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Chapter

# An Introduction to Wearable Technology and Smart Textiles and Apparel: Terminology, Statistics, Evolution, and Challenges

*Jennifer Xiaopei Wu and Li Li*

## Abstract

Within the last 6 years, there has been a palpable surge in interest and investment into wearable technology and Smart Textiles & Apparel, manifested both in academia and in the wide array of aspirational products available on the market. Recent market research on wearables also forecasts further growth in the next 3 years. However, as the field becomes increasingly saturated, potential terminology confusion and misconceptions may arise particularly among those in the industry who may not deal directly with the technologies but have interest in applying it to their work. Therefore in an attempt to provide clarity on an increasingly popular field to those perhaps less familiar with it, this chapter delivers an introductory overview of wearable technology and Smart Textiles & Apparel, which clarifies terminology encompassed within the field, reviews recent statistics and maps out how developments have been evolving over time, and assesses some of the challenges confronting the field.

**Keywords:** wearable technology, smart textiles, apparel, intelligent, electronic textiles

## 1. Introduction

The field of wearable technology has experienced evident exponential growth in the past 20 years (fueled by the significant increase in mobile device usage and in the expansion of the Internet of Things). Recent market research on wearables also forecasts further growth in the next 3 years [2]. This growth in wearable technology, exemplified in terms of products entering the market and academic research output [1], has been quoted by numerous articles and been used to justify further research potential in the field. However various statistics indicate that the sector of wearable technology on the market represented by Smart Textiles & Apparel, despite the abundance of research output in this sector, continues to be much smaller than that represented by (hard) accessories and devices (e.g., smartwatches and earbuds), which are by far dominating the wearable landscape. Furthermore, various studies show that even with the dominant sector of wearable accessories and devices, there is a high rate of abandonment by users after a short period of time [22].

Given that "wearable technology" and "Smart Textiles & Apparel" have already gained a great deal of attention and traction in the market and in academic research, there is a tendency for terms to be misused interchangeably or confused; therefore, this review begins by defining and distinguishing terminology used in the scope of Smart Textiles & Apparel. It will then outline the various ways in which Smart Textiles & Apparel have evolved over time by providing examples of innovations in the field. Finally, it will consider some of the practical barriers and challenges in the field.

By mapping out the evolution of Smart Textiles & Apparel as well as its practical barrier and challenges, it will help provide a more realistic sense of the direction the field is headed in the future and subsequently the potential opportunities which need to be addressed in order to propel the field forward—and ultimately toward making a valuable contribution to society.

## 2. Definitions

As the fields of wearable technology and Smart Textiles & Apparel have expanded and matured over the years, their scope has broadened to encompass increasingly more facets and applications. As a result, a great deal of associated terminology has emerged and some of which have the tendency to be interchangeably or confused with another. Therefore, it is relevant to take a moment to provide clarification and distinction on the quintessential terms of the field (as accepted in academia and the industry, as well as within the bounds of this article).

According to Google Trends (which presents statistics on the amount of interest a search term or topic has garnered online over the years), Web searches on topic of "wearable technology" skyrocketed between 2013 and 2015 by about 500% (see **Figure 1**), which aligns with the proliferation of commercially available wearables, such as the Apple iWatch (which was released in early 2015). However, **Figure 1** also shows that the topic of "wearable technology" had been circulating long (over 20 years) before its surge presence in the last 5 years [3].

The term "wearable technology" (often shortened to just "wearables" and sometimes used interchangeably with "wearable devices" or "smart devices")

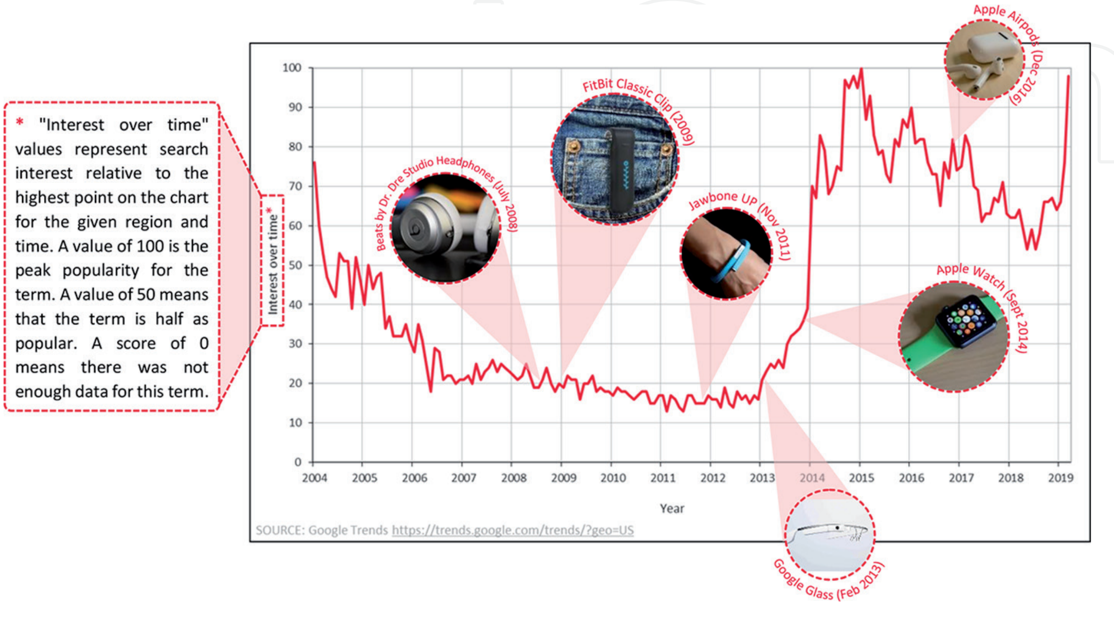


**Figure 1.**
*Graph of Google Trends "Web search interest" on the topic of "wearable technology" over time, with image markers indicating the release dates of the earliest iterations of some "landmark" wearable technology product lines [28–32].*

*DOI: http://dx.doi.org/10.5772/intechopen.86560*

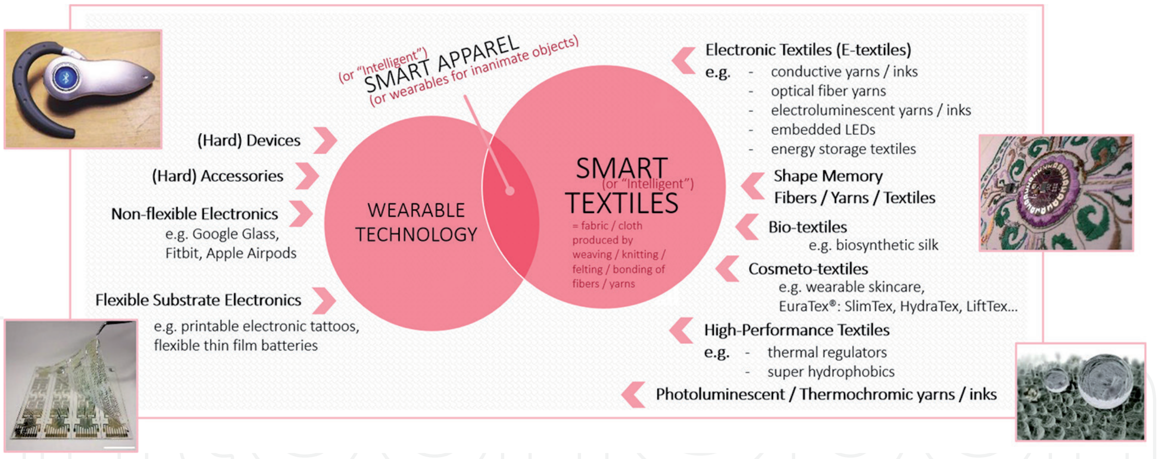


**Figure 2.**
*Diagram to help distinguish and clarify terms within wearable technology and Smart Textiles & Apparel [37, 38, 40, 41].*

originated to describe the integration of electronics and computers into clothing or accessories that could be worn comfortably on the body [4], given that the earliest developments, such as the 1999 "Wearable Motherboard," were motivated and enabled by the successive ubiquity of computers, mobile electronics, World Wide Web usage, and big data [5]. However, there are now many examples of advanced "technology" that are also "wearable," but which do not necessarily integrate electronic or computing components—these instead belong to the scope of "Smart Textiles & Apparel." **Figure 2** presents a visual to further help distinguish and clarify wearable technology and Smart Textiles & Apparel as well as provide examples of the types of technologies associated with each area. Therefore, as shown in **Figure 2**, "smart textile" is a category on its own which does not fully overlap with wearable technology, as even though there are wearable technology examples which involve smart textiles (in which case they count as "smart apparel or other wearables inanimate objects"), there are a great deal of smart textiles which are not used toward wearables but toward applications which do not require removal of the textile once applied (such as car interiors or wallpaper). Instead the key distinguishing quality of smart textiles is that they are "soft" materials with flexibility and drapability.

Another pair of terms which are often confused are "smart textiles" and "electronic textiles" ("E-textiles"). Essentially, smart textiles describe a novel category of textiles which have the capability to sense or/and react with or/and adapt to external conditions or stimuli [6], while E-textiles are generally defined as textiles with electronic components or conductive fibers integrated within to give it smart or intelligent functions [7, 8]. Therefore smart textiles are the overarching category which includes E-textiles as one type of smart textile; however, it also includes other types of textiles which exhibit smart or intelligent functions without electronic or conductive elements (see **Figure 2** for examples of the different types of smart textiles).

## 3. Statistics

To better understand the current and potential future state of Smart Textiles & Apparel, it is helpful to conduct a critical review of the statistics reflecting the progress in the field. One example of such statistics is shown in **Figure 3**, which shows the number of "Smart Textiles & Apparel"—related scholarly publications produced over the years, based on a search via the widely used scholarly publications database

Scopus using the following search criteria: TITLE-ABS-KEY (smart or intelligent or conductive or electronic or sensor) and TITLE-ABS-KEY (textile or apparel or clothing or fashion or knit or yarn or fiber or wearable). **Figure 3** indicates an obvious exponential growth in academic research output in the field of Smart Textiles & Apparel, which appears even more consistent and unwavering than the sporadic surge in Web search topic interest in "wearable technology" from Google Trend statistics (**Figure 1**). However, to gain a more balanced view beyond just academic research, statistics on market presence should also be considered. One source of information which can help gauge and compare the market presence of different forms of wearable technology is the annual attendance audit from the Consumer Electronics Show (CES), a highly prominent conference for innovative technologies being introduced to the market [9]. In particular, data on the number of exhibit attendees representing the "wearables" category was extracted from the annual CES audit summaries of 2012

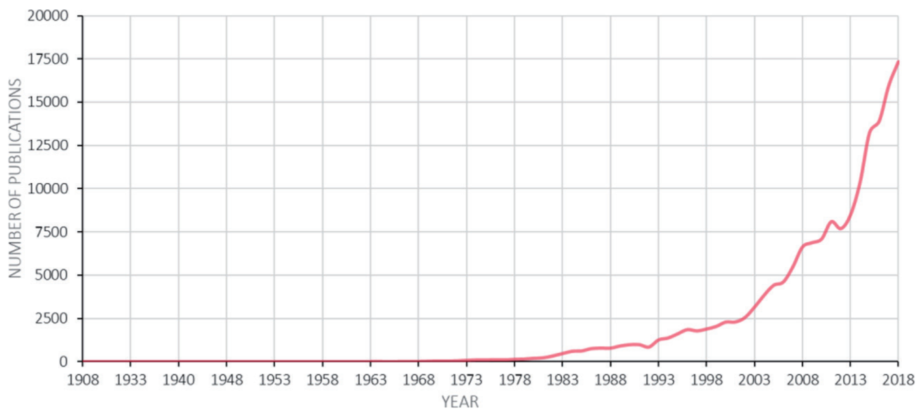


**Figure 3.**
*Number of publications on Smart Textiles & Apparel over time (based on Scopus database search results). Source: Scopus.*

**8 Attendee Profiles**

**Representation from Top 20 Product Categories**

| PRODUCT CATEGORY** | ATTENDEES* |
|---|---|
| Computer Hardware & Software | 17,440 |
| Wireless Devices | 15,676 |
| Accessories | 15,283 |
| Automotive Electronics/Vehicle Technology | 14,570 |
| Smart Home/Appliances/Energy Management | 13,598 |
| Other Consumer Technology | 12,161 |
| Audio | 12,106 |
| Wearables | 12,059 |
| Telecommunication and Infrastructure | 10,049 |
| Video | 9,862 |
| Digital Media/Online Media | 9,154 |
| Mobile Apps | 9,059 |
| E-Commerce | 8,965 |
| Audio, High-Performance/High-Resolution | 7,692 |
| Augmented Reality/Virtual Reality | 7,589 |
| Health and Biotech | 7,553 |
| Sensors | 6,742 |
| Gaming | 6,606 |
| Drones | 6,549 |
| 3D Printing | 5,952 |

**Attendees = Exhibits Only Attendance; Does not include media or exhibitor personnel*
***Attendees may represent multiple product categories*

**Figure 4.**
*An example of the CES annual audit summary data on the number of attendees representing the top 20 product categories, from the 2017 CES audit summary.*

*DOI: http://dx.doi.org/10.5772/intechopen.86560*

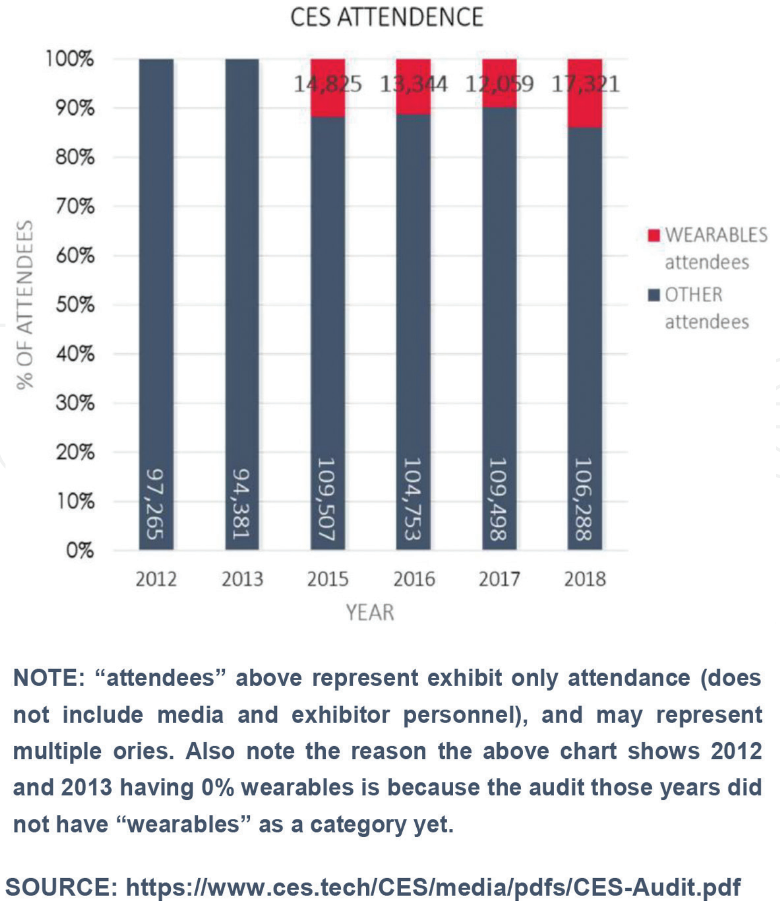


**Figure 5.**
*Numbers of CES exhibit attendees representing the "Wearables" category from 2012 to 2018 (obtained from the annual CES audit summaries).*

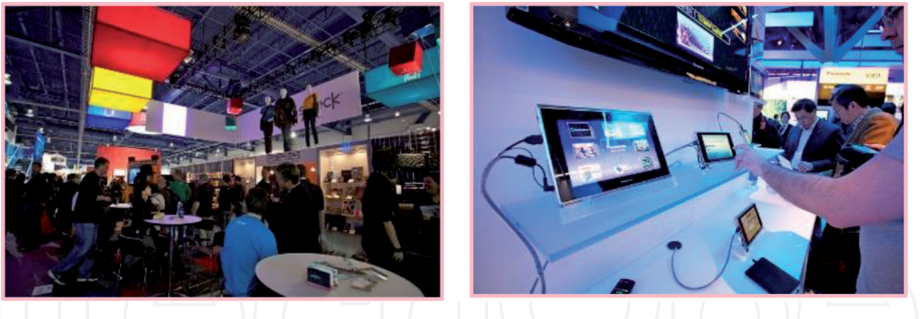

**Figure 6.**
*Photographs taken at the 2011 CES [39].*

to 2018 (a sample of this 2017 data is shown in **Figure 4**) and compiled into **Figure 5**. Given that CES is a prominent platform for technologies entering the market, its data compiled in **Figures 5** and **6** validates the growing presence of wearable technology in the market. However, according to statistics from Gartner (**Figure 7**), the share of wearable technology's growing presence occupied specifically by Smart Apparel is much less significant (less than 5% representation), while (hard) accessories (e.g., smart watches, ear-worn devices) represent the dominant category.

Statistics such as that shown in **Figure 7** suggest that Smart Textiles & Apparel still have room to grow in terms of market presence, despite its exponential growth in academic research output. This contrast between its growth in academia and in the market indicates a clear gap and prompts the question of what factors are deterring Smart Textiles & Apparel from being more prominent in the market. This article will start to address this question in the following sections.

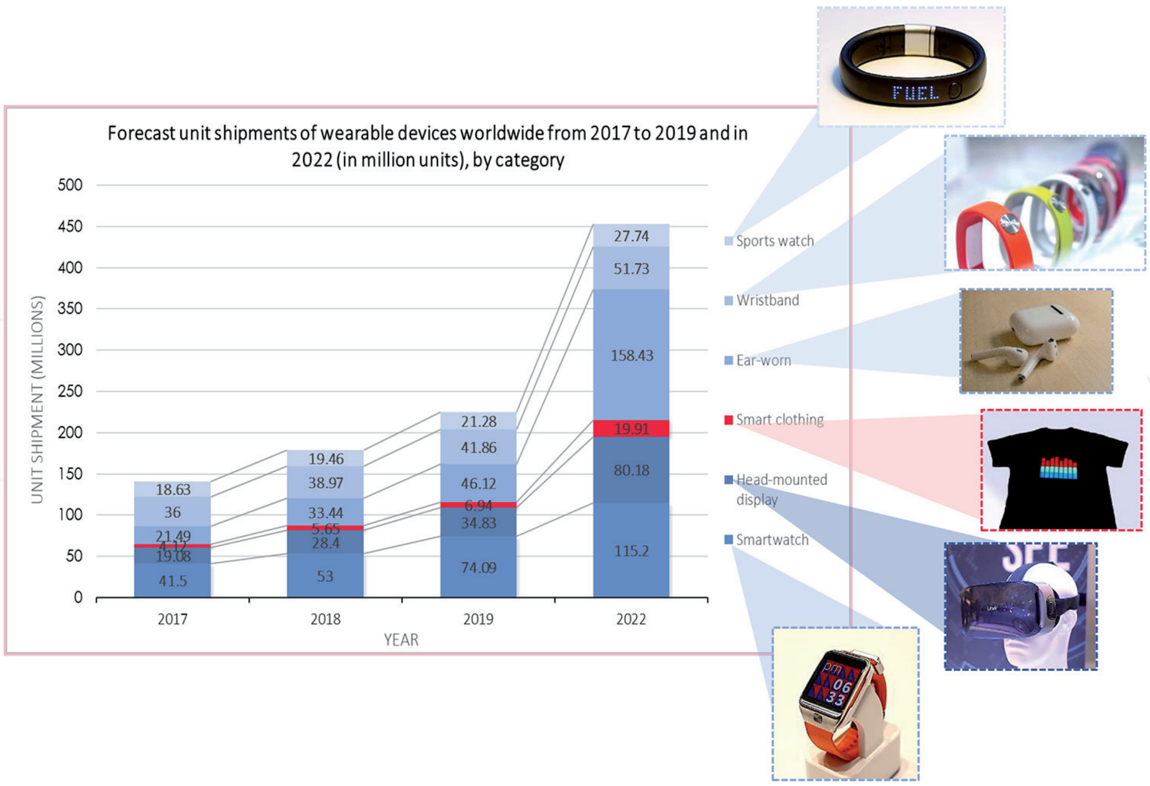


**Figure 7.**
*Global unit shipments of wearable technology by category (2017–2022), alongside image examples. Source: Gartner © Statista 2019 [27, 33–36].*

## 4. Evolution

Understanding how Smart Textiles & Apparel have evolved over the years will help anticipate the direction and opportunities of future growth. Based on an overview of literature, it was deducted that Smart Textiles & Apparel have evolved in three different ways: their degree of integration, their degree of intelligence (or "smartness"), and their degree of self-sufficiency (as summarized in the diagram of **Figure 8**)—each will be explained in the following sections.

### 4.1 Degree of intelligence (or "smartness")

Smart Textiles & Apparel have evolved in terms of their degree of intelligence (or smartness). This concept is based on the characterization of smart textiles as described by Tao and various other authors in the field, which classifies their degree of intelligence (or "smartness") according to whether they can perform one or more of the following functions: sense, react, and adapt [6, 10, 11].

Traditional textiles (e.g., woven cotton fabrics, knitted wools yarns, etc.), while still functional (i.e., providing warmth, softness, etc.), are latent and do not sense, react, or adapt to external stimuli. The minimum requirement for a smart textile is the ability to sense environmental conditions or an external stimulus, which qualifies it as "passive smart." If it further has the ability to react after sensing, then it qualifies as "active smart." Some examples of this include Grado Zero Espace's shape-memory shirt made from Oricalco fabric which reacts by changing shape based on sensing heat [12] and Aurelie Mosse's intentional use of electro-active light-responsive polymers to create textiles for interiors which sense light and react by changing shape for esthetic effect or for function [13]. Finally, if a smart textile cumulatively has the ability to sense, react, and adapt based on the learned experience from what it sensed and reacted to previously, then it qualifies as "very smart." A conceptual

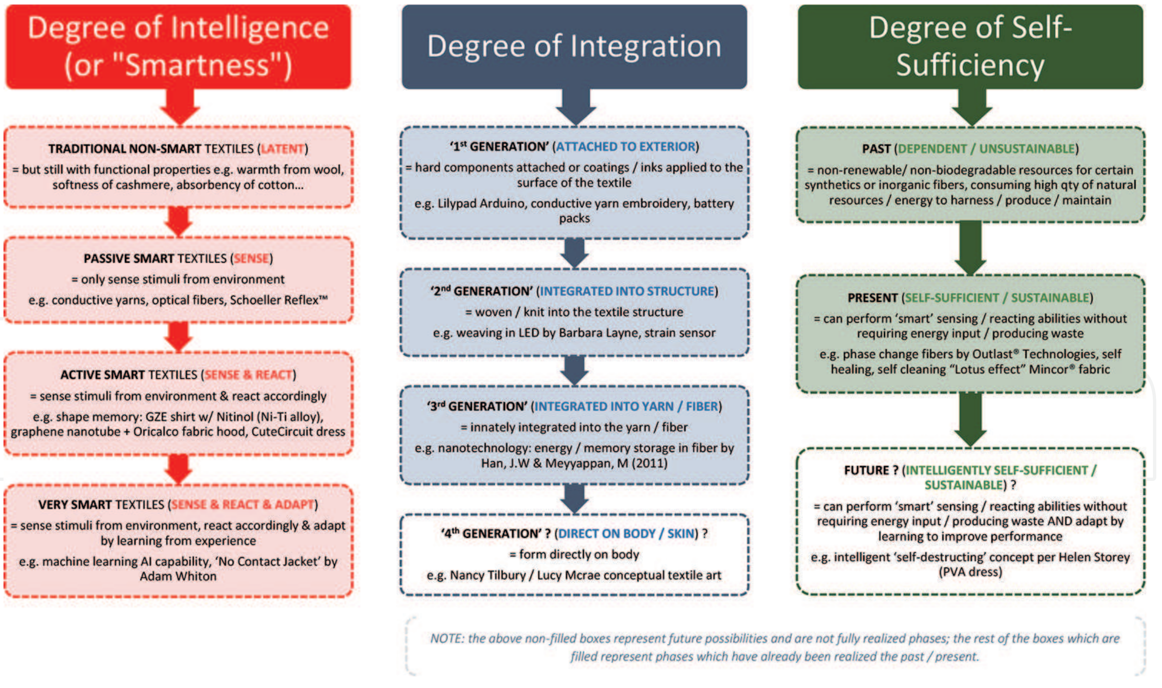


**Figure 8.**
*Flowchart summarizing the evolution of Smart Textiles & Apparel.*

example of this is exemplified in the "No-Contact Jacket" created by Adam Whiton and Yolita Nugent, which functions to sense heavy force applied to the jacket (e.g., when wearer is hit by an attacker) and reacts by emitting an electrical chart (i.e., to electrocute the attacker) but also could, in the future, have the potential to integrate machine-learning intelligence to record data on cumulative forces sensed and learn to differentiate between amicable forces (e.g., from a hug or tap) and violent forces, depending on position or amount of force or time of day [13].

See **Figure 8** which presents a visual overview of these definitions of degree of intelligence (or "smartness").

### 4.2 Degree of integration

Another way Smart Textiles and Apparel have evolved is in terms of their degree of integration. This refers to the extent to which the component/material/substance which performs the "smart" function is embedded into the textile. As Smart Textiles & Apparel have evolved, there has generally been a progression toward a higher degree of embeddedness or integration of the "smart"-functioning component material/substance into the textile. This progression is characterized by Hughes-Riley et al. as three generations: first generation, second generation, and third generation [7]. Although Hughes-Riley describes this progression in the context of E-textiles, it could very well apply to non-electronic smart textiles (e.g., thermo-chromic inks).

In first-generation smart textiles, the lowest degree of integration, the "smart"-functioning component/material/substance was applied or attached to the surface of the textile; this generation of Smart Textiles Apparel is typically more rigid and bulky and lacks drapability. Some examples of first-generation smart textiles include the use of the "LilyPad Arduino" electronic components on garments [14], printing circuits with conductive ink onto the surface of fabrics, or even embroidering conductive yarns onto fabrics to create conductive pathways. In second-generation smart textiles, the "smart"-functioning component/material/substance is integrated into the textile structure, for example, the weaving or knitting of conductive yarns to form a textile pressure sensor [15], Layne and Orth's work of weaving LEDs, or conductive yarns into the woven textile structure [13]. This generation of Smart Textiles & Apparel is typically more flexible but still tends to be lacking in comfort and versatility. In third-generation smart textiles, the highest degree of integration, the "smart" function is manifested innately as a part of the yarn or fiber and able to exist much more discretely within a textile design without interfering with its esthetic qualities and comfort level. Most examples of this generation of Smart Textiles & Apparel have been made possible by nanotechnology, such as embedding semiconductor systems within fibers for energy harvesting and storage [7] or the Mincor TX TT "lotus effect" coating of nanoparticles on yarns which allow a high level of hydrophobicity to enable a self-cleaning function [16].

The term "fourth generation" used in this article refers to the potential next degree of integration in which Smart Textiles & Apparel are progressing towards but have not yet been fully realized in production and therefore currently exist more as inspiring visionary concepts. One example of a "fourth-generation" concept is the idea of harnessing the innate "smartness" of the nature to create textiles which function "smartly," which is exemplified in the design research of Carole Collette. In her work titled "Suicide Pouf," Collette created cushions which would physically change shape with time as the fibers shed in their natural death process, i.e., relying on the biological process of cell death (apoptosis) to create a dynamic textile object. In "bio-lace," Collette demonstrates an inspiring idea of biologically engineered plants to grow roots which are able to form lace designs on their own [13]. Another visionary concept explored in the work of artists McRae and Tilbury is that of having the human biology or skin to contribute to the creation or modification of what we wear—so not just "smart" functionalities being more integrated into a textile but essentially engineering the human body's biological functions to form its own textiles [13]. Currently, these are rather conceptual ideas, far from mass-market realization. However, they stretch the imagination on the degree of integration that Smart Textiles & Apparel could possibly be achieved in the future.

See **Figure 8** which presents a visual overview of these characterizations of degree of integration.

### 4.3 Degree self-sufficiency

Smart Textiles & Apparel have also evolved in terms of their degree of self-sufficiency. This refers to the extent to which they can self-sufficiently perform their "smart" functionalities and sustain itself throughout its life cycle, without depending on (non-renewable) energy input or producing (non-biodegradable) waste output. The evolution of degree of self-sufficiency is categorized here as past, present, and future.

The "past" stage refers to Smart Textiles & Apparel which have been made from non-renewable or non-biodegradable raw materials and dependent on non-renewable energy resources to manufacture, to function (e.g., batteries), to maintain (e.g., laundry), and to dispose of. However the growing concern of how polluting the apparel and textile industry and the recent buzz of fashion companies committing to achieving carbon neutrality or employing 100% sustainable materials within the next 10 years [17–19] is motivating a progression toward the "present" stage of the degree of self-sufficiency evolution, which refers to Smart Textiles & Apparel that perform their "smart" (sensing and reacting) functions self-sufficiently (i.e., without requiring a non-renewable energy source input), are self-sustaining (e.g., self-cleaning, self-healing, energy harvesting), and produce limited environmental impact in its manufacture, maintenance, and disposal. The "present" stage factors in sustainability as not only an afterthought but as an intrinsic part of the development and life of Smart Textiles & Apparel. Some examples which fall in this category include the self-cleaning "lotus effect" coating of Mincor TX TT yarn, the use of natural yarns with shape-memory properties which give the textile structure the functionality of becoming more permeable when damp or warm [16], self-healing "green" composites [20], and the light energy absorbing and storing properties of phosphorescent pigments integrated into textiles [13, 21].

One potential "future" direction in the degree of self-sufficiency of Smart Textiles & Apparel could involve an additional element of intelligently adapting (and gradually improving) its self-sufficient smart functions by learning from each experience. So, for example, it could be manifested in the ability of a shape-memory textile to predict when to react without waiting on an external stimulus to trigger it or for a self-healing composite to learn where the weak points in a textile are and produce more self-healing agent in certain areas. These are, once again, only visionary ideas for now; however, with the help of quickly advancing artificial intelligent technologies, its realization could present itself sooner than we think.

See **Figure 8** which presents a visual overview of these characterizations of degree of self-sufficiency.

## 5. Challenges

Despite burgeoning research into Smart Textiles & Apparel, there remains a great deal of room for improvement in terms of market presence. Furthermore, even with wearable technology (hard) accessories which represent a larger portion of market share, there is the hurdle of low retention and high abandonment rates of such devices less than a year after purchase [22]. Hence below defines some of the challenges contributing to the above disparities and potential opportunities to help tackle those disparities:

- Lack of esthetic appeal: a common feedback on the Smart Apparel options in the market is that they are not fashionable and lack esthetic appeal [23, 24]. What becomes quickly apparent when browsing some of the most exciting wearable innovations at the 2019 Consumer Electronics Show [25] is that they still look more like "techy" electronic devices than something we would recognize as wearable. More and more consumers expect flexibility, comfort, and ease in clothing; however, most smart technologies approved for the market are still relatively bulky and difficult to integrate seamlessly and discretely into traditional clothing materials and styling and dressing habits. (Therefore, as **Figure 7** shows, the smartwatches and ear-worn devices lead in the wearables category at CES, because they have already been adopted as electronic devices that can be worn without causing disruption to or conflict with an outfit). But also, the lack of visibility and accessibility designers in the industry have to Smart Textiles & Apparel technologies is also a barrier to help breed better design esthetics in the field.

- Limited design options: even with wearables that are esthetically well-designed, they tend to come in limited varying options (e.g., in terms of size, colorways, silhouettes, etc.). Currently, the complexity of smart functionalities can limit the design flexibility, so once a successful design is established, it is not easy to vary. This is an issue as today's consumer demand options and flexibility in what they purchase. Therefore, there is a need for Smart Textiles & Apparel technologies to be more versatile, complement different materials, and able to be used in different textile manufacturing processes.

- Lack of assimilation with current supply chain processes/quality standards: the apparel and textile supply chain and quality standards have yet to adapt to the nuances and specific needs of Smart Textiles & Apparel [26]. Because the apparel and textile supply chain is still very much catered to the production of traditional textiles, many suppliers and retailers in the industry might be dissuaded from adopting "smart" technologies due to the time and cost needed to recalibrate processes in the supply chain to manage those "smart" technologies effectively. Furthermore, a great deal of "smart" technologies are not yet developed enough to meet the rigid, long-established quality standards of the textiles and apparel industry or vice versa in that the long-established industry quality standards are not being updated sufficiently to keep up with the incoming "smart" technologies.

- Lack of understanding real human and societal needs: an underlying impression of wearable technology is that it is creating a supply for which there is no real demand (i.e., trying to create a demand). Therefore, in order to make wearables more relevant and desired, there is a need to better understand real human and societal needs so that Wearables can improve in ways to meet those needs. For example, in today's connected world, it is clear that people desire to be connected, but how much so? Where do people draw the line in terms of where they want technology integrated into their everyday lives? When does it become disruptive? These are just some questions that need to be asked to better understand the true needs of humans and society.

- Lack of selling performance and consumer feedback: there is a great deal of statistics available on the quantity of wearable technology and Smart Textiles & Apparel entering or available in the market but limited statistics on how well products sold or on feedback from customers after use. Obtaining such information is important to formulating a clear understanding of real consumer needs. Furthermore, as there are evidently successful wearable technology commercial products out on the market, it would be informative to evaluate what differentiates the successful products from the rest.

## 6. Conclusion

This review has attempted to provide a brief introductory overview to the now expansive field of wearable technology and Smart Textiles & Apparel, starting by looking at the evident surge in interest in wearable technology in the last 6 years which has been fueled by the release of many "landmark" devices to the commercial market as well as an increasingly mobile-reliant and connected landscape. The exponential growth is also manifested in academic research output in the field, as well as wearable technology products released to the market (which is also forecasted to continue to grow in the future). This chapter also provided clarification on terminology, distinguishing wearable technology and Smart Textiles & Apparel as two separate fields which overlap only in some cases, but also each has their separate unique sub-categories. The chapter then presented the analysis of the progression or evolution of Smart Textiles & Apparel in terms of degree of intelligence, degree of integration, and degree of self-sufficiency. The chapter also takes on a more critical lens to realize the fact that Smart Apparel has a much smaller representation in the wearable technology boom (in comparison with the "hard" wearable accessories and devices such as smartwatches and earbuds which are the dominant categories) as well as the low retention rate of most wearable devices. Given these limitations, the chapter discusses some areas of opportunity for Smart Textiles & Apparel research and product development to enable it to gain more traction and ultimately make a more valuable contribution in the society.

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