Textile materials intended for sportswear

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Review

Active sportswear is clothing of certain functions with the aim of ensuring the expected properties of certain sports. An important aspect of sportswear is thermal physiological comfort, especially when sports activities take place in demanding atmospheric conditions (at high or low temperatures) over a long period of time. Proper selection of clothing can significantly reduce the dynamic and thermal loads of athletes. Innovations in textile science and technology is focused on research into the development of fibres of high and special properties for various applications. So, a lot of investment in technological innovations of textile materials from fibres, yarns to fabric and 3D textile structure which results in improved performance of sportswear. In addition, much attention is paid to design that also contributes to improving the performance of sportswear. Here, it will be pointed on significant achievements in the field of sportswear intended for professional athletes. Various aspects that affect the comfort of clothing, the impact of different types of fibres, yarns and innovative structures of textile fabrics intended for the production of sportswear are discussed. Also, special emphasis is given to innovations in the field of jerseys with cooling effect.

Keywords: *sportswear, special fibre properties, textile structures, clothing with cooling effect, thermo-physiological comfort of clothing*

1. Introduction

Sportswear plays an important role in athlete achievements. The performance of sportswear is influenced by the thermodynamic, aerodynamic and/or hydrodynamic properties of the textile material. In addition, design has a significant impact on the performance of sportswear [1].

In recent years, especially great progress is noted in the field of fibres for the manufacture of premium sportswear and sport equipment. With the advancement of technology and the development of high-performance materials, sportswear has improved properties, an emphasis is given to high aerodynamic and absorption properties, air and water permeability, strength and adhesion. Much has also been done in the field of design [2]. Sportswear is designed so that it does not restrict the athlete`s activity and provides him physical support while exercising.

According to the level of professionalism and purpose of use, sportswear can be classified into four groups: functional, basic, casual and fashion sportswear [3]. Functional sportswear is high properties clothing that enhances performance with special functionality. Thus, modern techniques and technologies of seamless knitting, which have opened up enormous possibilities of design and innovation (in terms of comfort, aesthetics and functionality) also contribute to improvement of sportswear [4]. Basic sportswear has a more appealing design [3], while casual sports-

Tab.1 Functional requirements for sportswear according to a specific sport

Sportswear	**Functional requirements**
Shirts and slacks for tenis, volleball, golf, footbool, basebool, athletic, track suits	Sweat absorbing, fast drying, cooling
Skiwear, wind breakers, track suits	Vapour permeability, water proofing, vapour permeability, water proofing, thermal insulation
Skiwear, wind breakers, track suits	Sunlight absorbing and thermal retention, Low fluid resistance
Swimming race and skating costume, ski jump and downhill skiing suits, cycling costume	Low fluid resistance for water and air
Snowboard wear, baseball uniform, football uniform	High tenacity, resistance to abrasion, stretchability

wear is a replica of functional sportswear, most often worn at home when no increased physical activity and sweating is expected [3, 5]. As a result of the cooperation of famous fashion designers, fashion houses and sports brands as well as professional athletes, fashion sportswear was created, in which the most attention is paid to modern design and likeability of clothing [2, 6-8].

Of course, the basic classification of sportswear is according to the sport for which it is intended. Depending on the sport there will be different requirements for functional properties. Some sports require more physical effort than others, i.e. they differ in the level of activity.

According to Chowdhury et al. [2] functional requirements for sportswear can be displayed according to a specific sport in Tab.1.

The basic characteristics of sportswear, which depend on a type of textile fibres, types and structures textile materials and design. The following properties are most commonly designed:

- thermal (thermoregulation),
- air permeability and water vapor,
- dimensional stability (often even in humid conditions),
- strength and durability,
- easy maintenance (care),
- comfort (convenience),
- design functionality.

The great popularization of healthy lifestyle and sports has led to a significant increase in the sports market over the last twenty years [3, 9]. American market research company Global Industry Analysts, Inc. predicts that the global sports and recreation clothing market will increase by about 26 % by 2024 [9].

2. Sportswear wearing comfort

Wearing comfort is one of the decisive criteria for assessing the quality of individual garments and is of great importance in the choice of clothing [10]. Comfort, which we feel while wearing clothes, is a subjective reaction that results from the action of various factors. The textile material from which the garment is made must have good porosity, so that when the body moves, the diffusion of water vapor through the pores towards the environment can take place. Clothing must enable thermal insulation in cold conditions, a high degree of moisture permeability and good ventilation to ensure optimum thermoregulation of the human body, as the body must be maintained in thermal equilibrium, i.e. the thermal energy created by metabolism and the energy obtained from the outside, must be equal to body's thermal energy loss. The result of balanced human-air-clothing interaction is expressed in human comfort when wearing clothing. In practice, often, especially in sports and activities, the heat of evaporation can't maintain balanced interactions, i.e. heat balance. This is reflected in the physiological response of the body, which secretes a larger amount of sweat, that can not evaporate from the surface of the body and therefore condenses. In order to achieve satisfying contact comfort, a condensed component must be removed as quickly as possible from the skin surface to the layers of clothing in to the environment. This is achieved by adsorbing moisture on the surface of the textile material and migrating it to further layers of textile material and by capillary transfer through the pores of fibres and yarns. Both mechanisms depend on the fibre's properties, the fineness of fibres and yarns, their surface characteristics, and the structural characteristics of the yarn and the textile material.

Therefore, the requirements that clothing as well as sportswear must meet are based on the following criteria [11]:

1) Physiological function, which is expected to ensure the thermal balance of the wearer;
2) Skin sensory comfort;
3) Ergonomic function: clothing must maintain ergonomic comfort;
4) Aesthetic function: clothing must meet fashion requirements (color, cut and design).

From the thermophysiological comfort point of view, clothing can be viewed as the so-called "quasi-physiological" system, which exchanges body's and environmental heat and ensures a good microclimate between the body and the environment [11]. Clothing with good thermophysiological properties must allow thermal and physiological equilibrium with a minimum body load under different climatic conditions and different physical activities of the wearer. This means that the person in the clothing feels neither cold nor warm but thermophysiological comfort [12]. The influence of clothing on human heat load at different physical loads and different combinations of climatic quantities can be experimentally determined by measuring physiological parameters: skin temperature, heart rate, amount of sweat excreted, and subjective assessment of thermal comfort. Human body temperature is an important indicator of heat-related characteristics, such as comfort, stress caused by heat, or cold [12].

Two physiological parameters play a significant role in the study of thermophysiological comfort of man: the average skin temperature (determines the comfort of clothing in cold conditions) and the amount of sweat excreted on human skin (determines the comfort of clothing in warm climates) [13].

Moisture management of fabrics intended for sportswear production has crucial role in determination of comfort level [14]. Athlete can produce up to 2.5 l/h of sweat in extreme environment conditions [15]. Moisture is transported through textile material by two related processes, wetting and wicking [14]. In the moment when the moisture gets in the touch with the fabric, wetting occurs. This process is carried by air and liquid interface with textile material. Studies of wettability are based on the measurement of contact angles, which refers to the degree of wetting when the liquid and the material are interacting [17]. Wettability of the textile material depends on different fibre properties as well as surface properties of textile materials [18-20].

Liquid is further transferred through textile material by the capillary action or wicking. Wickability depends on fibre type, yarn construction, fabric structure, finishing treatment, as well as relative humidity of the atmosphere and ambient temperature [16, 21].

Skin sensorial comfort, which is specified by the mechanical contact of the textile material and the skin, is determined by the satisfaction (or discomfort) of the wearer in the moment when the skin is in contact with garment i.e. how our basic senses perceive textile material. In addition to the surface properties of the textile material, this type of comfort can be influenced by factors such as attractiveness of the garment or even smell or sound of fabric [22]. On the contrary, ergonomic comfort is specified by freedom and possibility of unhindered movement. Movements such as flexion, extension and abduction are important factors in product development for high performance sportswear. The main aspects, which affect the ergonomic comfort, are design and construction of the garments as well as elasticity and thickness of the textile material [11]. Sportswear should allow unhindered movement of the athlete, otherwise, unpleasant sensation and pressure on the body may occur [23].

3. Fibres used in production of sportswear

The most commonly used fibres in the production of sportswear are: polyester, polyamide, cotton and merino wool fibres, elastane and their mixtures [24].

3.1. Polyester fibres

Active sportswear is most often made of polyester knitted fabrics [25]. Polyester fibres (PES) are man-made fibres made of synthetic polymers. The fibres consist of linear polyester macromolecules in which the mass fraction of diol esters and terephthalic acid is at least 85 % [26]. There are many different types of polyester fibres. The majority of polyester fibres are produced from poly(ethylene-terephthalate) (PET), obtained by polycondensation of terephthalic acid or dimethyl terephthalate, with 1,2-ethanediol. Most often, polyester fibres are produced as continuous filaments by a chemical melt spinning process, with spinning speeds of 1000 to 7000 m/min [27]. The density of PET fibres ranges from 1.36 to 1.41 g/cm^3, while these values for polybutylene terephthalate (PBT) and polycyclohexane terephthalate (PBT) fibres range from 1.22 to 1.23 g/cm^3 and from 1.36 to 1.41 g/cm^3 [28].

Polyester fibres have excellent mechanical properties, which can vary depending on the intended use. Polyester fibres are characterized by low moisture absorption and the ability to accumulate electrostatic charges on the surface. Also, polyester fibres are resistant to dilute acids, alkalis and organic solvents, but can be damaged in high concentrations [27]. The surface of the polyester filament is more uniform than other synthetic fibres with the exception of the curly staple fibre, where some inequalities can be observed on the inside of the bent part of the fibre [28].

The desired shape of cross-section of the polyester fibres can be obtained by applying different nozzles during polymer extrusion. Thus, polyester fibres can have a round, hollow round, trilobal, hollow trilobal cross-section, or they can be bicomponent [30]. It is also possible to produce specially designed cross-sections of polyester fibres that allow the improvement of certain properties such as moisture transfer, increased resistance to peeling, improved thermal properties, increased gloss, etc. [23, 31].

3.2. Polyamide fibres

Polyamide fibres (PA) as man-made fibres made of synthetic polymers are composed of linear macromolecules in which at least 85% amide groups (-CO-NH-) are linked to aliphatic but alicyclic segments [26]. They are spun from the melt of polyamide polymers. The best known are the fibres produced from polycaprolactam (PA 6) and from polyhexamethylene adipamide (PA 6.6). PA fibres come on the market under a number of trade names, the most famous being: PA 6.6 Nylon (PA 6.6) (developed at DuPont, USA), Perlon (PA 6) (Bayer, Germany), known as NylonTactel (PA 6.6) (ICI, UK), Toyobo Nylon (PA 6) (Toyobo, Japan) etc. The melting temperature of PA 6 fibres (215 - 220 °C) is lower than that of PA 6.6 fibres (255-265 °C). The properties of polyamide fibres vary depending on the type of polymer and the production conditions (spinning speed, elongation ratio and applied temperature), but are generally strong, durable, flexible and elastic. Tensile strength and elongation at break of PA 6 fibres is about 29 cN/tex, i.e. 46 %, and PA 6.6 in the range from 37 to 66 cN/tex, i.e. elongation 16 to 43 % [27]. The specific fibre densities of PA 6.6 and PA 6 range from 1.137 to 1.145 g/cm³ [29]. The fibres do not swell and have a better ability to absorb moisture from the air than PES fibres, they absorb sweat poorly (moisture absorption in a standard atmosphere is about 3.5 % for PA 6.6 and about 4.5 % for PA 6 fibres).

3.3. Cotton fibres

Cotton fibre is a fibre of plant origin that grows on the seed surface of the cotton plant *(Gossypium)* and accounts for about one-third of total world textile fibre production. This fibre contains between 90 to 95 % cellulose. In addition to cellulose, cotton fibre also contains pectins, waxes, organic acids and inorganic substances.

Cellulose is a linear polymer of a 1,4-β-D-glucose unit covalently bonded. The cellulose molecule degree of polymerization can be up to 10 000.

The properties of cotton fibres may vary depending on the botanical groups of the plant from which the fibre is obtained, climatic and weather conditions, agricultural practices, the area in which the plant is grown, and many other factors. The length of the fibres obtained from the seeds ranges from 3 to 63 mm. Fibres shorter than 12 mm are not used in textile industry, because they are not suitable for spinning and therefore have no commercial value. The tenacity of cotton fibres varies depending on the type of cotton and is in the range of 25 to 45 cN/tex [27], and specific density of cotton fibres ranges from 1.50 to 1.55 g/cm³ [32, 27].

Over the years, there has been a reduction in use of cotton fibres for the production of sportswear. The main reason is the increased absorption and retention of moisture inside the cotton fibres. In the dry state, cotton has excellent comfort properties. However, when cotton clothes are wet or damp, due to physical activity, the clothes become heavy and sticky and lead to an extremely uncomfortable feeling. The solution can be found in the combination of cotton with synthetic fibres (in blends with a higher proportion of cotton fibres) or in water-repellent treatments of cotton that reduce the water absorption of textile fabric [33].

3.4. Wool - Merino wool fibres

Fine wool fibres such as merino wool, is usually used for running apparel and bicycle wear. Merino wool fibre is hydrophilic and have excellent wicking properties, dries quickly and maintains body's own natural cooling system. Fine wool fibres such as Merino wool fibres have excellent absorption properties, maintaining the body's natural thermoregulatory system in different climatic conditions. Despite the poor strength wool has good durability and intermittent elongation (up to 50 % in the wet and 30 % in the dry state). The length of conventional wool fibres ranges from 35 to 350 mm, depending on the type, while the length of Merino wool fibres ranges from 60 to 110 mm. In addition, they have good air and water vapor permeability properties, odor control, environmental acceptability and renewable [34, 35].

3.5. Elastane fibres

Elastane fibres are man-made fibres characterized by the property of elastic elongation, and a very high ability of elastic recovery after stretching, the leases can be stretched at least three times the length and return to the initial length after the load ceases. From this group, the most important are *elastane* and *elastodiene* fibres. The most famous elastane fibre (EL) is known under the trade name *Lycra* (DuPont). For elastane fibres the general name *Elastane*, is accepted in the German-speaking area, and in English the general name is *Spandex*.

According to ISO 2076: 2013 [26], elastane fibres are constructed of at least 85 % by weight of segmented polyurethane, consisting of aliphatic polyesters or polyethers (soft areas) and polyurethane segments (hard areas). They can stretch up to 700 % with an elastic recovery of 95 %.

The most significant property of elastane fibres or filaments is their high tensile elasticity, the values of breaking elongation range between 300 and 700 %, and their elastic recovery reaches 95 %. Elastane filaments are rarely used alone, are most commonly used in yarns twisted with natural or other man-made fibres [36]. Thanks to this exceptional feature, their small presence in mixtures with other types of fibres, textiles (fabrics, knitted fabrics and clothing) ensures elasticity when worn, especially during physical activities.

4. Recent developments in the production of fibres and yarns intended for sportswear

An overview of new man - made fibres of synthetic and natural polymers and products made from mixtures of these fibres for the production of active sportswear is shown in Tab.2.

The following are the characteristics of some high-performance fibres, intended for the production of sportswear, such as hollow fibres, microfibers and high-comfort fibres.

4.1. Hollow fibres

A filament or staple fibres with one or more axially embedded hollow (air) cores is called a hollow fibre [46]. They were created on the impetus to produce fibres that would have a lumen like cotton fibre. Although almost all artificial fibres can be produced in the form of hollow fibres with the adaptation of technology, polyester and polyamide hollow fibres are most often used for sportswear. They can be produced with trilobal, square, hexalobal, and round cross section [46-49].

Tab.2 Man-made fibres of synthetic and natural polymers for the manufacture of sportswear

Fibre	Trade name	Properties	Application
Polyester fibre	Fieldsensor	Quickly absorbs perspiration; Carries perspiration rapidly to the fabric's outer surface. High breathability allows air circulation within the textile material.	Golf wear, athletics wear, cycle wear, Sky/Snowboard wear, Climbing wear [37-38]
	Coolpass	This microfibre has narrow openings, which have siphon effect. This provides better regulation of moisture. The sweat is removed from skin and transferred to outer layer of fabrics, which helps with regulation of body temperature and skin remains dry. Sportswear produced form this fibre have warm filing in the winter and cool during the summer.	Bottom layer in three-layer system [39]
	Triactor	Triactor absorbs sweat and dries much faster than conventional polyester fibres, thus keeping the inside of garment dry. This is achieved by changing the cross-section of PES filament in to Y shape. Its construction reduces the amount of material touching the skin, so it feels cool and refreshing.	Golf wear; Athletic training wear; Athletic socks [40]
Polyamide fibres	Tactel	This fibre has trilobal cross-section. This fibre is: soft to touch, lightweight, fast drying breathable, strong and resilient. This fibres dry up to eight times faster than cotton and achieve up to three times stronger textiles than cotton.	Windproof fabrics; Women's intimate apparel; dancing and gymnasts wear [41]
	Tactel Micro	Exceptional strength	Windproof fabrics [42]
	Supplex Micro	Exceptional strength	Windproof fabrics [42]
	Hydrofil	Polyamide polymer consisting of 85 % PA 6 and 15 % polyethylene oxide diamine. Has increased aspiration capacity to the level of cellulose fibres.	Sportswear [43]
	Meryl Satine	Soft touch and good wear resistance.	Clothing for extreme sports [44]
	Meryl Microfibre	Soft touch	Sportswear worn next to the skin [44]
	Meryl Next	Hollow fibre with good thermal insulation	Skiing clothes
Regenerated cellulose fibres	Tencel	Very high water absorption capacity. Unique structure of nano-fibrils. Smooth surface. Resistant to wear and tear. High tensile strength, both wet and dry. This fibre does lose some strength when wet, though not as much as rayon. Mix well with other natural and synthetic fibres.	Sportswear; outwear and underwear [45]

Hollow fibres have better thermal insulation than conventional fibres, and also have improved bending and torsion (twisting) properties compared to conventional fibres [47, 48]. They are often used to make clothes for various winter sports, as well as for clothes with thermal protection properties [47]. Due to the cavities in the structure, these fibres are very light [48].

Polyester hollow fibre of the trade name Welkey is used to make sportswear. With microcavities throughout the volume of fibres or with a central cavity of larger diameter, or combinations thereof, the possible absorption of moisture is significantly increased, and thus the comfort of wearing clothes made of such fibres, and the increased air space inside the fibres increases the thermal resistance of textile material [47].

Very popular in the production of winter sportswear is the fibre of the trade name Thermolite. Polyester fibre that "captures" air in the cavities of these fibres and provides warmth and comfort. Hollow fibres due to the significantly increased specific surface allows sweat to evaporate quickly, which helps the textile fabric from these fibres to dry up to 50 % faster than cotton textiles [49].

4.2. Microfibres

A microfibres are man-made fibres with high linear density, i.e. fibre is finer than 0.9 dtex, and most often below 0.4 dtex [50]. The main characteristic of microfibre is extreme lightness. Textile materials made of microfibres have exceptional strength (although the filaments are very fine), good breathability, durability and soft feel [56]. Microfibres are most often available in polyester and polyamide fibres, but they can also be acrylic, polypropylene and cellulose.

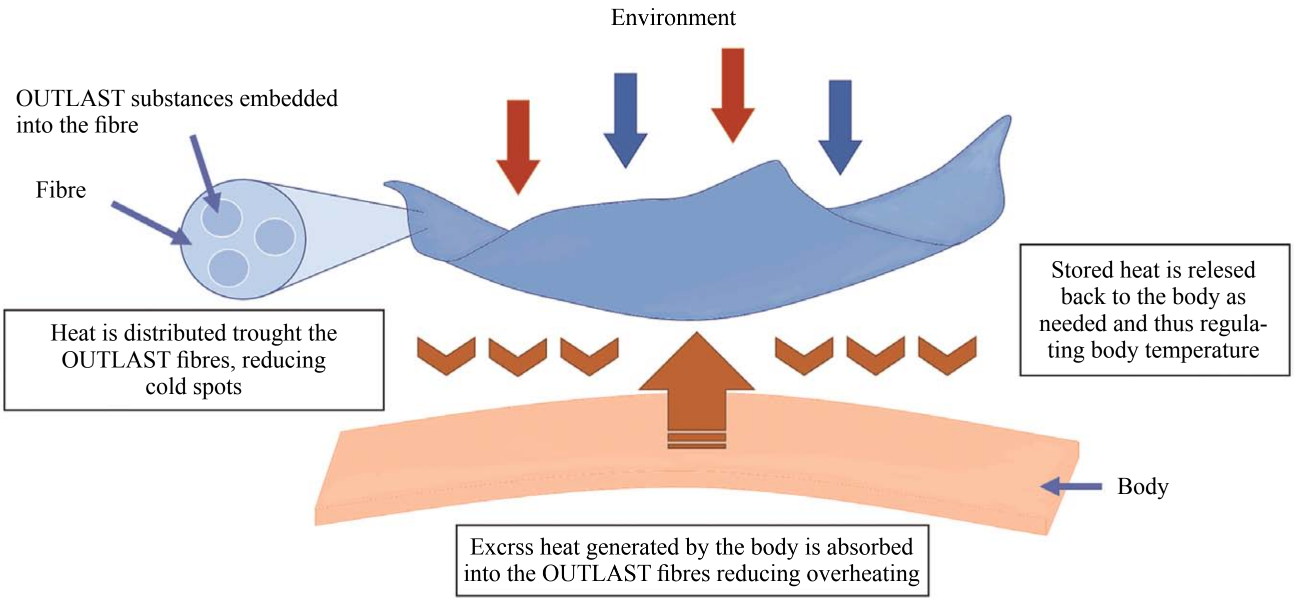

Fig.1 Working principle of Outlast fibre

In addition to high aesthetic characteristics, microfibers provide textile materials, depending on the manufacturing technology, some special properties, such as water repellency and water impermeability with simultaneous good air permeability, greater comfort compared to standard fibre types and excellent mechanical properties. Due to the high fineness of microfibers, higher porosity is achieved, which improves water vapor transfer from textile material and thermal control properties [51, 52].

5. Characteristic requirements of textile structures for sportswear

From the sportswear application point of view, especially when it comes to clothes for professional athletes, special requirements are set for thermal and physiological comfort, but also skin sensorial comfort. The specific characteristics of fibres, yarns and textile materials for achieving the desired properties of sportswear will be reviewed below.

5.1 Thermoregulated fibres

Thermoregulated fibres are able to improve thermophysiological comfort by absorbing or releasing heat. Clothing made of such fibres is able to warm or cool the body, depending on the outside temperature, so that the skin temperature is maintained in a narrow range (30 to 33 °C). These fibres contain phase-change materials (PCMs) which change its physical state when subjected to heating or cooling [53]. PCMs are able to absorb or release certain amount of energy in latent heat form [54].

Today, over 500 different natural and synthetic PMCs with different heat capacities and melting points are available. For textile applications paraffin is most commonly used [55]. One of the first applications of PMCs in textile was by National Aeronautics and Space Administration (NASA) USA in 1980s. They applied them in smart materials with goal to make garments with good thermoregulation that will prevent the adversity which comes from sudden temperature changes in the space [56].

Today thermoregulated fibres are used for production of different types of sportswear like sports underwear, active wear, hiking wear and underwear for cycling, running et cetera [57].

Application of PCM substances in the field of textiles can be achieved in two different ways:

a) by incorporating microencapsulated PCM substances into the fibre during melt-spun process [58],
b) by coating or laminating the PCM on to the fabric subtract [59].

The advantages of incorporating PCM material into fibre is improved thermal insulation in hot and cold conditions (without adding additional thickness to the textile material) [59]. In contrast to the incorporation of microencapsulated PCM substances into fibres, the application of the technique of coating or laminating PCM substances on a textile substrate affects the mechanical properties, increasing stiffness and weight of fabrics [65]. In contrast to the incorporation of microencapsulated PCM substances into fibres, the application of the technique of layering or laminating PCM substances on a textile substrate affects the mechanical properties, increasing stiffness and surface mass of fabrics [58]. Although the use of phase-changing materials is widespread today, the short-term effects of PCM are generally seen [60]. The results of the analysis of the impact of microcapsules with phase-change materials embedded in the business suit show that phase-change materials provide a weak and temporary cooling effect during activity changes [61].

Different commercially available thermoregulated fibres are used to-

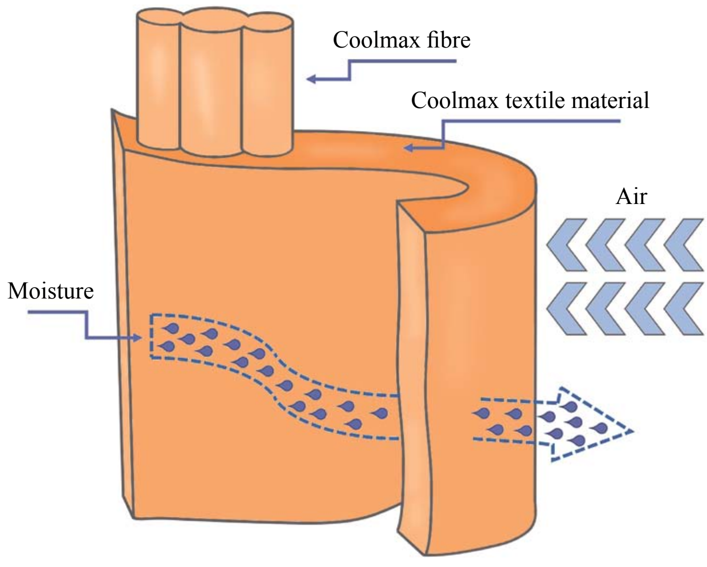

Fig.2 Schematic representation of the action of *Coolmax®* fibre

day, from which the most well-known is Outlast. Outlast technology uses acrylic and/or viscose fibres with PCM microcapsules, incorporated in yarns, fabrics, knitted fabrics and nonwovens, which absorb, store and release heat to obtain optimal thermal comfort for the user. Outlast technology works on the principle where excess heat produced by the body, due to physical activity or extreme weather conditions, is absorbed into the Outlast fibre, as illustrated in Fig. 1. The collected heat is returned to the body, maintaining the optimal wearer's temperature [53, 61]. The cooling effect of Outlast knitted fabrics (38 % Outlast PES, 52 % PES and 10 % Spandex) was investigated. The results showed that the duration of the effect of the PMC substance was about 15 minutes, with the effect being most pronounced in the first 3 minutes of wearing [61, 62].

In addition, it is necessary to mention high-comfort fibres, where specific morphological characteristics have a key role. By modifying the cross-section shape, dimensional gaps are created, at which strong capillarity can develop. Thanks to the capillary forces in these fibres, the transfer of moisture and water occurs significantly faster compared to standard fibres of circular cross-section. Such is e.g. *Coolmax®* active, *Ciebet, Viloft® thermal* and others.

Coolmax® active is a high-performance four- or six-channel polyester fibre from Invista that forms a transport system of increased specific surface area that allows improved moisture transfer from the skin to the outer layer of the textile fabric so that the human body remains dry and warm [63]. Fabrics made of *Coolmax®* fibres have the properties of high moisture control, breathability and fast drying, Fig.2 [65].

Viloft® thermal fibre from Kelheim Fibers GmbH is a flat (ribbon) viscose fibre of a specific shape which increases the specific surface area by more than 50 % and thus achieves changes in the structure of the yarn, i.e. fabric and clothing. These fibres, in addition to the naturalness of the raw material (wood cellulose from ecologically acceptable cultivation), have extremely good properties of softness, hygiene, and breathability. It is mainly used for underwear, socks and textile fabric intended for the production of sportswear. The most commonly available blends are with polyester and cotton. The high percentage of *Viloft* fibres provides improved thermal properties of textile fabric [65, 66].

Celliant® is the trade name for a synthetic polymer two-component fibre made from polyethylene terephthalate with optically active particles embedded in the core. According to the manufacturer, *Celliant®* technology in interaction with the electromagnetic emission emitted by the human body (the human body emits low infrared radiation) transforms heat into infrared energy, stimulating local circulation which increases oxygen levels in the body and reduces pain resulting from exercise. way improves sports results, improves sleep quality and health [67, 68]. The working principle of *Celliant* technology is shown in Fig.3 [68].

5.2. Influence of the yarn properties on the thermo-physiological comfort of sportswear

Thermal-physiological comfort when wearing clothes is influenced not only by the type and properties of the

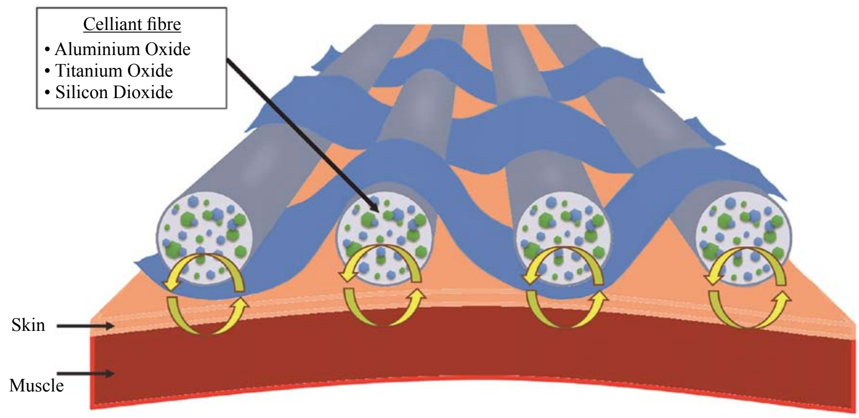

Fig.3 Working principle of Celliant technology

fibres, but also by the structural properties of the yarn embedded in the textile material. Investigations of thermal properties of rib cotton knitted fabrics of different structural properties such as: fineness, curl of yarn and type of used yarn (combed and carded yarn) have shown that knitted fabrics produced form finer yarn have lower thermal conductivity and show higher values of water vapor permeability, as well as a warmer feeling with a lower value of heat absorption [69]. It has been found that with increasing the yarn twist the values of heat absorption and water vapor permeability also increase, while the values of thermal resistance decrease. Knitted fabrics made of combed cotton yarn show lower values of thermal resistance compared to knitted fabrics made of carded cotton yarn, while the values of thermal conductivity, thermal absorbency and water vapor permeability are higher in knitted fabrics made of combed cotton yarn [70].

The comfort performance of the knitted fabrics made of different types of fibres (polyester, polypropylene and polyamide) and the linear density of the yarn on thermal properties (thermal resistance, thermal conductivity and thermal absorbency) were investigated by examining air permeability and sweat transfer rate.

Single-jersey plated knitted fabrics (plated with filament yarn) were investigated. Tests have shown that knitted fabrics with plated polyamide filaments in a layer facing the skin are more suitable for warm conditions as these knitted fabrics feel cooler on initial contact with the skin due to high thermal absorbency and permeability to air and water vapor. Knitted fabrics made with yarn of lower fineness (higher length mass) is less suitable in warm conditions, i.e. they are more suitable for the production of winter clothing due to the higher value of thermal resistance and lower values of air permeability and moisture transfer [71].

5.3. Structures of textile materials intended for production of sportswear

Structural variations (quality of yarn, pattern and finishing) can affect performance of textile materials and influence the performance of sportswear and the thermoregulation of human body [72]. The structure of textile material plays an important role in the design of sportswear [73]. Because of its good features, knitted fabrics has advantage compared to other fabrics in the production of sportswear. The main characteristic of knitted fabrics is high elasticity, which allows free movement of athlete and good moisture management properties [72]. Structural parameters of knitted fabrics such as thickness, porosity, pore size, density and stiffness are another reason for its wide application in production of sportswear [73].

The pattern of knitted fabric has a significant influence on its properties. Plain jersey knitted fabric possesses a better wicking properties and higher value of absorption in relation to knitted fabrics in pique and honeycomb pattern. Favorable moisture transfer properties of single jersey knitted fabric can be explained by the form of the loop, orientation of the sides of legs to the wale direction [74].

In recent years one of the ways to increase the wearer comfort is the application of micro web in textile material structure. This structure allows increased cooling effect and airflow through the textile material. Obtaining holes on the textile material can be achieved during the knitting process and by laser perforation. Openings on the textile material obtained by laser perforation are significantly smaller compared to ones obtained by knitting [75]. This kind of structures increases the breathability of textile material.

Multi-layer knitted fabrics also play an important role. Increased popularity of multi-layer knitted fabrics in sportswear production can be explained by its improved thermoregulatory properties compared to conventional knitted fabrics. Each layer has a special task. The layer next to skin, draws moisture to the outer layer where is absorbed and released into the atmosphere. This way the skin remains dry and the body's temperature is balanced [76, 77].

6. Biomimetic textile materials

Biomimetic textile materials are materials which imitates nature and its processes. Biomimetic is a young research field, specialized in biomimetic, chemistry and textile materials are active in research and development of biomimetic materials [85, 86].

As inspiration for hydrophilic textiles has been found in hydrophobic surfaces of different plants and animals (which are rough in microscopic level). Plant has a hydrophobic structure if the contact angle ranges from 150° to 90° [80], while super hydrophobic surfaces have contact angle greater than 150° and small angle of hysteresis (hysteresis contact angle is defined as the difference between rising and falling contact angles), which allows the water to descend with a smaller drop of 15° [78]. In addition, "ultra-hydrophobic" structures are used to describe a surface which shows both rising and falling contact angles greater than 150°.

Study in the field of surface of hydrophobic plant was conducted on over of two hundred different plant species [82]. Results showed that most of them have super hydrophobic surface. Advantages of super hydrophobic textiles are: active self-cleaning performance, excellent water and oil repellency [83]. Numbers of washing can be significantly reduced thanks to self-cleaning properties, which can lead to development of eco-friendly materials that will reduce the energy needed for laddering and lower water pollution [84].

Lotus leaves have super hydrophobic surface which is microscopically rough. This is the result of small protrusions or spikes located on the leaf which results in little contact surface. The peaks of these protrusions are covered with wax, which even further increases water repellency and also contribute to self-cleaning properties. When a drop of water falls on the lotus leaf, it rolls and takes the dirt away [84]. The possibility of production textile with Lotus effect can be achieved: by achieving surface roughness [85, 86] and by finishing treatments (when the surface free energy is decreased) [87, 88].

A pinecone has a closing and opening mechanism which is triggered by moisture content in the atmosphere [89]. This behavior has been inspiration for development of biomimetic textile materials whit adaptive structures [90, 91]. Pine cone effect provides a solution for discomfort induced by moisture and change of temperature in the garments [92]. Such biometric textile material has been produced by laminating the light (porous) woven material on to non-pours membrane and on the surface of this material small U-shaped cuts are being made. When the air humidity is high, U-shaped parts of fabric curl back and air permeability performance is significantly increased [93]. Different approach to achieve "pine cone effect" in textile was achieved by using bicomponent fibre with an eccentric sheath/core cross-section. Because of the structure of this fibre, when fabric absorb moisture, the yarn inside the structure is tighten. This behavior is opposite to traditional materials, where the yarn became swollen in the presence of moisture and the air permeability is reduced. This way microscopic pockets of air in the textile structure are created. When the fabric is dry, fibres are open which results in decrease of air permeability and increasing of insulation properties [92]. Biomimetic knitted fabrics was inspired by branching structure of plants was developed. Improved moisture and comfort properties of fabric were achieved by using four yarn system. The sweat is drowning from bottom to the top of biomimetic fabric by special fabric pattern (designed by intercalating od yarns which imitate system of water transport in plants). The results of study showed moisture transport has significantly accelerated which has the effect of improved properties of clothing [93].

Thanks to their anatomy in the special structure of their skin, sharks are one of the fastest fishes in the sea. Shark skin is covered with three-dimensional scales which are different than most fish scales. In addition to allowing rapid seaming, such structure of shark's skin has antibacterial effect and prevents the growth of bacteria and parasites on its structure [94]. Fastskin swimsuit is inspired by shark's body. This swimsuit fit is very tight and has compressing properties which helps to reduce fatigue, so the also the athlete's activity is prolonged and improved. Manufacturer claims that Fastskin can boost a swimmer's speed by up to 3 % [95].

7. A review of some innovative solutions in the field of textile materials for sportswear

The rapid growth in the popularity of sports and sportswear has contributed to the development of different types of sportswear from functional, basic, casual to fashion sportswear. Each of these types of sportswear is intended for different levels of professionalism and requires certain performance depending on the specific purpose. At the same time, remarkable achievements are being made in the field of fibres with very specific properties in order to achieve desired characteristics of a particular garment.

Below, are some of the solutions, based on high technology that allows the development of high and special properties fibres as well as the development of seamless garments for various applications in sports with aim to improve performance and comfort for athletes during and after physical activity, will be given. This can be achieved by using textile materials that has certain specific properties adapted to a specific purpose (hygroscopic, compression) using different types, structures and orientations of fibres or new techniques of joining garment parts.

In order to meet the needs of professional athletes, the clothing industry is constantly in the quest for solutions that would optimize sportswear and thus to improve performance and facilitate the exertion of athletes during and after physical activity. This can be achieved by textile materials with certain properties (hygroscopic, compression) using different fibre orientation and new bonding techniques of garment parts.

Textile materials with desired moisture management characteristics can increases the performance of the cardio-respiratory system of athletes [96]. The study which investigate impact of hygroscopic properties of textile materials on pitching speed and performance of baseball players show that performance of athletes can be improved by using textile materials with higher moisture absorption for production of sportswear [97].

Result of the use engineered knitted fabrics wich show different properties for different body parts with consideration of body construction have shown that the aerodynamic drag of cycling wear can be reduced [98], while the optimal orientation of fibres in fabric can also significantly affect the aerodynamic drag of swimsuit [99].

The product of cooperation between Speedo and NASA is LZR Racer swimsuit (Fig. 4) specially designed to reduce drag while swimming [100]. This swimsuit is made using the ultrasonic joining technique which reduce drag by 6 %, compared to conventional stitched seams. An additional water resistance reduction of 24 % compared to *Fastskin* biomi-

Fig.4 LZR Racer swimsuit [101].

metic swimsuit from the same manufacturer is reported. LZR Racer has also developed the so-called *Hydro Form Compression System*, i.e. a swimsuit shape that uses a compression system to adhere to the body like a corset. The compression effect on key areas of the swimmer's body allows him to swim longer and faster because they use less energy to maintain shape. Compression alone improves efficiency by up to 5 % [101]. Research has also shown that fitting of ski jumping suits correlates with aerodynamic performance with a full-scale wind tunnel testing [102].

Compression Athletic Wear is clothing designed on the basis of construction solutions tight cut and by taking into account the elasticity of the material. For this purpose, polyamide knitted fabrics are most often used [103, 104]. Professional athletes wear compression suits to improve their athletic performance and speed recovery from injury. Compression suits are used in high performance sports such as running, skiing, swimming, cycling, etc. [105].

Compression technology has long-term application for medical purposes [103]. Compression garments improve the perception of muscle damage and increase performance in endurance tests [106]. It is considered that compression athletic wear helps in regulation of muscle oxygenation and skin temperatures and decreasing of perception of fatigue [104].

It has been reported that the use of compression shorts can improve volleyball players performance by increasing power output over repeated jumps [107]. Also, compression shorts reduce fatigue by improving blood flow in the veins and reducing the cardiovascular load of athletes [108]. Compression pants help improve athletic performance and reduce injuries by reducing muscle oscillations [109], while wearing compression stockings (knee-length) has a positive effect on runner's hemodynamics [101]. The use of compression stockings reduces the risk of injury from the overall impact of physical exertion [106].

From the point of view of the development of sportswear, it should be emphasized that sports brands are constantly investing in innovations in textile materials, fibres and yarns in order to make sportswear better and more comfortable. Thus, Adidas has introduced a number of innovative textile materials, such as *Climalite, Climacool, Climachill* etc., which significantly affect wearing comfort. Climalite is a specially designed textile material which transfer liquid sweat from the body during training. It is based on a combination of cotton on the wright and polyester fibres on the wrong side of fabric, which is in contact with the body, and a hydrophilic treatment that enhances the effect of removing sweat from the inside to the outside. When sweat occurs, polyester fibres promote the extraction of sweat from the skin surface into the outer hydrophilic part of the material (cotton) where it evaporates quickly. The hydrophilic treatment of the material additionally acts to direct sweat from the body surface outwards, and the inner layer of polyester fibres gives a feeling of coldness to the body and prevents overheating [111].

Climacool textile structures are engineering-based textile materials that allow moisture control and ventilation to athletes. Climacool works by removing sweat from the skin by increasing micro-ventilation, e.g. by placing nets under the armpit and on the back of the T-shirt. It is used for production of sports bras, pants, T-shirts, and even shorts and shoes.

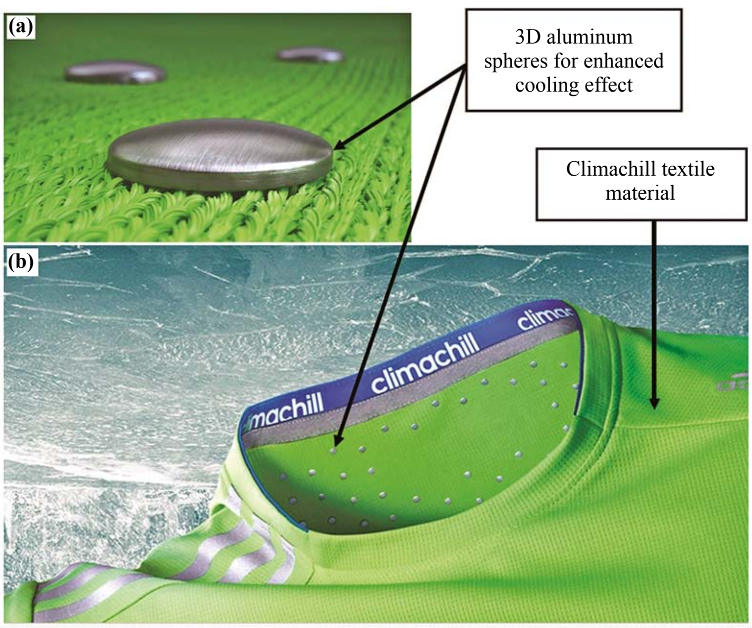

Fig.5 *Climachill* textile materiala form brend Adidas: a) 3D aluminum spheres with cooling effect, b) shirt detail [112]

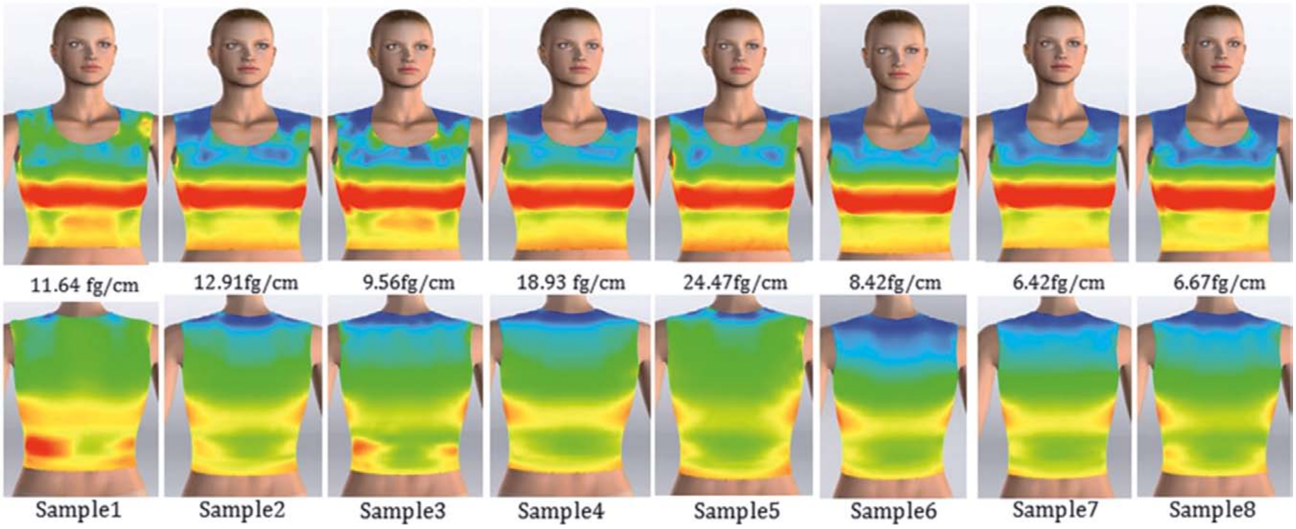

Fig.6 Gradient Tension Map for 8 different knitted fabrics [124]

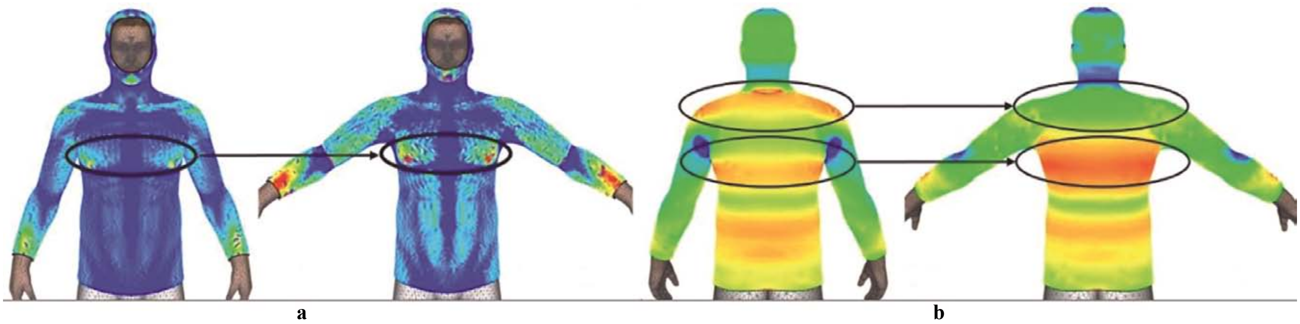

Fig.7 Dynamic fit analysis of a diving suit: a) the clothing pressure on the wearer's body, b) linear stretching in the *y* direction (weft direction) [125].

Adidas has introduced to the market *Climachill* [112] a material (Fig. 5) that provides a cooling effect by using *SubZero* yarn containing titanium and 3D aluminum spheres (Fig. 5a). Aluminum spheres are placed on the area of clothing that covers the parts of the body that are most heated, i.e. sweat (e.g. the upper back) for cooling. The *SubZero* yarn from which this textile material is made has a flat cross section which further improves the cooling properties. The manufacturer claims that the cooling capacity is increased by 36 % compared to the previous material with the cooling effect of *Climacool*.

An interesting material technology with cooling effect is *Omni-Freeze* and *Omni-Freeze ZERO* from Columbia, where cooling effect is achieved by using superabsorbent polymers embedded in the form of rings with a diameter of 0.381 cm in the inner part of the material. When sweating, they absorb moisture and sweat, and in the process of absorption and swelling they consume energy and therefore lower the temperature of the material [113]. The basic material is polyester, often treated with additional protection from ultraviolet radiation since these materials are used for sports activities in extreme thermal conditions. Columbia clothing has been tested by professional athletes in Grand Canynon (USA) at extremely high temperatures and has proven to be extremely effective [114]. In addition to materials with a cooling effect, Columbia has also developed a range of materials with a heating effect Omni-Heat ™ 3D, Omni-Heat ™ Reflection, Thermal Coil ™, etc. technologies with protective properties, such as for protection against rain, wind and similar.

Dri-FIT™ is one of the well-known brands of materials for sportswear with the ability to maintain a feeling of dryness during sports activities, i.e. during sweating. DRI-FIT is made of polyurethane microfibers, which allows moisture absorption and transport from the skin to the surface of the textile material. The result of using Dri-FIT material is to protect athletes from moisture and maintain dryness. This technology is used in the production of: blouses, shorts, tracksuits, socks, gloves, etc. [115].

8. Design of sportswear

Today, many different programs and software for 3D design and simulation of clothes are available. It is possible to simulate clothes by using virtual mannequin. This way clothing fit, design and drape can be simulated and evaluated [116].

In highly demanding sports, sportswear which fits athlete's body perfectly is important. This can be achieved by using different methods and techniques for the digitization of the human body are used today [1, 117]. 3D scanning of human body has been used in the clothing industry for last 20 years, but recently have become more efficient [121]. Different technologies of 3D scanning of human body. Commercially available 3D scanning systems can be divided into five basic groups [117 - 119]:

1. Laser scanning systems using lasers as a light source;
2. 3D scanning systems with structured light, mainly white light;
3. LED 3D scanning systems using infrared detectors;
4. Shadow 3D body scanning systems, which includes 2D images of video silhouettes (body contours) in different body positions converted to 3D model;
5. Systems that use radio waves to scan the body surface through clothing.

Extensive data on textile fabrics, such as mechanical and thermal properties, as well as aerodynamic or hydrodynamic properties [120-125], depending on the type and purpose of use of sportswear, are required to design optimal sportswear and its engineering modeling.

When designing sportswear one of the most important ergonomic factors is the thermal status of the athlete. Optimizing the microclimate when wearing sportswear can be achieved by appropriate engineering design of the so-called seamless knitted technology. Such clothing is designed to have different characteristics and properties (sorption and heat properties, breathability, etc.) on certain parts that require specific properties [123-125]. Seamless knitting technology is one of the fastest growing clothing technologies [119].

In sports that require a tight fit of sportswear, one of the most important parameters that must be taken into account when making clothing are the elastic properties of textile materials, especially tensile properties and elastic recovery. Due to the fit of tight-fitting clothing on a certain curved part of the human body, radial pressure is created. The pressure depends on the elasticity modulus of the embedded textile fabric, the curvature of the body, the ratio of the circumference of the garment to the part of the body and the contact surface. Based on the measurement of the compression force at certain points of the body and knowledge of the tensile characteristics of the textile material, a correlation can be determined between the elastic properties and the realized clothing model, in order to adapt to the shape and size of the part of the body on which it will be worn. Furthermore, it is necessary to point out the computer construction and 3D simulation of fitness sportswear, where research is focused primarily on the mechanical properties of different knitted farbics (which differ in elastic properties) intended for the manufacture of fitness sportswear. In addition, the ergonomic comfort of fitness sportswear was evaluated. The mechanical properties of the knitted fabrics are given in the form of Tension map (Fig.6), i.e. values (given in fg/cm) of the tension wich clothes do on the body of the virtual mannequin [124]. Tension map (Optitex) provides insight into simulated garments using a colored map showing the values of stretching, tightening and distance between clothing and a virtual model [126]. The values obtained in this way were compared with those obtained with a Pico Press pressure measuring device [124].

A 3D method of simulating the clothing fit was used for the computer construction of a diving suit [125]. The aim of this study was to determine whether the constructed model was good enough for use by professional athletes. Based on the value of the pressure measurement that the suit performs on the athlete's body (at predetermined points), a good correlation was achieved between the simulated and the realized protype of the diving suit. This method has proven to be extremely useful in designing sportswear where extremely tight fit is required [117, 125]. Fig.7 shows the dynamic fit analysis of the simulated model of the diving suit.

9. Conclusions

The importance of sports and active sports clothing has been increased worldwide. Sales of these products are growing every year. Comfort, functionality, attractive design and easy handling are the main requirements for sportswear depending on the type of sport and activities for which they are intended. Different properties of sportswear can be achieved by using the new types of fibres, fibre blends, structure and geometry of fibres, fabrics structure and finishing treatments. Moisture management features such as absorption of sweat, sweating evaporation, and quick drying are the primary functions of active sportswear that affect the comfort of players during sports activities. The thermophysiological aspect of the garment plays aimportant role in determining the selection and use of materials for sports.

Aside from important requirement is increased lightness and softness of textile materials, which is achieved by using microfibres. Other benefits of microfibres used in the sports industry are wrinkle resistance, and good drape properties as well as cotton like touch. Fabric manufactured from micro fibres is the one method to improve the moisture management property which comprises of wetting, wicking and moisture vapor transmission.

Much has been done to find the optimum fibres blends for sportswear. By using appropriate blend, the favorable properties of the user fibre can be obtained for the final product. The most common mixtures of polyesters, polyamides or cotton with lycra. By using this blend for sportswear skin sensorial and body movement comfort can be significantly improved.

For production of sportswear with demands good thermal isolation hollow and thermoregulated fibres are used. While for summer sportswear different type of polyester, polyamide fibres and microfibres are used and bigger attention is paid to the structure of textile materials.

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References:

[1] Chowdhury H., Alam F., Mainwaring D., Beneyto-Ferre, J. and Tate M.: Rapid prototyping of high performance sportswear. Procedia Engineering 34 (2012.), 38-43. doi: 10.1016/j.proeng.2012.04.008

[2] Chowdhury P., Samanta K. K., Basak S.: Recent Development in Textile for Sportswear Application. International Journal of Engineering Research & Technology 3 (2014.) 5, 1905-1910

[3] Manshahia, M., Das A.: High active sportswear – A critical review. Indian Journal of Fibre & Textile Research 39 (2014.) 39, 441-449.

[4] Power E. J.: Advanced knitting technologies for high-performance apparel. High-Performance Apparel, (2018.) 113–127. doi: 10.1016/b978-0-08-100904-8.00005-5

[5] Bartels V. T.: Improving comfort in sports and leisure wear. Improving Comfort in Clothing, Atmosphere, (2011.) 385–411. doi: 10.1533/9780857090645.3.385

[6] Why Are Sportswear Giants Nike and Adidas Embracing Fashion? Dostupno online: https://www.businessoffashion.com/articles/intelligence/nike-adidas-sportswear-fashiona. [Pristupljeno: 14.01.2019.]

[7] How Sportsweear became high fashion. Dostupno online: https://www.originoutside.com/insights/how-sportswear-became-high-fashion. [Pristupljeno: 20.1.2020].

[8] FASHIONBENS. How Sportswear Took Over Your Wardrobe. Dostupno online: https://www.fashionbeans.com/article/how-sportswear-took-over-your-wardrobe/ [Pristupljeno: 20.1.2020].

[9] The Growth of Sales in Sportswear. Dostupno online: https://www.prnewswire.com/news-releases/the-growth-of-sales-in-sportswear-639692863.html [Pristupljeno: 15.4.2018].

[10] Geršak J. and Grujić D.: Vpliv oblačila na toplotno fiziološko udobje človeka pri različnih obremenitvah in klimatskih pogojih, Tekstilec 46 (2003)

[11] Mecheels J.: Anforderungsprofile für Funktionsgerechte Bekleidung, Aachen, Germany: DWI-Schriftenreihe des Deutschen Wollforschungsinstitutes an der TH Aachen, (1992.) 263-268

[12] Geršak J: Physiological Responses of Human Body as Criterion for Estimating the Thermal Characteristics of a Clothing System. 7th Textile Bioengineering and Informatics Symposium Proceedings (2014).

[13] Mecheels J. Korper – Klima – Kleidung: Grundzüge der Bekliedungshopysilogie: Schiele & Schön GmbH, (1991).

[14] Senthilkumar M., Sampath B. M., Ramachandran T.: Moisture Management in an Active Sportswear: Techniques and Evaluation—A Review Article. Journal of The Institution of Engineers (India): Series E 93 (2013.). doi: 10.1007/s40034-013-0013-x.

[15] Shirreffs S. M., Aragón-Vargas L., Chamorro M., Maughan R. J., Serratosa L., Zachwieja, J.J.: The Sweating Response of Elite Professional Soccer Players to Training in the Heat, International journal of sports medicine 26 (2005) 90-5. doi: 10.1055/s-2004-821112.

[16] Musaddaq A., Boughattas A., Wiener J., Havelka. A: MECHANISM OF LIQUID WATER TRANSPORT IN FABRICS: A REVIEW, Fibres and Textiles, 4 (2017.) 55-65

[17] Kissa E.: Wetting and Wicking. Textile Research Journal 66 (1996.) 10, 660. https://doi.org/10.1177/004051759606601008

[18] Cazabat A. M., Stuart M. A. C.: Dynamics of wetting: Effects of surface roughness, The Journal of Physical Chemistry 90 (1986.) 22, 5845-5849

[19] Dettre R. H. and Johnson R. E.: Contact Angle, Wettability, and Adhesion, R.F. Gould, Ed., Advances in Chemistry Series, American Chemical Society 43, Washington, D.C., (1964.) 136.

[20] Sanders, E. M. and Zeronian S. H.: An analysis of the moisture-related properties of hydrolyzed polyester, Journal of Applied Polymer Science 27 (1982.) 11, 4477-4491

[21] Gorji M. and Bagherzadeh R.: Moisture management behaviors of high wicking fabrics composed of profiled Fibres, Indian Journal of Fibre & Textile Research 41, September 2016, 318-324.

[22] Sweeney M. M. and Branson D. H.: Sensorial Comfort: Part I: A Psychophysical Method for Assessing Moisture Sensation in Clothing. Textile Research Journal, 60 (1990.) 67, 371–377. https://doi.org/10.1177/004051759006000701

[23] Bishop P. A., Balilonis G., Davis J.K. and Zhang Y: Ergonomics and Comfort in Protective and Sport Clothing: A Brief Review. J Ergonomics (2013.) S2: 005. doi:10.4172/2165-7556.S2-005

[24] Nelson Raj A. E. and Yamunadevi S.: Application of textile fibres for technical and performance enhancements in sports. International Journal of Multidisciplinary Research and Development 3 (2016.) 12, 40-45.

[25] Manshahia M., Das A.: Comfort Characteristics of Knitted Active Sportswear: Heat and Mass Transfer. Research Journal of Textile and Apparel 17 (2013.) 3, 50-60. https://doi.org/10.1108/RJTA-17-03-2013-B006

[26] Standard ISO 2076:2013, Textiles — Man-made fibres — Generic names

[27] Grishanov S. : Structure and properties of textile materials. Handbook of Textile and Industrial Dyeing, (2011) 28–63. doi: 10.1533/9780857093974.1.28

[28] Društvo inženjera i tehničara za tekstil Maribor: Tekstilni priručnik, TEKSTILNI INSTITUT, Maribor, Slovenija 1987.

[29] Jovanović S.: Struktura i svojstva vlakana. Tehnološko-metalurški fakultet univerziteta u Beogradu, Srbija 1981.

[30] Karaca E, Kahraman N, Omeroglu S, Becerir B.: Effects of Fiber Cross Sectional Shape and Weave Pattern on Thermal Comfort Properties of Polyester Woven Fabrics. FIBRES & TEXTILES in Eastern Europe **3** (2012.) 92, 67-72.

[31] Bueno M. A., Aneja A. P., Renner M.: Influence of the shape of fiber cross section on fabric surface characteristics. Journal of Materials Science 39 (2004.) 557–564. doi:10.1023/B:JMSC.0000011511.66614.48

[32] Jovanović R.: Celulozna prirodna i hemijska vlakna, IRO »Građevinska knjiga« Beograd, Srbija 1989.

[33] Guruprasad R., Vivekanandan, M. V., Chattopadhyay S.: The Use of Cotton as a Sportswear Material: A Critical Analysis, Cotton Research Journal 7 (2015.) 1, 61-64.

[34] Merino Wool: Running Apparel Review. Dostupno online: https://ultrarunning.com/featured/merino-wool-running-apparel-review/ [Pristupljeno: 18.6.2018].

[35] Vinčić, A. (2016). Vuna cijenjeni materijal – radionica održana na Tekstilno-tehnološkom fakultetu u Zagrebu. Tekstil, 65 (11-12), 420-421. Preuzeto s https://hrcak.srce.hr/186578

[36] Šajn Gorjanc, D., Geršak, J., Bukošek, V., Nikolić, M.: Utjecaj konstrukcije pređe s elastanom na relaksacijska svojstva tkanina. Tekstil, 54 (2005) 10, 489-496.

[37] Todays, ALL ABOUT SPORTS FABRICS. Dostupno online: http://sportstextiles.toray/en/fieldsensor/fie_002.html [Pristupljeno: 20.6.2018].

[38] TORAY. GLOBAL. FIELDSENSOR. Dostupno online: https://www.toray.com/products/textiles/tex_0060.html [Pristupljeno: 20. 6.2018].

[39] HEROCKS. TECHNOLOGY/FABRICS & TREATMENTS. Dostupno online: http://www.herockworkwear.com/en/technology/fabrics-treatments/ [Pristupljeno: 29.6.2018].

[40] Triactor. Dostupno online: http://www.technica.net/NF/NF1/etriactor.htm [Pristupljeno: 30.6.2018].

[41] iTextiles, Tactel. Dostupno online: https://itextiles.com.pk/tactel-fiber/ [Pristupljeno: 30.6.2018].

[42] Tactel by Invista. Dostupno online: https://prezi.com/i0pddh_swncl/tactel-by-invista/ [Pristupljeno: 30.6.2018].

[43] Textile Today. Recent Advances in Textile Materials and Products for Activewear and Sportswear. Dostupno online: https://www.textiletoday.com.bd/recent-advances-in-textile-materials-and-products-for-activewear-and-sportswear-2/ [Pristupljeno: 26. 6.2018].

[44] MERYL® SATINÉ. Dostupno online: http://www.nylstar.com/shops/yarns/256-meryl-satine [Pristupljeno: 10.7.2018].

[45] Tencel. Dostupno on: https://www.tencel.com/active [Pristupljeno: 7.7.2018].

[46] Cheung T. W., Li L.: A review of hollow fibers in application-based learning: from textiles to medical. Textile Research Journal 89 (2019.) 3, 237–253. https://doi.org/10.1177/0040517517741164

[47] Kajiwara K., Nori, R., Okomoto, M.: New fibers from Japan. The Journal of the Textile Institute. 91 (2000.) 3, 32-78. https://doi.org/10.1080/00405000008659541

[48] Wada O.: Control of Fiber Form and Yarn and Fabric Structure. Journal of the Textile Institute, (1992.), 83(3), pp: 322–347. doi:10.1080/00405009208631207

[49] Bilimleri M., Dergisi T.: An Investigation Of Knitted Fabric Performances Obtained From Different Natural And Regenerated Fibres, Journal of Engineering Science and Design 1 (2010.) 2, 91-95

[50] Peran J., S. Ercegović Ražić: Mikrovlakna - proizvodi visoke tehnologije, Tekstil 63 (2014.) 3-4, 126-133 https://hrcak.srce.hr/142484. Citirano 26.05.2020.

[51] Pal S. K.: Microfibre – Production, Properties & Application, Textile ASIA, Vol. 24, (1993), pp: 53-58.

[52] Mukhopadhyay M.: Microfibers-An overview. Indian Journal of Fibre &Textile Research 27 (2002.) 307-314.

[53] Zhang X. X., Wang, X. C., Zhang H.; Niu J. J., Yin, R.B.: Effect of phase change material content on properties of heat-storage and thermo-regulated fibers nonwoven. Indian Journal of Fibre & Textile Research, 28 (2003.) 265−269.

[54] Iqbal K., Khan A., Sun D., Ashraf M., Rehman A., Safdar F., Basit A. and Shahzad H.: Phase change materials, their synthesis and application in textiles—a review, The Journal of The Textile Institute (2019.). doi: 10.1080/00405000.2018.1548088

[55] Pause B.: Driving more comfortably with phase change materials. Technical Textiles International, 11 (2002.) 2, 24–27

[56] Cheng W. L., Liu N., Wu W. F.: Studies on thermal properties and thermal control effectiveness of a new shape-stabilized phase change material with high thermal conductivity. Applied Thermal Engineering, 36 (2012.) 345–352

[57] Mondal S.: Phase change materials for smart textiles – An overview, Applied Thermal Engineering 28 (2008) 11–12, 1536-1550. https://doi.org/10.1016/j.applthermaleng.2007.08.009

[58] Zhang X. X., Wang X. C., Tao X. M., Yicky K. L.: Energy storage polymer/Micro PCMs blended chips and thermo-regulated fibers, Journal of Materials Science, 40 (2005.) 3729. https://doi.org/10.1007/s10853-005-3314-8

[59] Choi K., Cho G., Kim P., Cho, C.: Thermal Storage/Release and Mechanical Properties of Phase Change Materials on Polyester Fabrics. Textile Research Journal, (2004), 74(4), pp: 292–296. https://doi.org/10.1177/004051750407400402

[60] Colvin D. P.: Advances in heat and mass transfer in biotechnology. ASME HTD. (1990) pp: 44:199.

[61] Geršak, J.: Physiological responses of human body as criterion for estimating the thermal characteristics of a clothing system. V: LI, Yi (ur.). *Textile bioengineering and informatics symposium proceedings : TBIS*, The 7thTextile

bioengineering and Informatics Symposium in conjunction with the 5th Asian Protective Clothing Conference, August 6-8, 2014, Hong Kong, Textile Bioengineering and informatics Society, 2014, 934-945.

[62] Geršak J. and Marčič M.: The Effect of Clothing on Thermoregulatory Responses of Human Body in a Hot Environment, Journal of Fiber Bioengineering and Informatics 10 (2017.) 1, 1-12. doi: 10.3993/jfbim00252

[63] COLMAX. Dostupno online: https://coolmax.com/en/?id=243 [Pristupljeno: 29.7.2018].

[64] COLMAX air. Dostupno online: http://coolmax.com/en/Technologies-and-Innovations/COOLMAX-PRO-technologies/AIR [Pristupljeno: 20.7.2018].

[65] Demiryürek O., Uysaltürk D.: Thermal comfort properties of Viloft/cotton and Viloft/polyester blended knitted fabrics. Textile Research Journal, 83 (2013) 16, 1740–1753. https://doi.org/10.1177/0040517513478458

[66] VILOFT®. Dostupno online: http://www.viloft.com/ [Pristupljeno: 1.8.2018].

[67] U.S. FDA Determines Celliant® Responsive Textile Products Meet Criteria as Medical Devices and General Wellness Products. Dostupno online: https://www.prnewswire.com/news-releases/us-fda-determines-celliant-responsive-textile-products-meet-criteria-as-medical-devices-and-general-wellness-products-300493298.html [Pristupljeno: 28.7.2018].

[68] Celliant, Technology. Dostupno online: http://www.celliant.com [Pristupljeno: 2.8.2018]

[69] Özdil N., Marmaral A., Kreschmar S. P.: Effect of yarn properties on thermal comfort of knitted fabrics, International Journal of Thermal Sciences 46 (2007.) 46, 1318–1322. doi:10.1016/j.ijthermalsci.2006.12.002

[70] Singh M. K., Nihram A.: Effect of Various Ring Yarns on Fabric Comfort, Journal of Industrial Engineering (2013). http://dx.doi.org/10.1155/2013/206240

[71] Jhanji Y., Gupta D., Kothari, V. K.: Comfort properties of plated knitted fabrics with varying fibre type. Indian Journal of Fibre & Textile Research 40 (2015.) 11-18

[72] Kanakraj P., Ramachabdran R.: Active Knit Fabrics – Functional Needs of Sportswear Applications, Journal of Textile and Apparel Technology and Management 9 (2015) 2

[73] Prahsarn C., Barker R. L., Gupta B. C.: Moisture Vapor Transport Behavior of Polyester Knit Fabrics, Textile Research Journal 75 (2005) 4, 346-351. https://doi.org/10.1177/0040517505053811

[74] Patil U. K., Kane, C. D., Ramesh, P.: Walkability behavior of single-knit structures. The Journal of Textile Institute 100 (2009) 5, 457. https://doi.org/10.1080/00405000801893240

[75] Hogan, K., McQuerry, M.: Assessment of Ventilated Athletic Uniforms for Improved Thermal Comfort and Human Performance©, International Textile and Apparel Association, Inc. INTERNATIONAL TEXTILE AND APPAREL ASSOCIATION (ITAA) ANNUAL CONFERENCE PROCEEDINGS, 2017.

[76] Suganthi T., Senthilkumar P.: Thermo-physiological comfort of layered knitted fabrics for sportswear, TEKSTİL ve KONFEKSİYON 27 (2017.) 4, 352-360

[77] Lokhande M. B., Patil L. G.: Awasare, A. U.: Suitability of Bi-Knitted Fabric for Sportswear Application. International Journal of Engineering & Technology 3 (2014.) 7, 428-436

[78] Teodorescu M.: Applied Biomimetics: A New Fresh Look of Textiles. Journal of Textiles. (2014.) 1-9. http://dx.doi.org/10.1155/2014/154184

[79] Eadie L., Ghosh T. K.: Biomimicry in textiles: past, present and potential. An overview. Journal of the Royal Society Interface 8 (2011.) 59, 761–775. doi: 10.1098/rsif.2010.0487

[80] Koch K., Barthlott W.: Superhydrophobic and superhydrophilic plant surfaces: an inspiration for biomimetic materials. Phil. Philosophical Transactions of the Royal Society A 367 (2009.) 1893, 1487–1509. doi:10.1098/rsta.2009.0022

[81] Good R. J.: A Thermodynamic Derivation of Wenzel's Modification of Young's Equation for Contact Angles; Together with a Theory of Hysteresis. Journal of the American Chemical Society 74 (1952.) 20, 5041-5042. doi: 10.1021/ja01140a014

[82] Neinhuis C., Barthloot W.: Characterization and distribution of water-repellent, self-cleaning plant surfaces, Annals of Botany 79 (1997) 6, 667–677. doi: 10.1006/anbo.1997.0400

[83] Park S., Kim J., Park C. H.: Superhydrophobic Textiles: Review of Theoretical Definitions, Fabrication and Functional Evaluation. Journal of Engineered Fibers and Fabrics 10 (2015.) 4

[84] Barthlott W., Neinhuis C.: Purity of the Sacred Lotus, or Escape from Contamination in Biological Surfaces. Planta 202 (1997.) 202, 1-8.

[85] Sun T., Feng L., Gao X., Jiang, L.: Bioinspired surfaces with special wettability, Accounts of Chemical Research 38 (2005.) 8, 644–652. doi: 10.1021/ar040224c

[86] Yabu H. and Shimomura M.: Single-step fabrication of transparent superhydrophobic porous polymer films, Chemistry of Materials 17 (2005) 21, 5231–5234. doi: 10.1021/cm051281i

[87] Avram P., Teoderescu M., Curteza A., Agrawal P., Brinks G.: Biomimetic approach, from lotus leaves to superhydrophobic materials. in Proceedings of the 14th Romanian Textiles and Leather Conference (CORTEP '12), Performantica, 2012.

[88] McCarthy J. T., Langmuir D. O.: Ultrahydrophobic Surfaces. Effects of Topography Length Scales on Wettability. Langmuir 16 (2000.) 20, 7777-7782. doi: 10.1021/la000598o

[89] Dawson C., Vincent J. and Rocca A.: How pinecones open. Nature, 390 (1997.) 6661, 668-668. doi: 10.1038/37745

[90] Pine cones inspire new materials that change their shape according to stimuli. Dostupno online: www.robaid.com/bionics/pine-cones-inspire-new-materials-that-change-their-shape-according-to-stimuli.htm [Pristupljeno: 10.8.2018].

[91] INOTEK. BIOMIMETIC. Dostupno online: http://www.inotek-textiles.com/technology/ [Pristupljeno: 10.8.2018].

[92] Textile World. Inotek™: Comfort Trought Adaptive Breathability. Dostupno online: https://www.textileworld.com/textile-world/features/2016/07/inotek-fibers-comfort-through-adaptive-breathability/

[93] Sarkar M., Fan J., Szeto Y., Tao X.: Biomimetic of Plant Structure in Textile Fabrics for the Improvement of Water Transport Properties. Textile Research Journal 79 (2009.) 79, 657-668. doi: 10.1177/0040517508095604

[94] Sharklet surface texture. Dostupno online: https://asknature.org/idea/sharklet-surface-texture/ [Pristupljeno: 10.8.2018].

[95] Science in the news. Dostupno online: http://www.scienceinthenews.org.uk/contents/?article=8 [Pristupljeno: 10.8.2018].

[96] Hassan M., Qashqary K., Hassan A. H., Shady E., Alansary M.: Influence of Sportswear Fabric Properties on the Health and Performance of Athletes. Fibers &Textiles in Eastern Europe 4 (2012) 93, 82–88

[97] Park S., Tokura H., Sobajima M.: Effects of Moisture Absorption of Clothing on Pitching Speed of Amateur Baseball Players in Hot Environmental Conditions. Textile Research Journal 76 (2006.) 383, 383–387. doi: 10.1177/0040517506063388

[98] Spurkland L., Bardal L. M., Sætran L., Oggiano, L.: Low Aerodynamic Drag Suit for Cycling. Design and Testing. Conference: International Congress on Sport Sciences Research and Technology Support (2015)

[99] Morita H., Chowdhury, H., Alam F., Subic A., Smith A. J., Jssim R., Bajaba N. S.: Contribution of swimsuits to swimmer's performance. Procedia Engineering 2 (2010) 2, 2505-2510. doi: 10.1016/j.proeng.2010.04.023

[100] NASA SPINOFF. Space Age Swimsuit Reduces Drag, Breaks Records. Dostupno online: https://spinoff.nasa.gov/Spinoff2008/ch_4.html [Pristupljeno: 10.8.2018].

[101] Speedo. Dostupno online: https://www.speedo.com/on/demandware.store/Sites-spdeueur-Site/BRG%3aen_MU?geoip=geoip [Pristupljeno: 10.1.2020].

[102] Chowdhury H., Alam F., Mainwaring D.: Aerodynamic study of ski jumping suits. Procedia Engineering 13 (2011) 376–381. doi:10.1016/j.proeng.2011.05.101

[103] Nussera M., Sennera V.: High - Tech - Textiles in Competition Sports, Procedia Engineering 2 (2010.) 2845–2850. doi:10.1016/j.proeng.2010.04.076

[104] SCIENCE for SPORT. Compression Garments. Dostupno online: https://www.scienceforsport.com/compression-garments/#toggle-id-1 [Pristupljeno; 12.1.2020].

[105] Engel F., Stockinger C., Wall A. and Sperlich B.: Effects of Compression Garments on Performance and Recovery in Endurance Athletes (2016.). doi: 10.1007/978-3-319-39480-0_2

[106] Pérez-Soriano P., García-Roig Á., Sanchis-Sanchis, R., Aparicio, I.: Influence of compression sportswear on recovery and performance: A systematic review. Journal of Industrial Textiles (2018). https://doi.org/10.1177/1528083718764912

[107] Kraemer W. J., Bush J. A., Bauer J. A., Triplett-McBride N. T., Paxton N. J., Clemson A. L., Koziris P., Mangino L. C., Fry A. C. and Newton R.: Influence of compression garments on vertical jump performance in NCAA Division I volleyball players. Journal of Strength and Conditioning Research 10 (1996.) 3, 180-183.

[108] Sperlich B., Born D. P., Kaskinoro K., Kalliokoski K., Laaksonen M.: Squeezing the Muscle: Compression Clothing and Muscle Metabolism during Recovery from High Intensity Exercise (2013). doi: 10.1371/journal.pone.0060923.

[109] Lovell D. I., Mason D. G., Delphinus E. M., McLellan, C. P.: Do Compression Garments Enhance the Active Recovery Process after High-Intensity Running? Journal of Strength and Conditioning Research 5 (2011) 12, 3268. doi:10.1519/jsc.0b013e31821764f8

[110] Bieuzen F., Brisswalter J., Easthope C., Vercruyssen F., Bernard T., and Hausswirth C.: Effect of Wearing Compression Stockings on Recovery after Mild Exercise-Induced Muscle Damage. International Journal of Sports Physiology and Performance 9 (2014.) 2, 256–264. doi:10.1123/ijspp.2013-0126

[111] ADIDAS NEWS STREAM. Dostupno online: http://news.adidas.com/GLOBAL/Latest-News/ALL/New-adidas-apparel-lowers-your-temperature-and-raises-your-game-/s/27ef4204-b319-480a-9f97-18df78412f6b [Pristupljeno: 10.10.2018].

[112] Revievs. It's Cool—Really Cool—to Wear adidas Climachill Athletic Shirts When Temperatures Skyrocket! Dostupno online: https://www.runsociety.com/reviews/its-cool-really-cool-to-wear-adidas-climachill-athletic-shirts-when-temperatures-skyrocket/ [Pristupljeno: 10.10.2018].

[113] Van Parys, M.: Development and Research of Smart Functional Clothing Textiles. Dostupno online: http://www.golf.com/equipment/fashion-3-d-how-climacool-works [Pristupljeno: 10.10.2018].

[113] Columbia Omni-Freeze Zero fabric produces cooling effect from sweat. Dostupno online: https://newatlas.com/columbia-omni-freeze-zero/22902/ [Pristupljeno: 13.10.2018].

[114] GearJunkie. Magic Material? Clothing said to 'Cool Wearer with Sweat'. Dostupno online: https://gearjunkie.com/columbia-sportswear-cooling-clothing [Pristupljeno: 14.10.2018].

[115] NikePlus. WHAT IS NIKE DRI-FIT? Dostupno online: https://help-en-us.nike.com/app/answer/a_id/204 [Pristupljeno: 15.11.2018].

[116] Aydoğdu G., Yeşilpinar S. and Erdem D.: Evaluation of three-dimensional virtual perception of garments. IOP Conf. Series: Materials Science and Engineering (2017). doi:10.1088/1757-899X/254/15/152001

[117] Petrak, S., Mahnić, M., GERŠAK, J.: Sizing and fit for swimsuits and diving suits. V: Zakaria, N., Gupta, D. (ur.). *Anthropometry, apparel sizing and design*, (The Textile Institute book series). 2nd ed. Duxford; Cambridge; Kidlington: Woodhead Publishing; [Manches-

ter]: The Textile Institute. cop. 2020, str. 255-287, doi: 10.1016/B978-0-08-102604-5.00010-X.

[118] D'apuzzo N.: Recent advances in 3D full body scanning with applications to fashion and apparel. Optical 3-D Measurement Techniques IX, Vienna, Austria, (2009).

[119] Smart Body – Ergonomic Seamless Sportswear Design and Development. Dostupno online: http://iffti.org/downloads/papers-presented/x-RMIT,%202008/papers/p141.pdf [Pristupljeno: 28.12.2018].

[120] Chowdharhy H., Alman F., Mainwaring D., Subic A., Tate M., Foster D., Beneneyto-Ferrw J.: Design and Methodology for Evaluating Aerodynamic Characteristics of Sports Textiles, Sports Technology 2 (2009) 3, 81-86. doi: 10.1080/19346182.2009.9648505

[121] Chowdharhy H., Alman F., Subic A.: Aerodynamic Performance Evaluation of Sports Textile, Procedia Engineering 2 (2010.) 2, 2517-2522. doi:10.1016/j.proeng.2010.04.025

[122] Morita H., Chowdharhy H., Alman F., Subic A., Smith A.J., Jssim R.; Bajaba N. S.: Contribution of swimsuits to swimmer's performance. Procedia Engineering 2 (2010.) 2, 2505-2510. doi: 10.1016/j.proeng.2010.04.023

[123] Mingliang C., Yi L., Yueping G., Lei Y., Zhigeng P.: Customized Body Mapping to Facilitate the Ergonomic Design of Sportswear. Published by the IEEE Computer Society 35 (2016) 6, 70 – 77. doi: 10.1109/MCG.2016.110

[124] Jariyapunya N., Musilova B., Geršak J. and Baheti S.: The influence of stretch fabric mechanical properties on clothing pressure. Vlákna a textile 22 (2017) 2, 43-48

[125] Mahnić M., Petrak S., Geršak J., Rolich T.: Analysis of dynamics and fit of diving suits. V: 17th AUTEX 2017 World Textile Conference, Shaping the Future of Textiles, 29-31 May 2017 Corfu, Greece, (IOP conference series. Materials science and engineering (Online), ISSN 1757-899X, vol. 254). Bristol (UK): IOP Publishing Ltd. 2017, pp: 1-6. doi: 10.1088/1757-899X/254/15/152007