# E-textiles the Need to Breath: A Novel Manufacturing Process and Textile for Lightweight Transparent Sustainable E-textiles and Wearables

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***Abstract*—The adoption and growth of e-textiles and wearables is largely reliant on how discreetly electrical devices can be applied without limiting functionality and compromising textile qualities. Electrical components are an important parameter for a variety of applications where devices are required to be in close proximity to the skin. One example is within the health and leisure industry, where sensors are used for monitoring and tracking bodily functions. Historically, electronics were aesthetically intrusive when applied to textiles, although, by becoming smaller and flexible this is less of an issue. A method to compliment those advancements further would be to incorporate small electrical components into a complimentary, open structured, lightweight, transparent textile. This would provide increased breathability and reduce fabric weight, resulting in more comfort for the user. This paper introduces a novel manufacturing process that accommodates these features. A process whereby fabrication is achieved through entangling the fibres on the surface of yarn. Observation is used to assess the level of fabric openness in relation to air permeable capacity, transparency and end weight. Quantitative methods were used via tensile testing to establish if textiles manufactured by the novel process met industry strength requirements. Eight samples were tested in total, each showed slight variations in results. For example, two samples tested in the weft direction showed a difference of 40% strain capacity. It was assumed the irregularity was the result of differing quantities of fibre on the yarn surface used for entanglement. However, all eight samples that underwent tensile tests were confirmed to meet the British Test Standard ISO 2062.**

***Keywords-Wearables; Transparent e-textiles; breathability; Sustainable e-textiles; Novel textile manufacturing process; Lightweight e-textiles; electronic textiles; textile innovation***

## I. INTRODUCTION

Textiles are one of mankind's most used products. The earliest references to textiles come 27000 years ago in the form of impressions on pottery of yarn [5]. The earliest woven material was found in southern Turkey in Cayonu and is dated at 7000 BCE [2]. The earliest known examples of knitting have been found in Egypt and dates between the 11$^{th}$ and 14$^{th}$ century CE [6]. The knitting process involves the interlooping of a single yarn and the weave process involves the interlacing of at least two yarns [4]. Nonwoven fabrics are created from fibre webs that have not been spun into yarn [9]. Continuous agitation and pressing results in the hooking together of the fibre creating a uniform piece of nonwoven fabric [2]. Despite the multidisciplinary nature of electronic textiles and the market predicted to 'approach $5 bn by 2027' [3], the process for manufacturing e-textiles and wearables is limited to the three ancient practices. Wearable technology is a growing field. This can be credited to the decrease in size of electrical components and changes in people's attitudes toward personal electronics [8]. This further supports the need for additional textile manufacturing technology with the capacity to support the trend of electronics miniaturization.

The structure of this paper consists of the following: Section 2 provides the objectives of the research. Commencing by giving clarity to how the new process differs from known textile manufacturing. Methods is then presented in section 3, and this section identifies the methodology, machinery and materials used in this investigation. In section 4, the procedure, testbed, challengers and failures are discussed. Focus is given to revealing how the new process lends itself to particular aspects of current manufacturing practices, also, production challengers are addressed. Section 5 presents the results from the quantitative data collected. This information was derived from tensile tests obtained from eight samples manufactured by the new process. In section 6, there is discussion on fabrics created by the novel process. Particular attention is set around the capabilities and benefits that the new structure offers. This discussion is followed by the conclusion, section 7. Presented, is a summary of the functions, potential of the novel process and products created. Lastly, this section concludes by identifying industry sectors who would find value from the new method and materials.

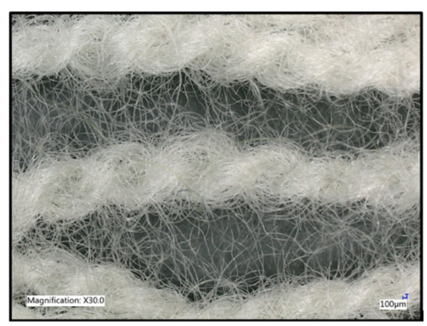


Figure 1. Microscopic image of the novel textile.

## II. OBJECTIVES

This paper presents a novel manufacturing process and textile that is created by yarn that requires neither interlinking or interlooping as in the woven and knitting structure. Therefore, providing a textile surface more suitable for the inclusion of electronics. The differing properties of electronics and textiles such as durability (bend, stretch, twist and shear) is a concern for e-textile development [1]. The new manufacturing process removes the necessity to bend the e-yarn or filament, totally removing interloping and interlacing, which have proven problematic during the production of E-textiles and wearables. In contrast, the new textile manufactures a fabric with a linear structure allowing individual yarn strands to be fully visible, as in Figure 1. Thus, allowing a straight surface for electrical components to easily and discreetly be attached or embedded, as in Figure 4.

FOYSE® is the name given to the novel manufacturing process. The word FOYSE is derived from the acronym: Fibre On Yarn Surface Entanglement. Two fabric structures have been manufactured using the FOYSE process to demonstrate design capability named Zephlinear® and Hover-Tex™. The name Zephlinear is derived from two words Zephyr and Linear and applied when the FOYSE process is used to manufacture a textile with one layer of yarn as in Figure 1 and 2.

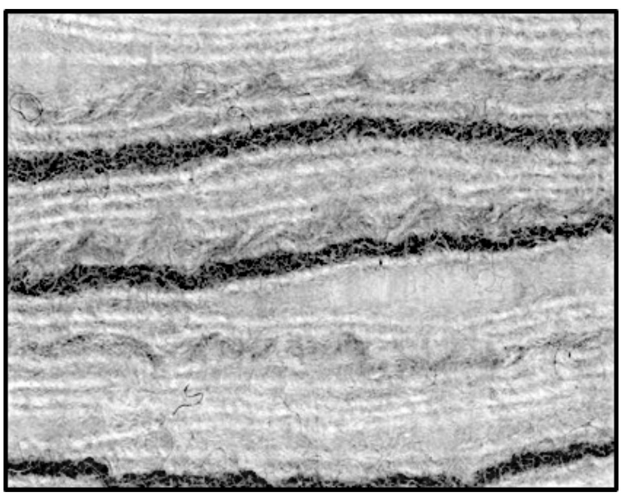

Figure 2. S. M. Reynolds, *Zephlinear Single Layer Stripes Multi Yarn Count (ZL047)*, Pennsylvania: University of Pennsylvania Fisher Fine Arts Library Material Collection.

Hover-Tex is applied when the FOYSE process is used to create a minimum of two-layers of yarn, giving the appearance of the second layer of yarn to hover over the first. The layering method provides space for the embedding of additional elements such as yarns or filaments as in Figure 3 and Figure 4. Hover-Tex is constructed by laying out one layer of parallel array of yarn and then a second layer placed at a 90-degree angle to the first. It is important to note that the process is not limited to create fabrics with a linear appearance, but yarn colour and positioning can be used to create a preferred end appearance or function. The fabric surface Hover-Tex is the material that will undergo mechanical testing and be discussed in this paper.

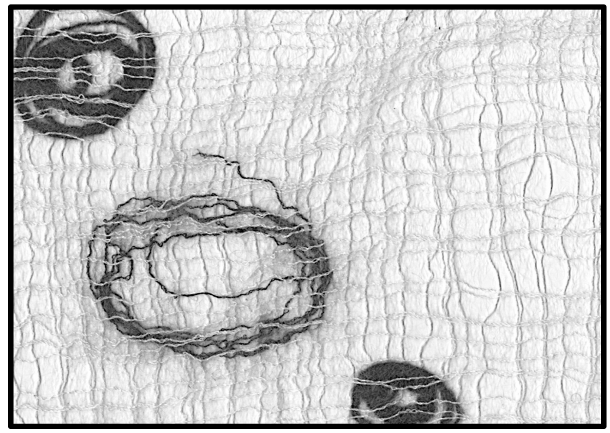

Figure 3. S. M. Reynolds, *Zephlinear Swirls Within Open Net (ZL044)*, Pennsylvania: University of Pennsylvania Fisher Fine Arts Library Material Collection.

## III. METHODS

Quantitative data was collected via tensile tests on eight Hover-Tex fabric samples. This data collection method is an established process to measure the breaking point of a textile material. By doing this, fabric strength is also determined. In addition, results provide numeric data that can be interpreted into several forms. Tensile tests were utilized as they are a proven method for evaluating the development of new materials while providing valuable information about a fabric and its associated properties. The sample in Figure 4 and 5 are manufactured using three layers of yarn. A first and third layer of yarn, 70% mohair and 30% silk, and the second layer of yarn, 100% merino wool twisted with fine copper wire containing a programable LED. The Hover-Tex fabric was divided into eight equal parts for tensile testing. Four samples in the warp direction and four in the weft direction to obtain breaking points and elongation measurement, which are illustrated in Figure 6 and 7. Visual observation was conducted with the LED switched on and off to demonstrate level of transparency and discreet embedding.

## IV. PROCEEDURE, CHALLENGES AND FAILURES

FOYSE manufacture is a semi-automated process that utilizes a hybrid approach, composed of adopting elements of the three current textile production methods. Laying out of a parallel array of yarn as in the woven process. The use of a single feed, or multiples thereof, to carry yarn similar to the knitting process. The entanglement of fibres via a wetting and drying of fibre as in the nonwoven process, albeit unlike nonwoven, this takes place after fibre has been spun into yarn. Yarn with high surface hairiness proved suitable for surface fibre entanglement. Yarns with minimal surface hairiness underwent an uncurling process via a brushing system to increase the capacity of surface fibre for entanglement. An Olympus Digital Microscope was used as a testbed to observe samples created by FOYSE. A Z2.5 Zwick/Roell tensile testing machine was used as a testbed for mechanical testing of FOYSE manufactured fabrics resistance against force. Optical microscopy, image analysis and tensile tests were conducted to investigate an assumed correlation between yarn surface entangled fibre, open areas and material strength. The research produced multiple challenges and failures, namely, methods to ensure fibre entanglement was limited to the fibre on the yarn surface. Identifying a method to regulate yarn position during entanglement is a present challenge as some yarns shift during the wetting and drying process. This results in yarns curving slightly which create fabrics with a wavy appearance.

## V. Results

Eight samples in total underwent tensile testing, four in the warp and four in the weft direction. The results from the first cycle of four Hover-Tex samples to be tested are presented in Figure 6 and 7. The warp of the Hover-Tex sample was constructed from mohair and silk mix yarn. The result stress-strain curve deviates from proportionality abruptly. This occurred as the yarn snapped due to pressure applied by the tensile testing machine. This resulted in changes at a peak point producing a zig zag visual appearance on the stress curve shown in Figure 6. The large open space per Hover-Tex sample also contributed to the sharp changes. In addition, the tight spinning of the mohair and silk yarn would contribute to the harsh change in the curves. The abrupt snapping of the yarn occurs at breaking point when the samples cannot withstand the stress applied, such as the nature of the tensile testing. The curves W2 and W4 exhibit breaking points 50% earlier than W1 and W3. This can be attributed to the samples having fewer yarns in the weft which can occur during the current manufacturing process. The results from the second cycle of four Hover-Tex samples to be tested are presented in Figure 7. The weft of the Hover-Tex samples is constructed from merino wool yarn. The stress curves on the graph presents a steady decline of each of the four curves in contrast to the snapping action portrayed in the samples in the warp direction. This illustrates that, although the merino yarn had less stress resistance, it provided almost 50% extra elongation capacity. Weft samples W2 and W4 showed a difference of 40% strain capacity. This is contributed to the slight variation in the length of fibre used to manufacture the yarn during the spinning process, in addition, the irregularity in which the fibre on the surface of the yarn entangles. Results confirmed that all samples have resistance strength suitable for textile material according to British Test Standard ISO 2062.

## VI. Discussion

Hover-Tex fabrics provide a structure with a unique linear appearance. In addition, they provide channels that offer an uncomplicated method for seamless insertion of electronic devices. The FOYSE process of manufacturing textiles, including adding yarn layer upon layer, provides benefits unachievable by woven and knitting technology. The removal of interlacing and interloping provides space between the layers of yarn to embed large or irregular shaped non-textile components. Incorporating different types of yarn elements and embellishments can dramatically alter the fabrics' unique appearance and character. Assembling the fabric with thick and thin yarns, or coloured yarn can create artistic designs that enhance visual appeal. The new textile can potentially weigh 70% less than traditional fabrics due to large open areas and air circulating the raised fibres on the yarn surface. This provides superior breathability, which in turn, enhances skin comfort as textiles are often used to regulate temperature, moisture levels and airflow.

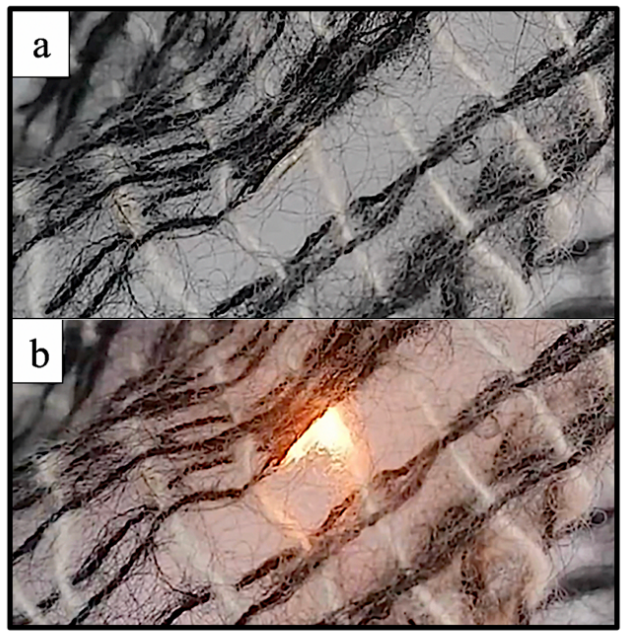


Figure 4. A 3mm light-emitting semiconductor device (a) switched off (b) switched on, embedded with Hover-Tex.

Control of airflow in woven and knit structures have been obtained by tightening or loosening the tension in the warp and weft to open up a gap in the fabric. However, this creates a fabric prone to movement, as within the woven and knitting process, the tightness of the interlacing or interloping contributes to the rigidness of the fabric. FOYSE fabrics provide options for increasing or decreasing insulation to regulate heat or cool, without loosening the fabric structure. This is due to the entangled fibre on yarn surface that sets the yarns in place. The level of fibre entanglement on the surface of yarn is only visible via observation through a microscope.

In Figure 5, the black fine yarn appears to rest or hover above the white yarn. Therefore, fabric manufactured by the FOYSE process can appear fragile and unrealistic for textile

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use. However, tensile test results shown in Figure 6 and 7 contradict the fragile visual appearance. The size of the open sections can be large yet have no bearing on moveability of the yarns once the fabrics manufactured by the FOYSE process have been finished. This is due to the fabric strength lays within the actual yarn or entangled fibres on the yarn.

Figure 5. Hover-Tex 2sq m sample with a 3mm programmable light-emitting semiconductor device switched on. Coin battery holder and circuit to power and control embedded device.

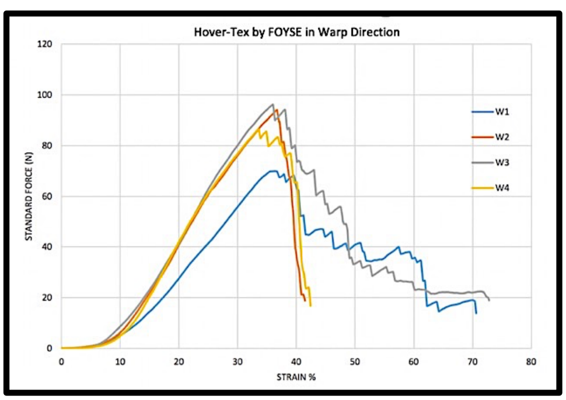


Figure 6. Results from the four Hover-Tex samples in the warp direction.

It is important to note, the yarns used to manufacture the Hover-Tex samples discussed in this paper are commercially available. Therefore, it is recognised that strength tests are conducted to confirm the yarn adequacy for constructing a textile. The FOYSE manufacturing process did not degrade the yarn structure based on the microscopic observation and tensile test results which are presented in Figure 6 and 7.

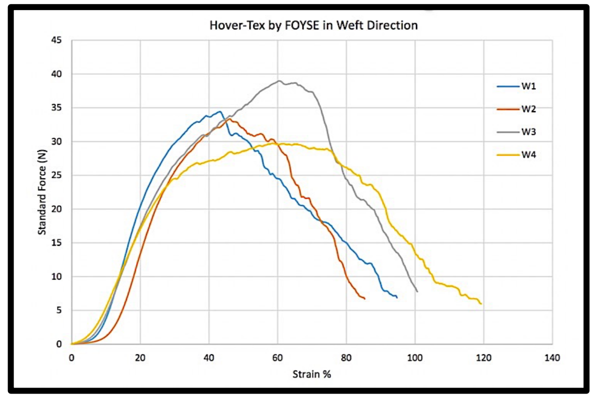


Figure 7. Results from the four Hover-Tex samples in the weft direction.

## VII. Conclusion

The FOYSE manufacturing process allows textile structures to be produced with large open areas for increased breathability, transparency and lightweight fabric surfaces. In addition, the process provides multiple opportunities for seamless and uncomplicated integration of a variety of elements used to create e-textiles. This can be achieved by using the FOYSE process to create fabrics that embed electronics within the yarn, yarn twisted with conductive filaments or embedding components within the actual layers of entangled fibres. Moreover, the FOYSE process has successfully created and characterized fabrics using 100% natural fibres, supporting the demand for sustainable textiles. Furthermore, data from mechanical testing confirms fabrics created by FOYSE have strength sufficient for industry standards. Therefore, the FOYSE manufacturing process and textiles created by FOYSE will be of interest to the textile innovation sector and to the e-textile and wearables industry.

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