cooled. Over 500 natural and synthetic PCMs, with varying heat capacities, are available, with paraffin being commonly used in textiles. NASA first applied PCMs in smart materials for space garments in the 1980s. Today, these fibers are used in sportswear, such as sports underwear and active wear. Incorporating microencapsulated PCMs during melt-spinning improves thermal insulation without adding thickness. Coating or laminating PCMs onto fabric affects mechanical properties, increasing stiffness and weight. While PCM use is widespread, short-term effects, like a temporary cooling effect, are observed in some applications **[**33].

Phase Change Materials (PCMs) are under development for sportswear, incorporating a chemical that transitions from a liquid to a gel state at approximately body temperature. This transformation modifies the fabric's insulation properties, allowing the creation of garments that maintain a constant body temperature regardless of external air conditions. These materials find application in cold weather protective gear such as gloves, boots, and hats. Phase change materials generate microcapsules filled with paraffin. Upon heating, the paraffin liquefies, storing heat energy. As the environment cools, the paraffin crystallizes again, releasing stored heat. The paraffin, available in various formulations with different melting points, serves as the phase change material (PCM). The versatility of paraffin formulations with distinct melting points enables the design of microcapsules to keep the wearer either warm or cool [34].

3.5.2. Killat N

Killat N, manufactured by Kanebo Ltd., is a nylon hollow filament where approximately 33 percent of the cross-section of each filament is hollow. This design imparts excellent water absorbency and heat retention properties. The yarn is created as a bi-component filament, with a soluble polyester copolymer serving as the core material and nylon as the sheath material. After the spinning process, an alkali treatment dissolves the polyester copolymer in the bi-component filament, resulting in the production of a hollow fiber. This hollow section facilitates capillary action for liquid transport and provides a warm feel due to the presence of an air pocket **[**35].

3.5.3. Hygra

Unitika Limited has introduced Hygra20, a sheath-core type filament yarn consisting of fibers crafted from a water-absorbing polymer and nylon. The unique network structure of the water-absorbing polymer enables it to absorb 35 times its own weight of water and provides rapid releasing properties that conventional water-absorbing polymers lack. Meanwhile, the nylon core contributes to tensile strength and dimensional stability. Hygra20 exhibits excellent antistatic properties even in low wet conditions. This filament yarn finds application in various sportswear categories, including athletic wear, skiwear, and golf wear **[**35].

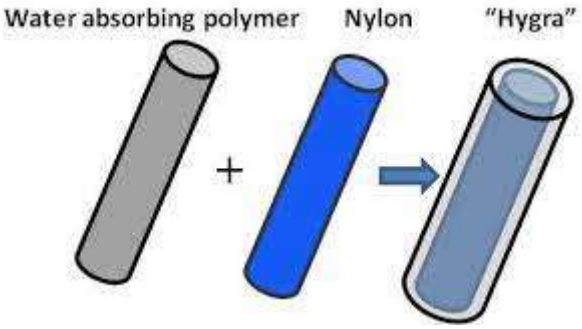

Fig. 1 - Schematic of mechanism of Hygra fibre[14]

3.5.4. Lumiace

Lumiace, another offering from Unitika, comprises polyester filaments with varying fineness (ranging from 0.5 to 2.0 denier per filament) and irregular cross-sections. The combination of Hygra and Lumiace in knitted fabric is highly favored among top Japanese athletes [35].

Unitika, a renowned material developer, has introduced Lumiace, a unique polyester filament specifically designed to elevate the wearability and performance of athletic apparel. Lumiace's defining characteristic lies in its variable fineness, ranging from 0.5 to 2.0 denier per filament. This variation contributes to a fabric with an exceptionally soft and luxurious feel. Unlike conventional round polyester fibers, Lumiace incorporates non-uniform, irregular cross-sections. This unique textural characteristic expands the surface area of the fibers, significantly enhancing their moisture-wicking and quick-drying capabilities. The aforementioned properties of Lumiace have positioned it as a preferred material for athletic clothing, particularly when combined with another Unitika innovation, Hygra. Top Japanese athletes specifically favour the combination of these two materials in knitted fabrics, attributing their preference to the perceived benefits. The combination is believed to deliver superior comfort due to the inherent softness and flexibility of Lumiace, translating to a more comfortable feel against the skin. Moreover, the exceptional moisture-wicking and quick-drying properties of Lumiace are believed to aid athletes in staying cool and dry during exercise, potentially leading to improved performance. Furthermore, the combined use of Lumiace and Hygra is believed to excel at moisture management, ensuring athletes' comfort and dryness throughout their activities.

3.5.5. Dacron

Dacron 4-Channel Polyester is a broad term referring to a high-performance four-channel fiber designed to efficiently transfer moisture and accelerate the evaporation of perspiration. This fabric excels in wicking action, drying time, as well as moisture absorption and transport. It stands out as a superior material for these properties.

Pioneered by DuPont in the 1950s, Dacron revolutionised the textile industry as the first widely available polyester fiber. Produced in Kinston, North Carolina since 1953, it's renowned for its exceptional durability, resilience, and versatility. Dacron's strength and resistance to wear and tear make it ideal for demanding applications, while its ability to retain shape minimises wrinkles and simplifies care. Additionally, its versatility allows seamless blending with other fibers to create diverse fabrics with varying properties, and its vast dye compatibility opens doors to a vibrant spectrum of colours. Through a process called polymerisation, Dacron transforms from its chemical state into long, versatile fibers used in a wide range of applications, including clothing, home textiles, industrial fabrics, and even medical textiles. This unique combination of desirable properties has solidified Dacron's position as a popular and valuable material across various industries, making it a cornerstone of the textile world [36].

3.5.6. Roica and Leofeel

Roica, a polyether-type spandex produced through dry spinning, and Leofeel, a soft nylon-66 yarn developed by Asahi Chemical, when combined in a mixed knitted tricot fabric, provide a soft touch and exceptional stretch. This combination is primarily utilized in the manufacturing of swimwear.

Asahi Kasei, leading a Japanese Innovator in materials, has developed two distinct fibers catering to different needs in the textile industry Roica is a premium stretch yarn, marketed under the brand name ROICA™, is essentially an improved version of spandex or elastane. Manufactured using the dry spinning technique, renowned for its quality and consistency, Roica offers exceptional elastic stretch and recovery, allowing garments to move freely while retaining their shape. Its high quality translates to durability and lasting performance, making it a popular choice across various applications. Asahi Kasei also emphasises its commitment to responsible manufacturing and circularity with Roica.

Leofeel , is a unique fiber, developed specifically for its softness and comfort, is a soft nylon-66 yarn. Its exceptional softness provides a luxurious feel against the skin, while the inherent properties of nylon-66, like strength, durability, and wrinkle resistance, add to its benefits. Leofeel primarily finds application in apparel, particularly for garments where comfort is paramount, such as swimwear, delicate lingerie, activewear tops and leggings. However, compared to Roica, readily available information about Leofeel is limited, suggesting it might be a specific product line within Asahi Kasei or potentially discontinued. If you require specific details about Leofeel, contacting Asahi Kasei directly might be the best option [37].

3.6. Recent Development Fabrics For Sports Application

3.6.1. Entrant Dermizax EV

Entrant Dermizax EV" is a lightweight fabric renowned for its remarkably smooth texture, offering outstanding waterproof and moisture permeability along with durable water repellency. With a water pressure resistance of 20,000 mm and moisture permeability reaching 30,000 g/m2 /24 hours, it stands as an exceptional active sportswear fabric. Globally recognized for its top-class waterproof and moisture permeability properties, it effectively maintains durable water repellency, making it a premier choice in the realm of performance fabrics for outdoor activities.

Entrant Dermizax EV is a lightweight fabric specifically designed for outdoor activities, manufactured by the Japanese company Toray Industries, which has a long history of developing innovative textile technologies. It boasts an exceptionally smooth texture, offering unparalleled comfort against the skin. Beyond its comfortable feel, Dermizax EV truly shines in its exceptional performance. It delivers outstanding waterproof protection with a water pressure resistance of 20,000 mm, meaning it can withstand significant amounts of rain and snow. At the same time, it maintains impressive breathability, measured at 30,000 g/m²/24 hrs. This allows moisture vapour to escape efficiently, preventing you from feeling clammy and uncomfortable during high-exertion activities. Additionally, Dermizax EV features durable water repellency (DWR), which helps water bead up and roll off the fabric surface, further enhancing its weather resistance. Entrant Dermizax EV combines exceptional waterproofness, breathability, and comfort, making it a top choice for a variety of outdoor activities, from hiking and mountaineering to trail running and cycling[38].

3.6.2. Toray

Toray has innovated with "H2OFF," a fabric crafted from polyester microfiber. This fabric boasts a distinctive high-density weave structure, incorporating millions of micro-crimped fiber loops. Notably, it offers exceptional and long-lasting water repellency, superior breathability, wind-chill resistance, and an appealing soft touch.

Toray, a leading Japanese multinational corporation known for its innovative materials science and engineering, has introduced "H2OFF," a revolutionary fabric crafted from polyester microfibre. Manufactured in Japan, H2OFF boasts a unique high-density weave structure, incorporating millions of micro-crimped fiber loops. This innovative construction empowers H2OFF with exceptional and long-lasting water repellency, superior breathability, and wind-chill resistance, all while maintaining an appealingly soft touch.H2OFF's exceptional properties make it a versatile fabric ideal for various applications, including outdoor apparel, sportswear, and even everyday clothing. Its water repellency keeps users dry in wet conditions, while its breathability allows for optimal moisture management and comfort during physical activity. Additionally, H2OFF's wind-chill resistance provides extra warmth in colder environments, and its soft touch ensures a comfortable wearing experience [38].

3.6.3. Entrant HB

"Entrant HB" is a new-generation fabric with a hybrid structure that synergistically integrates the advantages offered by a coating (well-balanced moisture permeability) and lamination (high waterproofness). It has high resistance to water pressure and high durability against repeated washings (80 points or higher after 20 wash cycles). Its main application is outdoor wear.

Pioneered by the Japanese company Toray, situated in Tokyo, Entrant HB is a revolutionary fabric technology pushing the boundaries of outdoor gear performance. This hybrid marvel seamlessly combines the strengths of both coating and lamination processes. A material boasting exceptional waterproofness, exceeding 30,000mm in water pressure resistance, while simultaneously maintaining excellent breathability, crucial for keeping you comfortable during intense activities. Additionally, Entrant HB demonstrates remarkable durability, retaining over 80% of its water resistance even after

20 washing cycles, making it a reliable companion for your toughest adventures. This innovative fabric is quickly becoming the go-to choice for leading outdoor apparel manufacturers, ensuring you stay dry and comfortable no matter the weather throws your way [39].

3.6.4. Entrant DT

"Entrant DT" is a microporous coated fabric that provides a smoother and refreshing dry touch, coupled with an appealing appearance achieved through innovative inner surface treatment technology. The coated membrane incorporates printed patterns, contributing to the improved dry touch. This fabric is characterized by its lightweight design, easy packability, and high levels of breathability and waterproofness.

Developed by Textile Innovation Corporation, a company headquartered in South Korea, Entrant DT is a microporous coated fabric designed to deliver exceptional comfort and performance. This innovative material boasts a smooth and refreshing dry touch, thanks to a combination of its microporous coating and a unique inner surface treatment technology. Additionally, Entrant DT features printed patterns incorporated into the coated membrane, further enhancing its visual appeal. Notably, this fabric is lightweight and packs easily, making it ideal for various applications. Furthermore, it offers excellent breathability and waterproofness, ensuring optimal comfort during wear [40].

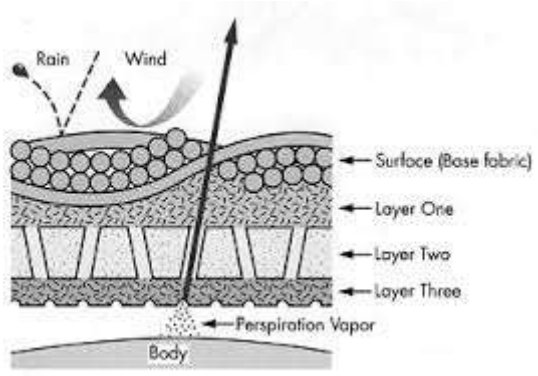

Fig. 1 – Entrant DT [40]

3.6.5. Field Sensor21

Field Sensor21, a highly sought-after high-performance fabric by Toray, utilizes a multilayer structure designed to swiftly absorb perspiration and rapidly transport it to the outer layer of the fabric through capillary action. The fabric features coarser denier yarn on the inner surface, in direct contact with the skin, and fine denier hydrophobic polyester yarn in a mesh construction on the outer surface, facilitating the accelerated evaporation of sweat.

Developed by Toray Industries, Inc. in Japan, Field Sensor is a highly sought-after high-performance fabric renowned for its exceptional moisture-wicking properties. This innovative material employs a unique multilayer structure that efficiently manages sweat during physical activity. The inner layer, composed of coarser denier yarn, provides a comfortable next-to-skin feel while effectively absorbing perspiration. This moisture is then rapidly transported through the fabric's core, leveraging capillary action, to the outer layer. This outer layer, constructed from fine denier hydrophobic polyester yarn in a mesh design, facilitates the swift evaporation of sweat, keeping athletes cool and dry. Field Sensor's exceptional moisture management capabilities make it a popular choice for athletes and active individuals seeking to stay comfortable and focused during intense workouts or competitions. The fabric's innovative design not only enhances performance but also contributes to a more enjoyable and hygienic experience during physical activity [41].

3.6.6. Soft Shell

Soft shells produced by the company are versatile and well-suited for a variety of leisure activities. These products feature qualities such as air permeability, lightweight, wind resistance, and stretch fabric constructions, making them highly suitable for "next-to-skin" applications. There are four types of Soft-shell fabrics available: (a) Ultralight, which consists of woven fabrics with a synthetic outer and cotton inner layer, (b) Efficient, incorporating double-weave fabrics with a synthetic outer and functional inner layer, (c) Warming, comprising a synthetic outer and wool inner layer, and (d) All-in-one, where Schoeller WB-400 fabric consists of a synthetic outer layer and various lining variants sandwiching a functional coating.

Developed by a leading outdoor apparel brand in the 1980s, a unique type of fabric has become popular among active individuals due to its impressive combination of comfort and performance. This innovative material offers several key benefits, making it a versatile choice for various outdoor activities. The fabric boasts remarkable breathability, allowing for excellent air circulation while maintaining a lightweight feel. Additionally, it effectively shields against wind, keeping wearers comfortable in breezy conditions. The inclusion of stretch fabric constructions further enhances mobility and comfort, making it ideal for "next-to-skin" applications.

This versatile material comes in four distinct types, each offering specific advantages:

- **Ultra-light:** Featuring a woven construction with a synthetic outer layer and a breathable inner layer, this option priorities lightweight comfort for warm-weather activities.
- **Performance-driven:** This type utilises double-weave fabrics with a synthetic outer layer and a functional inner layer, providing exceptional breathability during high-activity pursuits.
- **Warmth-focused:** This option combines a synthetic outer layer with a natural wool inner layer, offering an ideal blend of warmth and breathability for cooler conditions.
- **All-in-one:** This advanced option utilises a unique Schoeller WB-400 fabric construction, featuring a synthetic outer layer, various lining options, and a functional coating, delivering comprehensive protection and versatility.

This innovative fabric provides outdoor enthusiasts with a reliable and comfortable solution for various activities, making it a valuable addition to any outdoor gear collection [42].

3.7. Sports Basic Wear

The human body strives to maintain its core temperature at 37±1ºC, and this is regulated through four mechanisms of heat transfer: conduction, convection, radiation, and evaporation. In sports activities, approximately 80% of energy is converted into heat. In hot conditions, where the air temperature exceeds the body's core temperature, the body relies on evaporation to dissipate heat and regulate its temperature. The effectiveness of this heat loss is influenced by the rate of sweat evaporation, which, in turn, is contingent on atmospheric conditions. In warmer climates, the sweat rate can increase significantly, reaching up to 2.5L/h due to heightened metabolic activities in active sportswear. This increased sweat rate contributes to higher convective and radiative heat loads. Researchers have observed that fabrics with superior moisture absorption capabilities enhance the performance of players [14].Inner fabric layers in active applications, the preferred characteristics include good thermal conductivity, effective moisture management, and favorable tactile properties. A base layer fabric with good thermal conductivity can enhance cooling efficiency, while superior moisture management and tactile properties contribute to the necessary comfort for the wearer. Research assessing the human body's thermoregulatory response to base layers with hot and cold garments revealed that synthetic base-layer garments were more effective than cotton garments in actively reducing moisture retention while maintaining desired skin temperatures. It was emphasized that, during sports activities, effective control of body temperature for comfort necessitates the simultaneous dissipation of heat produced through the base layers of the fabric. Depending on the sport, the human body is anticipated to produce half to one liter of perspiration per hour. Therefore, base layer fabrics should absorb and efficiently dissipate heat and moisture to achieve a high level of comfort.

In addition, studies reported that blending wool with polyester fiber and bamboo fibers resulted in improved moisture management properties, with liquid moisture absorption rates increasing to 20% and 35%, respectively, with a 50/50 blend ratio. Another investigation into the moisture management properties of double-face knitted fabrics found that polypropylene x cotton fabric on the inner and outer face exhibited superior moisture management properties [43].

The effects of oversized and correctly fitted compression garments on thermoregulation and comfort were analyzed. Both fitted and oversized compression garments resulted in significant increases in skin temperature and had negative impacts on thermal comfort and thermal sensation compared to exercise shorts. However, no significant differences were observed between oversized and fitted garments. The negative effects of compression garments during exercise could be attributed to greater body coverage, as more of the skin's surface is covered by material, negatively impacting heat transfer from the body to the environment. On the contrary, the lack of significant differences between oversized and correctly fitted garments may be explained by similar amounts of pressure exerted by the compression garments, as both were considered tight-fitting. Clearly, future research is required to compare the effects of tight-fitted and loose-fitted clothing on microclimate, thermoregulation, and overall comfort. Such investigations could provide clothing recommendations regarding fit and skin coverage for athletic and recreationally active populations exercising in specific environmental conditions **[44].** Ergonomic comfort is contingent upon the fit, allowing freedom of movement, and is influenced by fit design, fabric elasticity, and pattern construction. In dynamic sports activities like running, the skin undergoes extension and contraction due to the extensive body movement, leading to changes in body measurements. It is imperative for sportswear to accommodate these movements, as restricting them could result in discomfort caused by undue garment pressure on the body. The use of elastic fabric is a common practice in the construction of tight-fit running shorts, ensuring both the desired shape and size while providing ample room for unrestricted body movements **[**13].

A. Introduction

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J. Recent Development Fabrics For Sports Application

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