CHAPTER

1.1

Wearables: Fundamentals, Advancements, and a Roadmap for the Future

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1. WORLD OF WEARABLES (WOW)

In today's digital world the term "wearable" has a new meaning! It no longer conjures up images of clothing such as an elegant evening dress or a heated Sherpa jacket worn by a mountaineer at a base camp on Mount Everest. Rather, today it brings up images of accessories such as a smart watch on a business executive's wrist, a head-mounted display worn by an immersive gamer, a tiny sensor on a cyclist's helmet, or a smart garment a runner uses to track and monitor his steps. In recent years, the dimensions of fashion and protection typically associated with the traditional wearability of clothing have expanded to include "functionality" on the go. This functionality can essentially be characterized as mobile information processing – whether it is the executive checking e-mail, the gamer shooting at a target that is also being simultaneously chased by a fellow gamer on the other side of the world, the cyclist's trainer ensuring that the rider is maintaining proper posture on the curve, or the runner tracking his workout for the day. Just as clothing can be personalized and customized for each person (depending on the physical dimensions,

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taste, and style preferences) and/or occasion (business, evening, casual, home, and hiking), the new wearable too can be configured for personalized mobile information processing for specific applications such as immersive gaming, fitness, public safety, entertainment, healthcare, etc. In short, the world of wearables (WOW) is transforming our lives.

Figure 1 shows a snapshot of people interacting with their personalized wearables. Today's avid gamers want total immersion and expect the gaming experience to be "natural." They do not want to be constrained by traditional interfaces (e.g., joysticks, keyboards, mice, etc.), but prefer games that let them perform body movements that are realistic [1]. For example, when hitting a ball, players prefer swinging their arm or leg, rather than sliding a mouse or pressing a button. Moreover, wearables are enabling immersive multi-player games with tangible and physical interaction not ever experienced by anyone [2]. As a result, the videogame market is growing and the revenue, including mobile games on smartphones and tablets, was $66 billion in 2013 (up from $63 billion in previous year) and is expected to grow to $78 billion in 2017 [3].

Wearables are not just for fun though. They are also used to keep first responders safe and alive by monitoring their physical conditions (e.g., vital signs) and the ambient environment for the presence of dangerous gases and hazardous materials. Without these, the casualties amongst the world's 25.3 million first responders – 2.3 million of them on the frontlines and others supporting them – would be significantly higher [4].

Wearables are also used to monitor racecar drivers. The racecar driver is experiencing 4 + G-force while traveling at over 190 miles per hour, all the time losing water, which can

FIGURE 1 WOW: The world of wearables is enabling digital lives.

be up to 10 pounds over a three-hour period. While this feeling can be exhilarating for the driver, there is also potential risk to the driver's health. Using wearables, the driver's pit crew and manager can mine real-time data to track his physical condition and decide whether he is at risk. At the same time, the video stream from the driver's wearable (camera) can provide a unique "on-the-track" experience for fans.

Likewise, as shown in the figure, wearables can deliver unique value to users and to those accessing the data being collected by the wearables. For example, wearables can help the "sandwich generation" caring for elderly parents monitor their health and well-being and increase their independence. Wearables have also been used to help parents care for young children.

1.1 The Role of Wearables

Fundamentally, wearables can perform the following basic functions or unit operations in each of the scenarios shown in Figure 1:

- Sense
- Process (Analyze)
- Store
- Transmit
- Apply (Utilize)

Of course, the specifics of each function will depend on the application domain and the wearer, and all the processing may occur actually on the individual or at a remote location (e.g., command and control center for first responders, fans watching the race, or viewers enjoying the mountaineer's view from the Mount Everest base camp).

Figure 2 is a schematic representation of the unit operations associated with obtaining and processing situational data using wearables. For example, if dangerous gases are detected by a wearable on a first responder, the data can be processed in the wearable and an alert issued. Simultaneously, it may be transmitted to a remote location for confirmatory testing and the results – along with any appropriate response (i.e., put on a gas mask) – can be communicated to the user in real-time to potentially save a life [5]. This

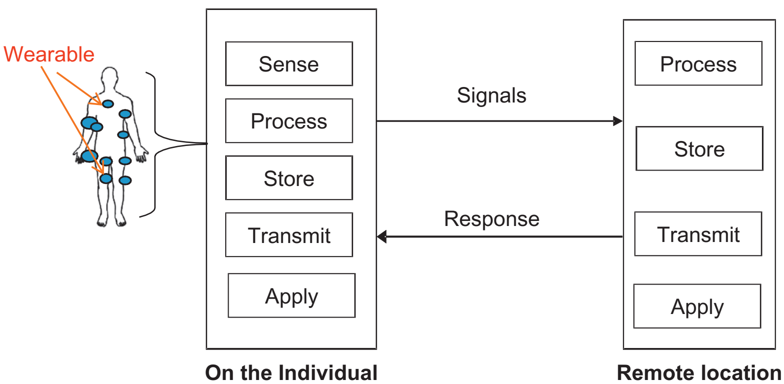

FIGURE 2 Unit operations in obtaining situational awareness: role of wearables.

same philosophy can also be used by an avid gamer who might change his strategy depending on what "weapons" are available to him and how his opponents are performing. Each of these scenarios requires *personalized mobile information processing*, which can transform the sensory *data* to *information* and then to *knowledge* that will be of *value* to the individual responding to the situation.

While wearables are being used in many fields, as discussed, this chapter will focus primarily on wearables in the healthcare domain. Inferring the potential of wearables in other application domains should be straightforward and can be accomplished by instantiating the fundamental principles and concepts presented here.

1.2 Data-Information-Knowledge-Value Paradigm

Figure 3 shows the data-value transformation paradigm [6]. Let's consider a patient visiting a physician. In triage, the nurse documents the vital signs gathered using instruments (e.g., thermometer, blood pressure monitor, electrocardiogram, or EKG machine) that convert the raw signals (the *data*) from the body into meaningful *information* (temperature, heart rate, diastolic/systolic pressure) and thus add value as shown in the figure. When the physician processes this information, he or she gains insight into the potential condition of the patient. The physician adds value by drawing upon the *knowledge* – expertise and experience accumulated over time – to come up with a diagnosis and a plan of action or treatment. This course of treatment – in the form of medication and other interventions – is the *value* derived by (or delivered to) the patient resulting in the curing of the illness. Thus, the raw data gathered by the instruments is valuable only when it is properly transformed and harnessed to benefit the individual. For this transformation to occur seamlessly there is a need for an information/knowledge processing ecosystem.

1.2.1 The Emerging Concept of Big Data

Park and Jayaraman discussed the role of wearables in relationship to "big data" [7]. Big data refers to large amounts and varieties of fast-moving data from individuals and groups that can be processed, analyzed, and integrated over time to create significant value by revealing insights into human behavior and activities. According to McKinsey, if the US healthcare system could use "big data creatively and effectively to drive efficiency and quality," the potential value from data in the sector could be more than $300 billion

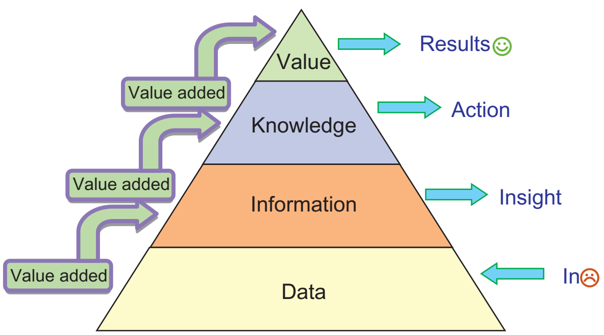

FIGURE 3 Data-information-knowledge-value transformation paradigm.

every year, two-thirds of which would be in the form of reducing national healthcare expenditures by about 8% [8]. Likewise, in the private sector, McKinsey estimates that a retailer using big data to the fullest extent has the potential to increase its operating margin by more than 60%. McKinsey also projects a 50% decrease in manufacturing and assembly costs. Thus, it is clear that there is value in harnessing big data in a wide spectrum of activities and industries. Let's consider one such example in healthcare, an application domain in which wearables are being increasingly deployed.

1.2.2 *Medical Loss Ratio and Wearables*

The Patient Protection and Affordable Care Act of 2010 requires health insurance companies to spend at least 80 to 85% of premiums collected on providing medical care [9]. Known as the Medical Loss Ratio (MLR), the objective behind this provision is to bring down the overhead costs of providing medical care and limit it to 20% for individual and small-group coverage and to 15% for large-group coverage. With the increasing shift from volume-based to value-based reimbursement for services rendered, healthcare providers are incentivized to provide holistic care to patients by closely monitoring them to ensure compliance with medication and promoting healthier lifestyles.

Wearables enable this remote health monitoring of patients. The health data can be wirelessly sent to the physician's office by the wearable, negating the need for office visits. Consequently, the cost of care decreases. Moreover, the ability to continuously track patients' health can help identify any potential problems through preventive interventions and thus enhance the quality of care while eliminating unnecessary procedures since the cost of prevention is significantly less than the cost of treatment. The resulting higher quality of care at lower costs would also contribute to better operating efficiencies and lower overhead costs for insurance companies since their resources can be better spent on actually providing care and not on measures to ensure that a high quality of care is being provided.

Thus, at the heart of the concept of "big data" is the individual who is simultaneously the source of the data and the recipient of the resulting "value" after the processing/harnessing of the data. This is where wearables have a critical role to play in creating and serving as the core of an ecosystem essential for facilitating the seamless transformation of data to deliver value.

1.3 The Ecosystem Enabling Digital Life

The advancements in, and convergence of, microelectronics, materials, optics, and bio-technologies, coupled with miniaturization, have led to the development of small, cost-effective intelligent sensors for a wide variety of applications. These sensors are now so intimately interwoven into the fabric of our lives that they are not only pervasive, but are also operationally "invisible" to end-users. The user interface is so simple that with the touch of a few buttons a different "programming" sequence can be launched by anyone — from a young kid to a senior citizen — for a wide variety of tasks, e.g., from monitoring vital signs to controlling the ambience in the room. Thus, the ease of the user interface coupled with the invisibility of the "embedded" technology in the various devices and systems has contributed to the proliferation of these sensors in various applications such as those represented in Figure 1. By effectively taking advantage of these technological advancements, it is possible to create an ecosystem that facilitates the harnessing of large amounts of situational awareness data.

1.3.1 Smart Mobile Communication Devices

A key component of the ecosystem is the smart mobile communications device – smartphone and/or tablet – that provides a platform for "information processing on the go" for anyone, anytime, and anywhere. According to *The Economist*, both the number of individuals with access to and connecting to the Internet is increasing as are the number of places providing connectivity at ever increasing speeds [10]. Citing Ericsson, the telecoms-network provider, *The Economist* states that the volume of mobile data traffic in 2017 is expected to be 21 times greater than it was in 2011, while the number of mobile-broadband subscriptions (mostly for smartphones) will jump from 900 million to 5 billion.

1.3.2 Social Media Tools

Easy-to-use social media tools complete the ecosystem that is digitizing, connecting, and continuously transforming our lives. Indeed, virtually everything is being captured and is being reduced to a sequence of 0 s and 1 s inside the hardware, but with significant value to the user/viewer on the outside!

Now that we have defined a wearable, established the important role of wearables, and have defined the components of an ecosystem to enable digital life with wearables at its core, we will discuss the salient attributes of wearables, develop the taxonomy, and discuss the advancements in the field.

HUMAN SKIN AS THE ULTIMATE SENSOR

While the different types of sensors and wearables are relatively *new* in the timeline of civilization, there has been one piece of "sensing" technology that has been there since the dawn of civilization: human skin. It is the *ultimate* sensor. As the largest organ of the human body, it not only provides a physical barrier that protects a human's insides from the outside elements, it also senses, adapts, and responds based on both external and internal stimuli such as heat, cold, fear, pleasure, and pain. In fact, it has the intrinsic and rather unique ability to respond to all the five senses of touch, sight, sound, smell, and taste. Physically, it is soft, smooth, flexible, strong, and evolves over time to meet the changing needs of the individual, including physical needs. When injured or damaged, it heals, and, in most instances, returns to its "original" state with very little, if any, residual impact of the injury.

Interestingly, in the computing paradigm, the skin is an input/output (I/O) device that senses and passes the stimulus (input) to the brain (the CPU), which draws upon its knowledge (the processing power of the CPU) to come up with the interpretation and action that is eventually reflected in the skin's response (the output).

Thus, human skin is a powerful and versatile sensor that nature has designed and is akin to an I/O device in a computing system. The Holy Grail in sensor or wearables design is to create one that has all the desired attributes of human skin and performs as well as it does!

2. ATTRIBUTES OF WEARABLES

A sensor is defined as "a device used to detect, locate, or quantify energy or matter, giving a signal for the detection of a physical or chemical property to which the device responds" [11]. Not all sensors are necessarily wearable, but all wearables, as discussed earlier and shown in Figure 2, must have sensing capabilities. The key attributes required of an ideal wearable are shown in Figure 4.

From a physical standpoint, the wearable must be lightweight and the form factor should be variable to suit the wearer. For instance, if the form factor of the wearable to monitor the vital signs of an infant prone to sudden infant death syndrome prevents the infant from (physically) lying down properly, it could have significant negative implications. The same would apply to an avid gamer – if the form factor interferes with her ability to play "naturally," the less likely that she would be to adopt or use the technology. Aesthetics also plays a key role in the acceptance and use of any device or technology. This is especially important when the device is also seen by others (the essence of fashion). Therefore, if the wearable on a user is likely to be visible to others, it should be aesthetically pleasing and, optionally, even make a fashion statement while meeting its functionality. In fact, with wearables increasingly becoming an integral part of everyday lives, the sociological facets of the acceptance of wearables opens up exciting avenues for research. Ideally, a wearable should become such an integral part of the wearer's clothing or accessories that it becomes a "natural" extension of the individual and "disappears" for all intents and purposes. It must have the flexibility to be shape-conformable to suit the desired end use; in short, it should behave like the human skin.

The wearable must also have multi-functional capability and be easily configurable for the desired end-use application. Wearables with single functionality (e.g., measuring just the heart rate) are useful, but in practical applications, more than one parameter is typically monitored; and, having multiple wearables – one for each function or data stream – would make the individual look like a *cyborg* and deter their use even if the multiple data

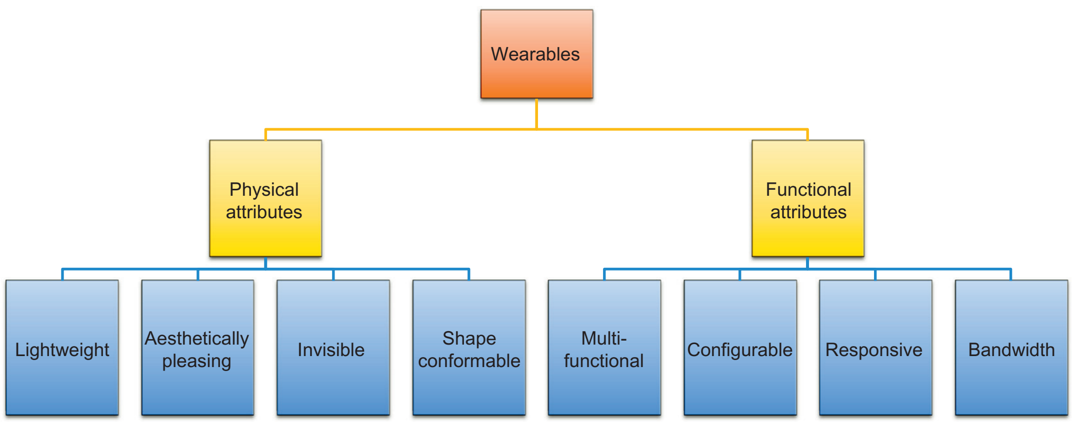

FIGURE 4 Key attributes of wearables.

streams could be effectively managed. The wearable's responsiveness is critical, especially when used for real-time data acquisition and control (e.g., monitoring a first responder in a smoke-filled scene). Therefore, it must be "always on." Finally, it must have sufficient data bandwidth to enable the degree of interactivity, which is key to its successful use.

Thus, the design of wearables must be driven by these attributes.

2.1 Taxonomy for Wearables

Figure 5 shows the proposed taxonomy for wearables. To begin with, they can be classified as single function or multi-functional. They can also be classified as invasive or non-invasive. Invasive wearables (sensors) can be further classified as minimally invasive, those that penetrate the skin (subcutaneous) to obtain the signals, or as an implantable, such as a pacemaker. Implantable sensors require a hospital procedure to be put into place inside the body. Non-invasive wearables may or may not be in physical contact with the body; the ones not in contact could either be monitoring the individual or the ambient environment (e.g., a camera for capturing the scene around the wearer or a gas sensor for detecting harmful gases in the area). Non-invasive sensors are typically used in systems for continuous monitoring because their use does not require extensive intervention from a healthcare professional.

Wearables can also be classified as active or passive depending upon whether or not they need power to operate; pulse oximetry sensors fall into the former, while a temperature probe is an example of a passive wearable that does not require its own power to operate. Yet another view of wearables is the mode in which the signals are transmitted for processing – wired or wireless. In the former, the signals are transmitted over a physical data bus to a processor; in the wireless class of wearables, the communications capability is built into it, which transmits the signals wirelessly to a monitoring unit. Sensors can be for one-time use or they can be reusable. Finally, wearables can be classified based on their field of application, which can range from health and wellness monitoring to position tracking as shown in the figure. "Information processing" is listed as one of the application areas because many of these traditional functions such as processing e-mail can now

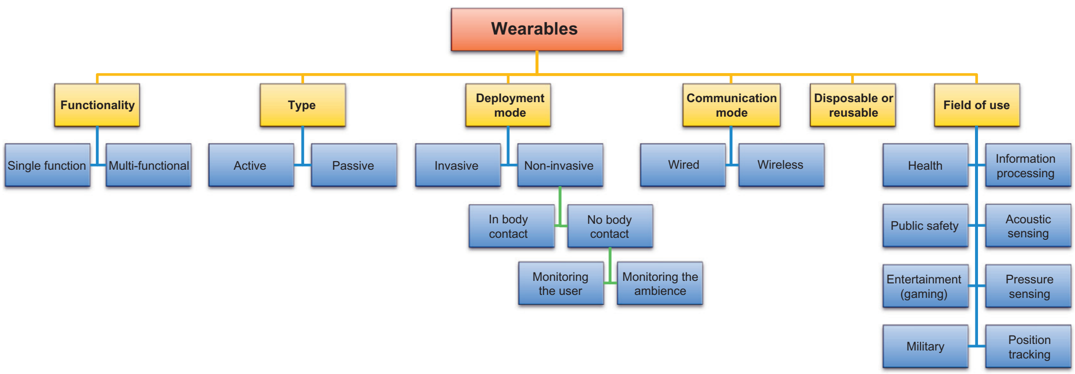

FIGURE 5 The taxonomy for wearables.

be done on a wearable in the form of a wristwatch. It is important to note that not all the classes are mutually exclusive. For instance, a wearable can be multi-functional, active, non-invasive, and be reusable for health monitoring.

The proposed taxonomy serves two key functions: first, it helps in classifying the currently available wearables so that the appropriate ones can be selected depending upon the operating constraints; second, it helps in identifying opportunities for the design and development of newer wearables with performance attributes for specific areas that need to be addressed.

2.2 Advancements in Wearables

Today's "wearables" can be traced back to the concept of wearable computers. Jackson and Polisky provide an excellent account of the development of wearable computers going back to the early 1960 s with the work of Thorp and Shannon to predict the performance of roulette wheels [12]. In the 1980s, Mann defined the following attributes for wearable computers: Constant, unrestrictive to the user, unmonopolizing of the user's attention, observable by the user, controllable by the user, attentive to the environment, and personal [13]. Mann's criteria for wearable computers include it being eudaemonic, existential, and in constant operation and interaction [14]. Weiser proposed the concept of ubiquitous computing in which the computers themselves "vanish into the background" [15]. In 2002, Xybernaut introduced its Poma Wearable PC, but it was not a commercial success. One of the reasons this paradigm of "wearable computers" did not catch on was because they were technology-driven; they only focused on making the bulky computer "wearable" and did not attempt to rethink the information-processing paradigm itself to address the usability of the technology. Moreover, the resulting systems (e.g., Xybernaut) were far from aesthetically pleasing, which further hindered their acceptance.

2.2.1 The Wearable Motherboard – a User-Centric Approach to the Design of Wearables

Beginning in late 1996, Jayaraman and co-workers took a fundamentally different approach to the field of wearables and developed the concept of a wearable motherboard. Driven by the needs of soldiers – the end user – to be monitored in real-time in the battlefield so that they would receive medical care in the event of being shot, they developed fabric-based wearable technology to monitor the vital signs of soldiers in an unobtrusive manner and also to detect any shrapnel penetration when shot [13–17]. This concept was called the wearable motherboard as it is conceptually analogous to a computer motherboard.

The computer motherboard provides a physical information infrastructure with data paths into which chips (memory, microprocessor, graphics, etc.) can be plugged in to meet performance requirements for specific end uses such as gaming, image processing, high-performance computing, etc. Likewise, the wearable motherboard – in the form of a fabric or a piece of clothing such as an undershirt – provides an information infrastructure into which the wearer can plug in sensors and devices to achieve the desired functionality, say, for example, vital signs monitoring. Thus, it fulfills the twin roles of being: (i) a flexible information infrastructure to facilitate the paradigm of ubiquitous computing, and (ii) a platform for monitoring the vital signs of individuals in an efficient and cost-effective manner with a "universal" interface of clothing. This development essentially led to the birth of the field of smart textiles. According to Park and Jayaraman, “clothing can indeed have the third dimension of ‘intelligence’ embedded into it and spawn the growth of *individual networks* or *personal networks* where each garment has its own IN (individual network) address much like today’s IP (Internet protocol) address for information-processing devices [18]. When such IN garments become the *in* thing, personalized mobile information processing would indeed have become a reality for all of us!” Looking back (twelve years later), this prediction has turned out to be true with today’s “Internet of Things” paradigm.

Following the promise of the technology spawned by the Smart Shirt (a more common name for the wearable motherboard), a considerable amount of research has been going on in this field, judging by the number of books, special issues of journals, number of papers, and the establishment of the IEEE Technical Committee on wearable biomedical systems [19–28].

2.2.2 Research in Flexible Electronics

Another class of wearables — known as flexible electronics — is focused on printing electronics (thin-film transistors, thin-metal films, nanomaterials, and carbon nanotubes, among others) onto elastomeric substrates resulting in “electronic skins” with pressure and temperature sensing capabilities, among others; these can be directly applied to the human body [29].

2.2.3 The Latest Trends in Commercial Wearables

The newest generation of wearables is shown in Figure 6 [30–33]. These typically have only some of the attributes of wearables discussed earlier and shown in Figure 4. For instance, most of these perform a *single* function (e.g., measuring heart rate during a workout) and so their application domain is limited. The recent arrival of Google Glass® appears to be the tipping point in terms of accelerating the wearables movement into the

FIGURE 6 The emerging set of wearables.

mainstream since Google is an entity with sizable technical and financial resources. Yet another form of wearable is smartwatches, like those from from Sony [34] and Samsung [35]. These have the ability to check e-mail and surf the Internet.

3. TEXTILES AND CLOTHING: THE META-WEARABLE

A critical need for extensive deployment of wearables for personalized mobile information processing is that they should not impose any additional social, psychological, or ergonomic burden on the individual. For instance, Google Glass significantly impacts social dynamics since the ones without this wearable device are not sure of what the wearer is doing with the device while being part of the conversation. What is therefore needed is an infrastructure or *platform* that will be unobtrusive, natural and pervasive, and not adversely impact social interaction.

Moreover, for many real-world applications, some of which are shown in Figure 5, multiple parameters must be simultaneously acquired, processed, and used to develop an effective response. This leads to the following requirements for creating and developing a useful wearable sensor system [36]:

- Different *types* of sensors will be needed for various parameters to be monitored *simultaneously*; for instance, sensors to monitor the various vital signs (e.g., heart rate, body temperature, pulse oximetry, blood glucose level) are of different types. Likewise, for monitoring hazardous gases, another class of sensors (e.g., carbon monoxide detection) will be required. Accelerometers will be required to continuously monitor the posture of the gamer or an elderly person to detect falls.
- Different *numbers* of sensors may be needed to obtain the signals to compute a single parameter (e.g., at least three sensors are required to compute the electrocardiogram or EKG).
- Sensors need to be positioned in *different* locations on the body to acquire the necessary signals (e.g., sensors for EKG go in three different locations on the body, whereas pulse-ox sensors and accelerometers go in other locations on the body).
- Different *subsets* of sensors and devices may be used at different times, necessitating their easy attachment and removal, or *plug and play*. For instance, the gamer may want to record how his body feels and reacts while being immersed in the game and, at other times, may also want to record his experience.
- The signals from the various sensors and in different physical locations (such as first responders responding to a disaster scene) have to be *sensed*, *collected*, *processed*, *stored*, and *transmitted* to the remote control and coordination location.
- Signals from different types of sensors (e.g., body temperature, EKG, accelerometers) have to be processed in parallel to evaluate the various parameters in real-time.
- Since a large number of sensors is usually required, these sensors would have to be low cost and hence would likely have minimal built-in (on-board) processing capabilities.
- The sensors should be power-aware (i.e., have low power requirements).
- Power must be supplied (distributed) to the various sensors and processors.

Thus, there is a need for a platform that has both a physical form factor and an integral information infrastructure. In addition to serving as a wearable in its own right, the platform must be able to *host* or hold other "wearables" or sensors in place and provide *data buses* or pathways to carry the signals (and power) between sensors and the information-processing components in the wearable network [37–38]. Simply attaching different types of sensors and processors to different parts of the body is not the ideal solution. What is needed is a *meta-wearable* [7]. That *meta-wearable* is textiles.

3.1 Attributes of the Textile Meta-Wearable

A textile is a *meta-wearable* because it meets all the attributes of the wearables in Figure 4. For instance, textile yarns, which are an integral part of the fabric, can serve as *data buses* or communication pathways for sensors and processors and can provide the necessary bandwidth required for interactivity. The topology, or structure of placement of these data buses, can be engineered to suit the desired sensor surface distribution profile, making it a versatile technology platform for wearables. In addition, textiles and clothing have the following key attributes [17,32–33]:

- Humans are used to wearing clothes so, in general, no special "training" is required to wear them, i.e., to use the interface. In fact, it is probably the most *universal* of human–computer interfaces and is one that humans need, use, have familiarity with, and which can be easily customized. Often termed the "second skin," it is the next best wearable (other than a smile).
- Humans enjoy clothing and this universal interface of clothing can be "tailored" to fit individual preferences, needs, and tastes, including body dimensions, budgets, occasions, and moods in which the wearables will be used.
- Textiles are flexible, strong, lightweight, and generally withstand different types of operational (stress/strain) and harsh environmental (biohazards and climatic) conditions.
- Textiles, unlike other engineering structures such as buildings, are unique in combining strength and flexibility in the same structure, and so they conform to the desired shape when bent but retain their strength.
- Textiles can be made in different form factors including desired dimensions of length, width, and thickness, and hence "variable" surface areas that may be needed for "hosting" varying numbers of sensors and processors for the desired application can be created.
- Textiles provide the ultimate flexibility in system design by virtue of the broad range of fibers, yarns, fabrics, and manufacturing techniques (e.g., weaving, knitting, nonwovens, and printing) that can be deployed to create products with engineered performance characteristics for desired end-use applications.
- Textiles are easy to manufacture in a relatively cost-effective (inexpensive) manner – roll-to-roll – compared to traditional printed circuit boards.
- Textiles obviate issues associated with entanglement and snags when using the system since the data buses or communication pathways are an *integral* part of the fabric.

- Textiles can easily accommodate "redundancies" in the system by providing multiple communication pathways in the network.
- Textile structures enable easy power distribution from one or more sources through the textile yarns integrated into the fabric, thus minimizing the need for on-board power for the sensors.

Therefore, from a technical performance perspective, a textile fabric (or clothing) is a true meta-wearable, making it an excellent platform for the incorporation of sensors and processors to harness situational awareness data while retaining its aesthetic and comfort attributes, among many other textile-unique properties.

3.2 Realization of the Meta-Wearable: The Wearable Motherboard

The Wearable Motherboard or Smart Shirt briefly mentioned earlier is the first such meta-wearable that has been successfully developed [39]. It has since paved the way for today's wearables revolution. The comfort or base fabric provides the necessary physical infrastructure for the wearable motherboard shown in Figure 7. The base fabric is made from typical textile fibers (e.g., cotton, polyester) where the choice of fibers is dictated by the intended application. The conducting yarns integrated into the fabric serve as data buses and constitute the information infrastructure. An interconnection technology has been developed and used to route the information (signals) through desired paths in the fabric, thereby creating a motherboard that serves as a flexible and wearable framework into which sensors and devices can be plugged.

For instance, when sensors for vital signs such as heart rate, electrocardiogram, and body temperature are plugged in, the wearer's physical condition is monitored.

3.2.1 Wearable Motherboard Architecture

The wearable motherboard architecture is shown in Figure 8. The signals from the sensors flow through the flexible data *bus* integrated into the structure to the multi-function

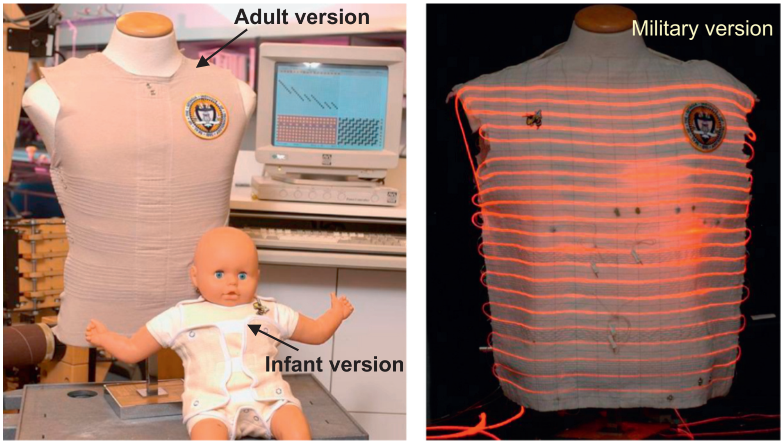

FIGURE 7 The wearable motherboard: adult, baby, and military versions.

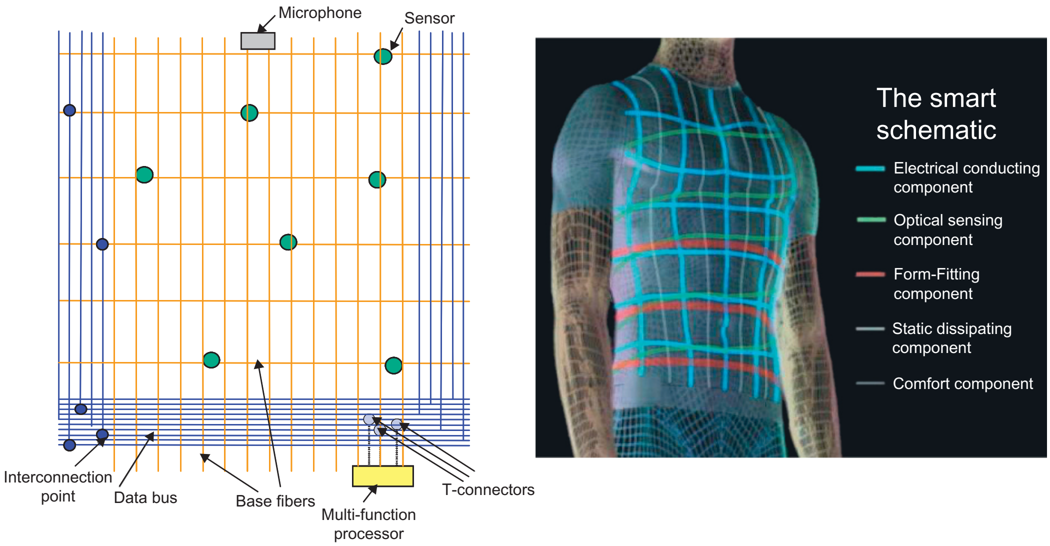

FIGURE 8 Wearable motherboard architecture.

processor/controller. This controller, in turn, processes the signals and transmits them wirelessly (using the appropriate communications protocol) to desired locations (e.g., doctor's office, hospital, battlefield triage station). The bus also serves to transmit information *to* the sensors (and hence, the wearer) from external sources, thus making the Smart Shirt a valuable bi-directional information infrastructure. The controller provides the required power (energy) to the wearable motherboard. With the advent of the smartphone, all the processing and communication can be shifted to it, thereby obviating the need for the controller.

The advantage of the motherboard architecture is that the *same garment* can be quickly reconfigured for a different application by changing the suite of sensors. For example, to detect carbon monoxide or hazardous gases in a disaster zone, special-purpose gas sensors can be plugged into the same garment and these parameters in the ambient environment can be monitored along with the first responder's vital signs. Similarly, by plugging in a microphone into the Smart Shirt, voice can be recorded. Optionally, the conducting fibers in the wearable motherboard can themselves act as "sensors" to capture the wearer's heart rate and EKG (electrocardiogram) [40]. Likewise, the military version of the Smart Shirt shown in Figure 7 uses optical fibers to detect bullet wounds in addition to monitoring the vital signs of the soldier during combat conditions. The wearable motherboard can be tailored to be a head cap so that the gamer's brain activity can be tracked by recording the electroencephalogram (EEG). Thus, the wearable motherboard is an effective meta-wearable and the structure has the *look* and *feel* of traditional textiles with the fabric serving as a comfortable information infrastructure.

3.2.2 Convergence and Interactive Textiles

The wearable motherboard is a platform that enables true convergence between electronics and textiles. Due to the modularity of the design architecture, the extent and duration of convergence can be controlled by the user. For example, as long as the sensors and processors are plugged into the wearable motherboard, there is true convergence and the resulting wearable (in the form of clothing) is smart and can perform its intended function, e.g., monitor the wearer's vital signs or other situational awareness data. When this task is completed, the sensors and processors can be unplugged and the garment laundered like other clothes. Thus, the usually *passive* textile structure is temporally transformed into a *smart interactive* structure and embodies the new paradigm that clothing is an *information processing structure* that *also* protects the individual while making him/her fashionable.

3.3 Applications of Wearables

Figure 9 is an artist's rendering of the role of wearables during the day in the life of a typical family. It is clear from the illustration that the number of applications is only limited by the imagination. They range from monitoring babies to senior citizens, i.e.,

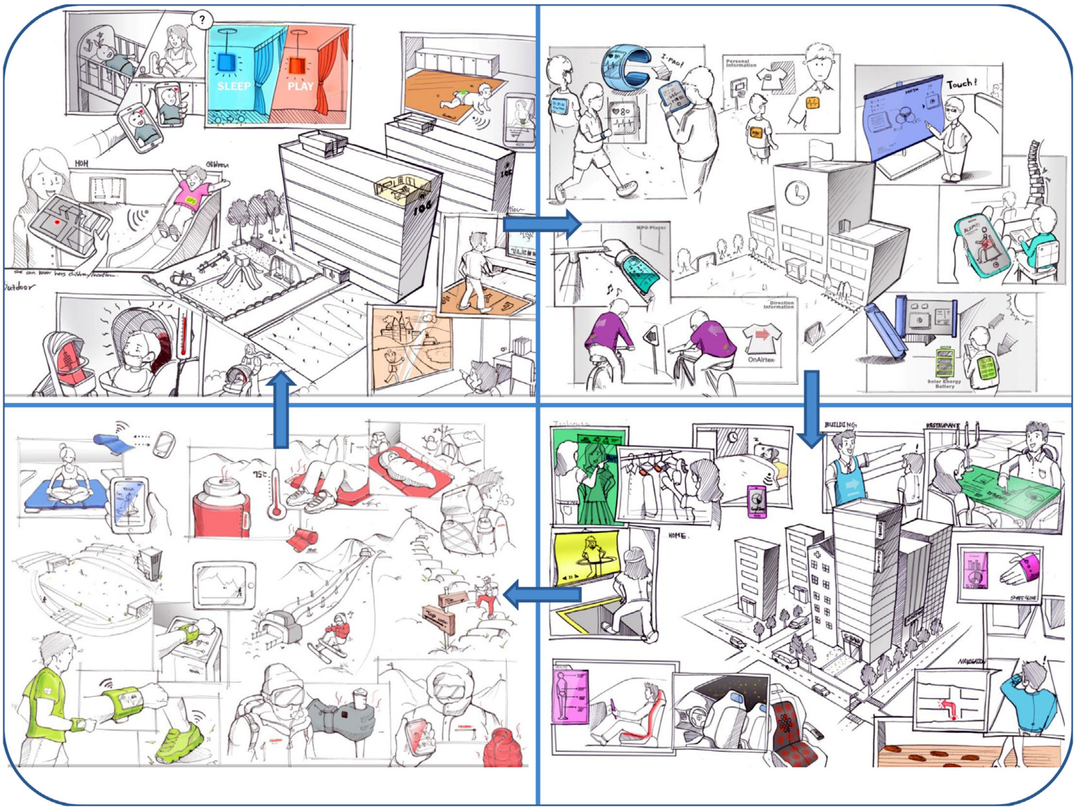

FIGURE 9 Wearables in the twin continuum of life and activities.

TABLE 1 Applications of Wearables

Sports Application: Coyle et al. have developed a wearable sensing system that integrates a textile-based fluid handling system for sample collection and transport with a number of sensors including sodium, conductivity, and pH sensors [41]. Together with sensors for sweat rate, EKG, respiration, and blood oxygenation, they were able to successfully monitor a number of physiological parameters together with sweat composition in real-time.
Public Safety (Protection) Application: The ProeTEX project, funded by the European Commission, has developed a wearable system for the protection of first responders [42]. It monitors the health of the users (heart rate, breathing rate, body temperature, blood oxygen saturation, position, activity, and posture) and environmental variables (external temperature, presence of toxic gases, and heat flux passing through the garments) and transmits the information to the coordination center to ensure the safety of the personnel.
Entertainment Application: The Philips Lighting project for the Black Eyed Peas group created a wearable system for the singers with organic light-emitting diodes (OLED) and LEDs that light up during the performance and provide a new experience for the audience and the entertainers [43].

the continuum of life, and span the continuum of activities in which the individuals are engaged.

Table 1 provides a summary of the various fields of application along with the typical parameters monitored for that application; the target population is also shown. In each application example, the wearable system is responsible for sensing, processing, analyzing, and transmitting the results to the user. Illustrative examples for three of the major classes of applications are presented here.

Despite the promise of wearables in the various fields of application and the projected market sizes, they have not become an integral part of many users' "must-have" accessories or technologies. We will now discuss the challenges encountered by wearables and the opportunities to successfully transition the technology to the marketplace.

4. CHALLENGES AND OPPORTUNITIES

The success of any innovative product in the marketplace depends on:

- Its effectiveness in successfully understanding the user's needs and meeting them
- Its compatibility with or similarity to existing products or solutions
- The extent of behavioral change needed to use the new product
- The reduction in the cost of current solutions or technologies it aims to supplant
- The improvement in the quality of service (or performance)
- The enhancement of the user's convenience

The innovation should provide a tangible advantage to the user and it should be consistent and compatible with the user's values, beliefs, and needs. Many an innovative technology has not been a marketplace success for one or more of these aforementioned reasons. For example, Apple's Newton, the first handheld device did not make it in the market, but spawned the highly successful Palm Pilot and generations of personal digital assistants because the latter addressed many of the issues that plagued the Newton. In the process, they spawned the ongoing innovation in tablets. Thus, factors related to the diffusion of innovation must be considered in addition to the technical and business challenges to ensure the successful transition of wearables from the laboratory to the highly competitive marketplace. A roadmap analyzing the technical, business, and public policy issues, including the need for a "killer app" to influence the adoption and acceptance of wearables, has been proposed [44].

4.1 Technical Challenges

The key technical challenges in the adoption of wearables are as follows:

- The success of wearables depends on the ability to connect them seamlessly in a body-worn network. This means the meta-wearable framework must have the ability to route the signals and power between desired points in the structure (Figure 8). The interconnection process for creating such junctions in textile materials has been manual to-date. The concept of textillography to automate interconnections during the fabric manufacturing process has been proposed [45]. An automated process that can provide precise, rugged, and flexible interconnections will help facilitate mass production and also lower the costs associated with wearables.
- In the event of damage to the data buses in the meta-wearable framework, the "failure" in the network must be recognized and alternate "data paths" must be established in the fabric to maintain the integrity of the network by taking advantage of the redundant data buses in the fabric. Preliminary work on the concept of "soft" interconnects has resulted in a programmable network in a fabric that enables real-time routing that can be configured on the fly [46].
- Currently, the so-called "t-connectors" and button snaps are being used for connecting sensors and processors to the meta-wearable. There is therefore the need for a common interface similar to the RJ-11 jack for telephones for connecting these sensors and processors to the meta-wearable so that general-purpose sensors and devices can be developed, thereby reducing their cost.
- Many of the wearables, especially those used for health monitoring applications and immersive gaming, are prone to motion artifacts, which can potentially affect the integrity of the results. There is therefore the need for in-depth studies to develop robust signal processing algorithms and systems to ensure the quality of the data generated by the wearables.
- While currently available conductive fibers can fulfill the basic requirements for the first generation of textile-based wearables, it is important to develop new materials that will have the conductivity of copper and the properties of textile fibers such as cotton, polyester, or nylon, and be available in commercial quantities. Research is needed to develop fibers that can also retain their conducting properties after repeated laundering.
- Today's wearables are powered by lithium-ion rechargeable batteries, which is another limiting factor in the adoption of the technologies due to the rigidity of the battery in relation to the flexible nature of the wearables, a key desired attribute of wearables

shown in Figure 4. This bottleneck is being addressed by research on two fronts, piezoelectric-based energy-harvesting systems and flexible textile battery, respectively. A textile battery, developed using a woven polyester fabric as a substrate, has exhibited comparable electrochemical performance to those of conventional metal foil-based cells even under severe folding–unfolding motions simulating actual wearing conditions [47]. The 13 mAh battery retained 91.8% of its original capacity after 5,500 deep folding–unfolding cycles. The researchers also successfully integrated the flexible textile battery with lightweight solar cells on the battery pouch to enable convenient solar-charging capabilities.
- The seamless integration of wearables in healthcare settings and for remote monitoring faces the challenge of ensuring compatibility with existing wireless technologies and established operational protocols in those settings [48]. Strategies and solutions must be developed to address this important aspect to help the adoption of wearables for remote monitoring.
- The challenges associated with protection of individual privacy, data security, and other social aspects of the acceptance of wearables must be addressed because the wearables are collecting personal information. The electronics and communications industry in collaboration with privacy protection organizations must develop appropriate protocols that will identify proper technology and public policy solutions to further the free acceptance and use of wearables.
- The supply chains for textiles/clothing and electronics are significantly different. Apparel manufacturing is a labor-intensive operation whereas electronics manufacturing is highly automated. Consequently, the production rates are much higher in electronics manufacturing. The apparel industry is not as precise in terms of topology and interfaces between the different components when compared to the electronics industry whose operating paradigm is precision. Thus, the differences between these manufacturing paradigms must be addressed for the widespread adoption of textile-based meta-wearables for the various applications listed earlier in Table 1.
- Finally, the same wearable may be used in a range of environmental conditions – indoors to outdoors – which may include disaster zones involving high temperatures (e.g., fire) and hazardous materials. Therefore, they should be designed to function effectively and seamlessly in a wide range of ambient environments.

4.2 Making a Business Case

The litmus test for wearables lies in demonstrating their value to the end user and those involved in paying for the technology. The key activities for transitioning the technology from the laboratory to the market are shown in Figure 10. It begins with articulating the need for the technology in a chosen domain and demonstrating its effectiveness through the metrics of cost, quality, and convenience. The various stakeholders responsible for effecting the transition are also shown in the figure. The end user – a patient in the case of a wearable for the healthcare market or a gamer in the gaming market, and so on – must experience the value of the technology which will motivate the user or the payer (the healthcare insurance company in the case of healthcare or the individual gamer) to pay for

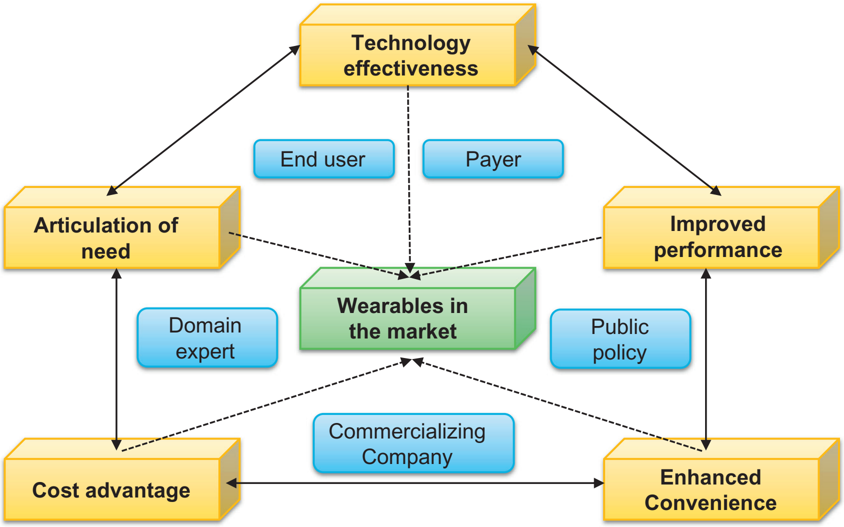

FIGURE 10 Making a business case: stakeholders and metrics.

it as it would benefit the payer in the long-run. Public policy comes into play in the adoption of wearables because of the associated privacy and data access issues. Once the needs are articulated well by the domain expert and the benefits are corroborated by the end user, the commercializing company will be incentivized to proceed with developing and marketing the wearable technology. Thus, all the stakeholders are critical for the success of wearables in the marketplace and a total lifecycle approach that goes beyond just the basic cost of the technology must be adopted in developing the market for wearables.

We will now attempt to gaze into the future of wearables and define a research roadmap to realize it.

5. THE FUTURE OF WEARABLES: DEFINING THE RESEARCH ROADMAP

The paradigm of "Information Anywhere, Anytime, Anyone" is a reality today. For instance, a racing car enthusiast in Cupertino, California can see – on his mobile device – the driver's view of the track as he negotiates the Daytona Speedway. He can instantaneously access all the "stats" associated with the lap, the race, the standing, the history, and so on, thanks to the convergence of high-performance computing, communications, video, and data fusion technologies.

5.1 Imagine the Future

What if the driver's racing suit changes color as the G forces acting on different parts of his body change during the course of the race [7]? What if his suit also captures biometrics such as heart rate, electrocardiogram, body temperature, water loss, and calories burned, and displays these parameters on the fan's mobile device? What if the pit crew can use this real-time data and integrate that with the archival data to decide on *when* to take the next pit stop and *what* actions to take during the stop? Imagine further if the fan in California could *physically* "experience" the G forces acting on the driver during the race with varying degrees of compression on his body?

The meta-wearable of clothing with its integrated sensors and devices can make this possible. The driver's biometric and contextual/experiential data can be captured through the driver's smart clothing – a meta-wearable. This information can be wirelessly transmitted to the fan; the fan's meta-wearable – the smart clothing called *ExpWear* for Experience Wear – can, in turn, transform the data and recreate the remote ambient environment so that the fan's clothing lights up the same way as the driver's and the fan also experiences the G forces experienced by the driver through a suite of sensors, actuators, and other devices integrated into the garment. What if the *ExpWear* also displays the fan's biometrics on the left sleeve and the driver's on the right sleeve? In other words, imagine a world in which the fan can recreate and experience in Cupertino the remote ambience in Daytona through his meta-wearable *ExpWear*. This is the world of *sportatainment* that represents the integration and transformation of sports actions into entertainment using the meta-wearable of textiles and clothing.

Another example: It is the Super Bowl 2014 and Peyton Manning's Smart Jersey – the meta-wearable – is monitoring him and his heart rate is displayed on it (Figure 11). With just 45 seconds left in the game, he is tackled; the force he experiences is displayed on his Jersey. Immediately, on another continent, a football fan watching the game in his *ExpWear* experiences the *pain* of the tackle! Indeed, he feels like he is "in the game" thanks to the meta-wearable of textiles and clothing. While the sports domain has been chosen as an example, it is easy to visualize transformations in other areas and to see the potential for wearables in the dynamic world of Internet of Things.

FIGURE 11 Sportatainment: Enabled by the meta-wearable of clothing.

5.2 The Research Roadmap: A Transdisciplinary Approach to Realizing the Future

There is a need for a transdisciplinary approach to realize the future of wearables, which means that it should be pursued as a *new* field of endeavor that brings together knowledge (both foundational and technological advancements) from other established fields such as materials/textile science and engineering, electronics, manufacturing and systems engineering, computing and communications, industrial design, and social sciences [49].

Figure 12 attempts to capture this transdisciplinary approach to wearables research. The major building blocks of wearables, viz., sensors, actuators, processors, energy sources, and interconnections are shown in the figure; the standards governing the design and use of wearables, which must be developed, are also shown in the figure. The materials and manufacturing methods that are integral to the realization of wearables are shown in the left and right panels to signify their key roles in bringing the building blocks together and making the wearable a reality. A change to any of the building blocks will affect the others and, in turn, influence the wearable that is shown in the center of the figure. It is therefore important to view this as a unified ecosystem rather than as a collection of individual pieces. For this key reason, the transdisciplinary paradigm should be adopted to drive the advancements in the field of wearables. Such an approach will bring an innovative perspective leading to revolutionary advancements. This is because a transdisciplinary inquiry focuses on *the* issue, viz., the wearable, rather than what each of the disciplines can *individually* bring to the table and "contribute" to it (the interdisciplinary mode of inquiry and research).

In closing, wearables are increasingly becoming an integral part of our digital lives and the potential application areas are only limited by our imagination. Indeed, it is hard to fathom life without a wearable! A transdisciplinary approach will indeed move us rapidly forward on this exciting journey towards the Holy Grail of wearables and, in the process, enable us to "do well by doing good."

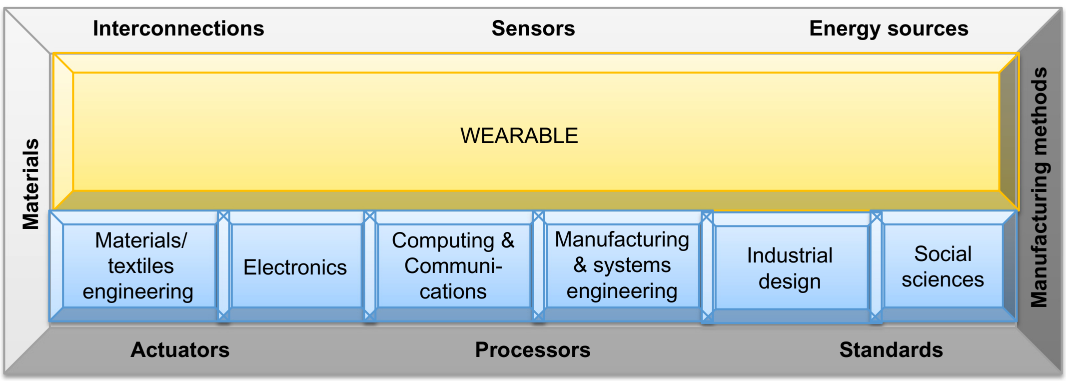

FIGURE 12 Research roadmap for wearables: Need for a transdisciplinary approach.

References

[1] M. Rocetti, G. Marfia, A. Semeraro, Playing into the wild: A gesture-based interface for gaming in public spaces, J. Vis. Commun. Image Representation 23 (3) (2012) 426–440.

[2] J. Tedjokusumo, S. Zhou, S. Winkler, Immersive multiplayer games with tangible and physical interaction, IEEE Trans. Syst. Man Cybern. A Syst. Hum. 40 (1) (2010) 147–157.

[3] M. Nayak, FACTBOX - A look at the $66 billion video-games industry, <http://in.reuters.com/article/2013/06/10/gameshow-e-idINDEE9590DW20130610>, (Last Accessed: 18.11.13).

[4] T.A. Cellucci, Commercialization: The First Responders' Best Friend, US Department of Homeland Security: Science and Technology, Washington, DC, 2009.

[5] S. Park, S. Jayaraman, Wearable sensor network: a framework for harnessing ambient intelligence, J. Ambient Intell. Smart Environ. 1 (2) (2009) 117–128.

[6] S. Jayaraman, Reinventing Clothing: Clothing of Nations to the Health of Nations, The Second TIIC International Symposium, Seoul, South Korea, 2012.

[7] S. Park, S. Jayaraman, The Wearables Revolution and Big Data: The Textile Lineage, Proceedings of the 1st International Conference on Digital Technologies for the Textile Industries, Manchester, UK, 2013.

[8] McKinsey Global Institute, Big Data: The Next Frontier for Innovation, Competition and Productivity, 2011.

[9] <http://www.cms.gov/CCIIO/Programs-and-Initiatives/Health-Insurance-Market-Reforms/Medical-Loss-Ratio.html>, (Last Accessed: 29.11.13).

[10] P. Lane, A Sense of Place, Special Report, The Economist, October 27, 2012, <http://www.economist.com/news/special-report/21565007-geography-matters-much-ever-despite-digital-revolution-says-patrick-lane>, (Last Accessed: 02.11.13).

[11] E. Kress-Rogers, Biosensors and electronic noses for practical applications, in: E. Kress-Rogers (Ed.), Handbook of Biosensors and Electronic Noses: Medicine, Food, and the Environment, CRC Press, New York, NY, 1997, pp. 3–39.

[12] K.L. Jackson, L.E. Polisky, Wearable computers: information tool for the twentyfirst century, Virtual Real., 3, 147–156.

[13] S. Mann, On the bandwagon or beyond wearable computing? Pers. Technol., 1:203–207.

[14] S. Mann, Smart clothing: the wearable computer and WearCam. Pers. Technol., 1:21–27.

[15] M. Weiser, The Computer for the 21st Century, Sci. Am. (1991) 94–104.

[16] S. Park, C. Gopalsamy, R. Rajamanickam, S. Jayaraman, The Wearable motherboard™: an information infrastructure or sensate liner for medical applications, pp. 252–258. Studies in Health Technology and Informatics, vol. 62, IOS Press, 1999.

[17] C. Gopalsamy, S. Park, R. Rajamanickam, S. Jayaraman, The wearable motherboard™: the first generation of adaptive and responsive textile structures (ARTS) for medical applications, Virtual Real. 4 (1999) 152–168.

[18] S. Park, S. Jayaraman, Adaptive and responsive textile structures, in: X. Tao (Ed.), Smart Fibers, Fabrics and Clothing: Fundamentals and Applications, Woodhead Publishing Limited, Cambridge, UK, 2001, pp. 226–245.

[19] A. Lymberis, D. DeRossi, Wearable eHealth Systems for Personalised Health Management, IOS Press, Amsterdam, The Netherlands, 2004.

[20] D. DeRossi, A. Lymberis, New generation of smart wearable health systems and applications, IEEE Trans. Inf. Technol. Biomed. 9 (3) (2005) 293–294.

[21] A.V. Halteren, R. Bults, K. Wac, N. Dokovsky, G. Koprinkov, I. Widya, et al., Wireless body area networks for healthcare: the MobiHealth project, Stud. Health Technol. 108 (2004) 181–193.

[22] A. Lymberis, D. Dittmar, Advanced wearable health systems and applications: Research and development efforts in the European union, IEEE Eng. Med. Biol. 23 (3) (2007) 29–33.

[23] R. Paradiso, A. Gemignani, E.P. Scilingo, D. DeRossi, Knitted bioclothes for cardiopulmonary monitoring, Proc. 25th Ann. Int. Conf. IEEE EMBS 4 (2003) 3720–3723.

[24] M.D. Rienzo, F. Rizzo, G. Parati, G. Brambilla, M. Ferratini, P. Castiglioni, MagIC system: a new textile-based wearable device for biological signal monitoring. Applicability in daily life and clinical setting, Proc. 27th Ann. Int. Conf. IEEE EMBS (2005) 7167–7169, Shanghai, China.

[25] P. Bonato, Wearable sensors/systems and their impact on biomedical engineering, IEEE Eng. Med. Biol. 22 (3) (2003) 18–20.

[26] M.A. Hanson, H.C. Powell, A.T. Barth, K. Ringgenberg, B.H. Calhoun, J.H. Aylor, et al., Body area sensor networks: challenges and opportunities, Computer 42 (2009) 58−65.

[27] K. Cherenack, L. von Pieterson, Smart textiles: challenges and opportunities, J. Appl. Phys. 112 (2012) 091301−091314.

[28] S. Patel, H. Park, P. Bonato, L. Chan, M. Rodgers, A Review of wearable sensors and systems with application in rehabilitation, J. Neuroeng. Rehabil. 9 (2012) 21.

[29] S. Bauer, Flexible electronics: sophisticated skin, Nat. Mater. 12 (2013) 871−872.

[30] Fitbit®, <http://www.fitbit.com/>, (Last Accessed: 02.11.13).

[31] Jawbone®, <https://jawbone.com/up>, (Last Accessed: 30.08.13).

[32] Nike FuelBand®, <http://store.nike.com/us/en_us/pd/fuelband-se/pid-924485/pgid-924484?cp = usns_kw_AL!1778!3!30651044462!e!!g!nike%20fuelband>, (Last Accessed: 15.11.13).

[33] Welcome to a World Through Glass, <http://www.google.com/glass/start/what-it-does/>, (Last Accessed: 30.08.13).

[34] <http://store.sony.com/smartwatch-2-zid27-SW2ACT/cat-27-catid-Smart-Watch>, (Last Accessed: 15.11.13).

[35] <http://www.samsung.com/us/mobile/wearable-tech/SM-V7000ZGAXAR>, (Last Accessed: 15.11.13).

[36] S. Park, S. Jayaraman, Sensor networks and the i-textiles paradigm, Proceedings of the Next Generation PC 2005 International Conference, COEX, Seoul, Korea, 2005, pp. 163−167.

[37] S. Jayaraman, Fabric is the Computer: Fact or Fiction? Keynote Talk at Workshop on Modeling, Analysis and Middleware Support for Electronic Textiles (MAMSET) at ASPLOS-X (Tenth International Conference on Architectural Support for Programming Languages and Operating Systems), San Jose, CA, October 6, 2002.

[38] S. Park, S. Jayaraman, Smart textiles: wearable electronic systems, MRS Bull. (2003) 586−591.

[39] R. Rajamanickam, S. Park, S. Jayaraman, A structured methodology for the design and development of textile structures in a concurrent engineering environment, J. Text. Inst. 89 (Part 3) (1998) 44−62.

[40] S. Jayaraman, S. Park, A novel fabric-based sensor for monitoring vital signs, US Patent No 6,970,731, November 29, 2005.

[41] S. Coyle, King-Tong Lau, N. Moyna, D. O'Gorman, D. Diamond, F. Di Francesco, et al., BIOTEX—biosensing textiles for personalised healthcare management, IEEE Trans. Inf. Technol. Biomed. 14 (2) (2010) 364−370.

[42] D. Curone, E.L. Secco, A. Tognetti, G. Loriga, G. Dudnik, M. Risatti, et al., Smart garments for emergency operators: the proetex project, IEEE Trans. Inf. Technol. Biomed. 14 (3) (2010) 694−701.

[43] See What Light Can Do – Black Eyed Peas Project, <http://www.lighting.philips.com/main/connect/lighting_university/led-videos/black-eyed-peas-project.wpd>, (Last Accessed: 17.11.13).

[44] S. Park, S. Jayaraman, Smart textile-based wearable biomedical systems: a transition plan for research to reality, IEEE Trans. Inf. Technol. Biomed. 14 (1) (2010) 86−92.

[45] S. Jayaraman, S. Park, Method and apparatus to create electrical junctions for information routing in textile structures, US Patent 7, 299,964, November 27, 2007.

[46] S. Park, K. Mackenzie, S. Jayaraman, The Wearable Motherboard: A Framework for Personalized Mobile Information Processing (PMIP), Proceedings of DAC 2002, New Orleans, Louisiana, USA, 2002, pp. 170−174.

[47] Y. Lee, J. Kim, J. Noh, I. Lee, H. Kim, S. Choi, et al., Wearable textile battery rechargeable by solar energy, Nano. Lett. 13 (2013) 5753−5761.

[48] H.S. Ng, M.L. Sim, C.M. Tan, C.C. Wong, Wireless technologies for telemedicine, BT Technol. J. 24 (2) (2006) 130−137.

[49] S. Park, S. Jayaraman, The engineering design of intelligent protective textiles and clothing, in: P. Kiekens, S. Jayaraman (Eds.), Intelligent Textiles and Clothing for Ballistic and NBC Protection: Technology at the Cutting Edge, NATO Science for Peace and Security Series B: Physics and Biophysics, Springer, The Netherlands, 2012, pp. 1−27.