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Eco-Design of Multifunctional System Based on a Shape Memory Polymer and ZnO Nanoparticles for Sportswear

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Abstract**—**Since the beginning of the 20th century, sportswear has a major contribution to the impact of fashion on our lives. Nowadays, the embracing of sportswear fashion/looks is undoubtedly noticeable, as the modern consumer searches for high comfort and linear aesthetics for its clothes. This compromise lead to the arise of the athleisure trend. Athleisure surges as a new style area that combines both wearability and fashion sense, differentiated from the archetypal sportswear, usually associated to "gym clothes". Additionally, the possibility to functionalize and implement new technologies have shifted and progressively empowers the connection between the concepts of physical activities practice and well-being, allowing clothing to be more interactive and responsive with its surroundings. In this study, a design inspired in retro and urban lifestyle was envisioned, engineering textile structures that can respond to external stimuli. These structures are enhanced to be responsive to heat, water vapor and humidity, integrating shape memory polymers (SMP) to improve the breathability and heat-responsive behavior of the textiles and zinc oxide nanoparticles (ZnO NPs) to heighten the surface hydrophobic properties. The best results for hydrophobic exhibited superhydrophobic behavior with water contact angle (WAC) of more than 150 degrees. For the breathability and heat-response properties, SMP-coated samples showed an increase in water vapour permeability values of about 50% when compared with non SMP-coated samples. These innovative technological approaches were endorsed to design innovative clothing, in line with circular economy and eco-design principles, by assigning a substantial degree of mutability and versatility to the clothing. The development of a coat and shirt, in which different parts can be purchased separately to create multiple products, aims to combine the technicality of both the fabrics used and the making of the garments. This concept translates itself into a real constructive mechanism through the symbiosis of high-tech functionalities and the timeless design that follows the athleisure aesthetics.

Keywords**—**Breathability, sportswear and casual clothing, sustainable design, superhydrophobicity.

I. Introduction

NOWADAYS, consumers evolved to a more comprehensive approach of their clothes, both on their functionalities as well as in their environmental impact. Considering the more traditional approach to sportswear, there was a lack of significance given to its aesthetic and to its fashionability. There was a strict distinction between the clothes that you wore on your sports activity or on the gym and the clothes worn for your job or your leisure time. However, the rise of fitness as not only a hobby but also as an all-around lifestyle, combined with the increased interest of consumers on comfort and functionality [1] lead to the rise of a new trend – athleisure, allowing the refinement the degrees of formality for each social/professional occasion.

Athleisure has been a major contributor in the sportswear market growth, resulting in an inflation of 42% in the last eight years, and was valued in 2018 at $270bn dollars [2]. Thus, it has evolved from being considered a fad to be now widely and globally considered as a "super trend".

In 2017, there were a small bump on the road for athleisure; however, it still managed to increase in rates of around 7%, less than in previous years, but well above regular fashion and footwear – *ca.* 3%. Indeed, it is projected that the activewear market could hit 350$bn globally in 2020 [2]. Even the initial definition of athleisure has now evolved, from simply being considered as the use of gym clothes outside this environment and the consequent (misguided) judgment of someone being sloppy or lazy, to be considered a versatile way of dressing. The combination of comfort with performance and the appeal of streetwear gave a spotlight to this type of clothing, which led to a high investment of major brands on this sector - strong products both on its performance as in its projection, branding and merchandising.

Another key development on consumers' mind was the impact of sustainability in clothing. The fast fashion driven market – the annual production level for this kind of garments has doubled since 2000, establishing a remarkable maximum level of production, above 100 billion garments, in 2014 - according to McKinsey's Sustainability & Resource Productivity 2016 report [3] – is now slowly shifting to a more sustainable driven one. Positively, there are lots of different approaches that could help diminish the impact of fashion on environment – from the selection of raw fiber, to the decrease in chemical use on the processing of fabrics to the design of garments to have an increased life, there are now countless brands, movements, non-governmental organizations (NGOs) and even research institutes focusing on this huge task. Thus, nowadays, eco-design is a must when presenting new products, even when considering the use of recycled and not virgin materials.

Eco-design is a sustainable design approach, considering the environmental impact of the product during its whole life cycle. The life cycle of a product mainly includes 4 phases: procurement, manufacture, use and disposal [4]. Life Cycle Assessment (LCA) is a methodology to review and weight the environmental impacts and resource consumption implicated

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along transformation and expenditure cycle, “from cradle to grave” *per se*, of a product [5], [6]. Starting from raw material extraction, it considers material processing, manufacture, distribution, use, maintenance and repair, and disposal. The traditional 3R concept promoting green manufacturing technologies (Reduce, Reuse and Recycle) has been surpassed by the more recent 6R concept forming the basis for sustainable manufacturing (Reduce, Reuse, Recover, Redesign, Remanufacture, Recycle) reshaping an open-loop, single life-cycle paradigm to a theoretically closed-loop, multiple life-cycle paradigm [7].

The main goal of this work was to develop and produce two distinct garments, interchangeable and with parts that can be removed to be used with different purposes (bag, backpack among others). The garments were designed and imagined considering a concept of modularity, due to the use of different fabrics to be applied in different parts of the body, leading to an increased life cycle of the final product. This increment is achieved by the versatility of the garments obtained (different combinations of the “modules” lead to garments ideal for sports activity or to be used on everyday life) as well as with the increased quality of the raw materials used and the fashionability of the final garments.

II. Materials and Methods

A. Fabrics

Cotton is one of the most abundant natural fibers in the world and has been used as a textile fiber for over 7000 years. This fiber has been receiving exhaustive attention in technical textiles, due to its excellent properties such as biodegradability, high mechanical stability, strong absorption, capability and low cost [8], [9]. It can be said that this fiber was linked to the remote origin of clothing and to the evolution of textile production [10], [11]. Cotton is essentially composed of cellulose (90-93%) and a small percentage of waxes and minerals, 7-10%. It has a soft and a warm feel to touch. Regarding the mechanical and physical properties, this fiber has some elongation range between 6 and 9%, a fiber length within 13-40 mm and a density of 1,55 g/cm^3. It also exhibits high levels of moisture absorption and water retention. The elasticity of the cotton is relatively low, but it has sufficient elongation, having the best values for vegetable fibers [12]. The main goal of the cotton production is to deliver the highest quality products economically viable and with the lowest environmental impact. However, currently, conventional cotton production depends on the use of the chemical products, fertilizers and wastes obtained from agriculture production. In contrast, the organic cotton production does not allow the use of many synthetically compounded chemicals, such as fertilizers, growth regulators, insecticides, among others. In this way, the production of the organic cotton is considered more environmentally friendly [13].

The use of yarn made from recycled fibers, which are used in final products is increasingly common in areas such as home textiles, fashion items, sportswear and many other categories. The most common recycled fibers are polyester and cotton, but nowadays other fibers including wool, nylon and even aramids are recycled to produce yarn [14]. Polyester is a synthetic fiber composed by terephthalic acid and ethylene glycol. This type of polyester has excellent abrasion resistance and tensile strength (tenacity) properties, as well as good wrinkle resistance. This type of synthetic fiber can be spun together with natural fibers, in order to reach some blended properties (i.e. blends of cotton and polyester can improve the tear-resistant and reduced shrinkage) [14].

Polyamide is a synthetic fiber and it is considered as the noblest fiber of this group. It is very versatile and is used for various applications from lingerie, thin socks, sports and leisure wear, sewing thread, rugs and even in technical applications such as balloon fabric, falls, cloth for cars among others. It has high mechanical resistance (6-8.5 g/den), low moisture absorption and high softness. Furthermore, different finishing materials can be easily applied to this fiber, allowing the production of fabrics with different visual aspects [15]. Nylon and aramid fibers are a part of the polyamide fiber groups. Nylon fibers generally are tough, durable and useful for the variability of textile applications, and aramid fibers have exceptional mechanical strength, dimensional stability and resistance to elevated temperatures [15], [16].

Elastane is well recognized for its high elasticity and is usually used as the generic term to describe fabrics such as Lycra or Spandex. This fiber is composed by a long chain polymer, popularly known as polyurethane (PU). However, in more technical circles this is known as a fully synthetic polyether-polyurea copolymer [17]. In terms of properties, this material is recognized for its high temperature resistance, softness, high breathability and high elastic deformation capability (400-700%), which makes this material ideal for incorporation into various types of polyester. Therefore, elastane may be used in different percentages in order to provide more or less resistance to the expansion of the textile structure [18].

In the past, cotton was the most used material for the sportswear production. However, the prevalence of synthetic fibers such as polyester, polyamide, elastane (Spandex), nylon, polypropylene among others have been increasing [19].

Athletes increasingly want to wear lighter clothing that keeps them at a desirable body temperature for sports. For this purpose, new generations have sought to offer the best heat/ weight ratio by focusing on reducing volume without reducing isolation [20].

All these specifications and features from a fiber scale were manipulated to produce technical knits in order to increase the level of operability and structure of the garments. Hence, knits were conceived and manufactured by Tintex Textiles SA (Vila Nova de Cerveira, Viana do Castelo), having as a result the following textile pieces, where the science of knitting, dyeing, finishing and coating was strived to deliver different and unique compositions, constructions and characteristics:

- Loop back jersey: 62% cotton/36% polyamide/2% elastane, with a mass per unit area of 280 g/m^2 - Super elastic article with dimension in all directions. Idea of modulation/transformation of the body, physical and motor adaptation combined with electric tone ideal for active wear;

- Interlock 100% cotton, with a mass per unit area of 410 g/m^2 - Natural and fluid movement with a soft touch. Ideal for active and comfortable clothes due its weight and stability;
- Jersey 100% polyester, with a mass per unit area of 105 g/m^2 - The application of extra-fine cork coating formulation in a light and delicate knit results in an innovative jersey by the color and texture of the coating – unique technology with a granulometry delimitation process, using pre-consumer cork waste. Recycled polyester structure featured as Extra Fine Cork where cork is more fluid and delicate. The perfect product for those who love performance and fashion;
- Loop back jersey 100% cotton - Delicate structure of discreet diagonals designed for an active life that reconciles formal appearance and casual comfort. This loopback jersey has smaller loops on the back, which makes this knit a little lighter weight in feel. It has excellent drape and a luxurious feeling with a subtle glow. The face of the knit is formed by a coating layer with a soap touch hand feel, which will naturally perform the water resistance and permeability.

The materials used for the hydrophobicity improvement were zinc acetate dehydrated ($Zn(CH_3COO)_2.2H_2O$) and sodium hydroxide (NaOH). The synthesis of the ZnO NPs was made accordingly to the method described in [21], with some modifications. For the deposition of the NPs into the coating surface different approaches were tested, in order to select the best method for ZnO NPs finishing. The best method for the ZnO NPs finishing was using the dip-pad-dry technique and drying at 100 °C for 3 min, as shown in [22].

The material used for the enhanced of the breathability of the fabrics was a SMP (MS-2520) obtained from SMP Technologies Inc. The application of this material in the fabric surface was made using a flat screen textile printing machine. After the printing all the samples was pre-dried at 120 °C for 5 min, to remove the polymer solvent (DMF) and thereafter cured at 150 ° for 10 min.

The ZnO functionalized samples were characterized and evaluated by Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive Spectroscopy (EDAX), Ground State Diffuse Reflectance (GSDR), WCA and the SMP-coated samples by FESEM, optical microscopy, water vapour and air permeability tests. The wash fastness of all samples was also evaluated.

B. Garments

The manufacture and design of all the garments were aligned with the principles pointed by the anatomy and physiology of sport and exercise sciences, aiming to, seamlessly, endow the textile elements with the capabilities of managing autonomously the homeostasis and react to cyclic body motions, acting in the muscular contraction and relaxation, and in the body impulsion, movement, posture, metabolism reactions, such as sweat eradication and thermoregulation. This was envisioned by assigning breathability/acclimation sections, one for each side of the body in the armpit, down to the hip regions, and across the dorsum. The hydrophobic behaviour and water repellent actions were assigned to the hood accessory, which is adapted both for the jacket and sweater, as well as to the sleeves of the jacket.

In order to address the versatility and easiness of the alteration and mutability procedure, a combination between the garments and the following fasteners and stitching techniques was assembled:

- A subtle 15 mm painted neutral metal snaps for both the sweater and jacket short sleeves;
- A central hidden 6 mm neutral metal spiral zipper, of 65 cm length, for the jacket main structure, and two 4 mm neutral metal spiral zipper, for the jacket long sleeves;
- The garment parts were stitched with 301 and 406 class types;
- A 5 mm neutral drawstring, composed by 100% cotton, of 1.5 m length, for the hood.

Furthermore, circular economy and process sustainability policies are focused on the selection of these materials, valuing and revitalizing the least traded materials that constitute the product stock.

III. Results and Discussion

A. Fabrics

The wettability is one of the most important properties when it comes to superhydrophobicity. The chemical composition and geometrical structures (roughness) of the surface influence this property. In order to evaluate the wettability of the samples and to ensure the accuracy of the results, the WCA was measured for all samples in 10 different sites. When the WCA is equal or higher than 150° the surface is considered superhydrophobic. When WCA is equal or higher than 90° and equal or lower than 120° the surface is only considered hydrophobic [23]. When the ZnO NPs were incorporated onto the fabrics, the WCA increased for the superhydrophobic level. Characterization analyses confirmed that the ZnO NPs were conferred in the finishing of the fabrics surface and disclosed that from all tested concentrations, the 0.2 M concentration is the only one that reaches the superhydrophobicity level, with WCA values of 153° which proves that the precursor concentration (zinc acetate) used in this synthesis influenced the hydrophobic properties of the samples, as can been shown in [22]. All the other characterizations analyses led to the conclusion that the ZnO NPs were incorporated onto the fabrics efficiently, by the dip-pad-dry technique.

Breathability is the ability of the textile to control vapour release/permeation, mainly characterized by its water vapour diffusion/transfer rate through the textile structure to the surrounding atmosphere. It is an essential property in different textile areas, namely in sportswear, where it is necessary to provide thermal and physiological comfort to the users [24]. In order to evaluate the responsive performance of the SMP-coated samples, a water vapour permeability test was performed under controlled temperature and humidity conditions. This assay was done for 16 h and, the temperature was approximately 35 °C. The results showed that the SMP coated sample has higher permeability values than the uncoated samples, with an increase of about 50%. Thus, it was possible to conclude that the behavior of the SMP coating adapts to a dynamic thermal disturbance characteristic of the body. This result is very important for the breathability and humidity release of the samples, which is essential in sportswear clothes. Furthermore, through the optical microscopy analysis it was possible to verify that the pores of the samples expanded and shrunk accordingly to the temperature variation. When the temperature gets close to 35 °C the pores of the SMP coated samples opened about 20 µm, making the sample more breathable. The same was confirmed by the air permeability test, where the SMP coated fabrics showed higher values than the uncoated fabrics. Above 40 ºC the material does not respond to the stimulus, so it is possible to conclude that the polymer has a stagnation temperature.

This work validated the development of superhydrophobic and breathable surfaces, obtained through the ZnO NPs finishing and SMP coating respectively, for sportswear clothes.

B. Garments

Two main garments were envisioned during this work: a) a transformable jacket-vest, mutable with b) sweater that reversely switches into a t-shirt, Fig. 1.

Fig. 1 Sketches of the envisioned garments

To increase the lightness of the upper body protection it was additionally conceived a hood as an accessory that is also mutable into a bag, Fig. 2.

The interchangeability of the envisioned garments surges from an increasing inclusion and adaptability of sportswear to our everyday lifestyle, reflecting the fast pace to which, more and more, humans are used to and endure. There are almost no free times, leading to the need of more practical, adaptable and comfortable garments, allowing free movements, acting as a perfect second skin by minimizing physical restrictions or stress.

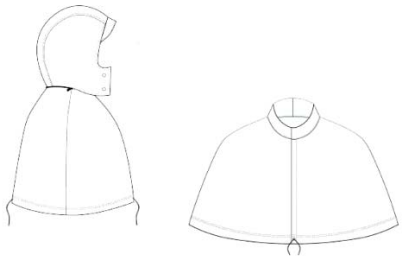

Fig. 2 Sketch of the hood

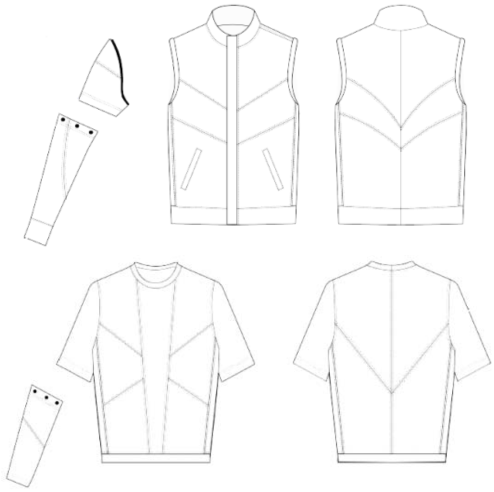

Fig. 3 Interchangeability illustration on the designed garments

Considering the technical requirements of these materials, an approach to the final product was envisioned by merging/ hybridizing two fashion styles, sportswear and business casual. Thus, the focus was not to develop a line for sportswear, but to create a line of products where the sportswear spirit was impressed, only as a graphic and visual reference. In order to be able to answer to these assumptions, a group of connections and approaches, linked to the visual culture of the urban and sport lifestyle, was outlined. Establishing the correlation of different concepts of personality, color, geometric shapes, lines, versatility, adaptability, dynamic, overlapping, was essential as these are some of the main factors that could support the guidance, definition and shaping of the proposed ultimate goal. The evaluation and comprehension of these factors needs to be crosslinked simultaneously, with the imagination/application/ adaptation of sport nature, for the development of garments for casual use.

After a thorough analysis, of the actual trends and behavior of consumers, the retro style was identified, as a cared bonding factor between the past and the present. Nowadays, shapes and lines are oriented to a more playful language - displaying fun and the ludic part of our lives – in order to interact in a very emotive way and dimension, aiming to have an impact on the state of mind and personality of the consumers and its surrounding counterparts. The cuts made on the garments point directly to the abdomen – centre of vitality and energy, according to the traditional Japanese concept *Hara* – focusing and concentrating the attention to our gravitational center, which takes us to an introspection inducing neutral and reassuring vibes. Blue, main color presented on the garments, is traditionally associated to "tranquility universe". This color varies in the different applications where it is presented - these chromatic nuances depict the emotional fickle flow for which the human being is faced upon, not only on its everyday life, but also throughout its life. Red surges as a symbol of positivity and strength, notions that must, at all moments, surround our vital energy, our personal focus.

Overall, shapes, colors and patterns can also be connected to urban subcultures – with strong emphasis on the 70´s and 80´s. These decades were a landmark of aesthetic movements focusing on freedom of speech, provocation and revival, with a heavy influence of the pop culture of the time. Thus, the search of lines with identity and personality emerged as a concept capable of transmitting dynamic, versatility and adaption with high impact in different cultures, capable of distinguishing generations and creating icons.

Aligning suburban aesthetical approaches of the 70´s and 80´s, it can be easily distinguished the need of mutability and versatility. The fact that the products can be distinguished as a graphic interface capable of adjustment and update through interchangeable parts and, adaptability towards everyday challenges, allows consumers to be able to consider them as a "live organism" in constant transformation. This evolution/ comprehension leads to the search for the equilibrium between the human and product state of affairs, by combining the retro and vintage style with the capability of establishing a Consumer-Product bond.

The details used for the finishing of the garments – sews on the outside – depict the need in internal change that posteriorly will cause external repercussions, gradually visible. Soothing hand feels guarantee a mutable protection, underlined by the modularity of the garments. All these design theories and details were addressed to foresee and produce garments that unfold multiply – jacket transformable into vest, a sweater that transforms into a t-shirt – as it also appeals to the internal unfolding and resolve, needed for the well-being of each individual, positively interacting in its community and the world.

IV. Conclusions

Altogether, the high-end functionalization and design components, imparted into the garments, aim to acknowledge the clothing industry and trading paramount needs, pointed throughout this paper. The achievement of super hydrophobicity and increased permeability are two milestones for the presented garments, that aim also to be aesthetically appellative as well as modular, in its response to the versality of the day to day climate or closed environments conditions of most humans.

Nowadays, one of the biggest challenges that fashion industry faces in its path to sustainability is fast fashion or the overconsumption that the fashion world is showing. This work embraces this challenge on a different level, much to what was presented by *Fletcher and Grose* [25]: "Yet, if the ultimate goal of optimized lifetimes is to slow the natural resources through fashion system, then designing more emotionally durable products may be as limited a strategy as physical durability". The envisioned artwork pieces, detailed in this work, attempt to incite a wider impact towards the rhetorical perception of the concept of clothing, by combining several different approaches, instead of using a unidimensional one.

Idealizing the implementation of technological concepts on the fashion industry, this work aims to overcome the prejudice surrounding fashionable gimmicks, evolving them from a mere fad to what we envision as the possible future of sophistication in garments.

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