An Overview of Wearable Computing

Gary M. Weiss and Md. Zakirul Alam Bhuiyan

Abstract This chapter provides a high-level user-oriented overview of wearable computing. It begins by defining wearable computing and describing its key characteristics. It then provides an historical view of wearable computing devices, beginning with an abacus ring from the 17th century and progressing to modern wearable computing devices. Lessons learned from this history and their implications for future wearable devices are discussed. Key application areas for wearable computing are then introduced, and sample applications from each area are described. Two case studies are provided to demonstrate the role of data analytic methods, and how they can yield more powerful wearable applications. The chapter concludes with a summary of the current state of wearable technology.

1 Introduction

Wearable computing has been around in a limited form for several centuries, but has entered the mainstream only recently, due to the increasing availability of very small and low-powered computational devices and sensors. Some of these devices, such as the smartphone, are not perfect examples of wearable computing due to the significant amount of time and attention it takes to access them, but are incredibly important due to their enormous impact on our economy and society. Better examples of wearable computing devices, like smartwatches, have thus far enjoyed only moderate commercial success, while much more ambitious and potentially revolutionary wearable computing devices, like Google Glass, have encountered difficulty with widespread adoption. Although resistance to these new technologies makes the market for such devices uncertain, the future for wearable computing is still quite promising, due to the increasing availability of inexpensive sensors, low-cost processors, and inex-

G. M. Weiss (✉) · Md. Z. A. Bhuiyan
Department of Computer & Information Science, Fordham University, Bronx, NY, USA
e-mail: gaweiss@fordham.edu

Md. Z. A. Bhuiyan
e-mail: mbhuiyan3@fordham.edu

H. M. Ammari (ed.), *Mission-Oriented Sensor Networks and Systems: Art and Science*, Studies in Systems, Decision and Control 164,
https://doi.org/10.1007/978-3-319-92384-0_10

pensive memory. This chapter will provide the reader with an overview of wearable computing: what it is, how it has developed, what has been created, what applications it can support, and what the future may hold. This overview is not intended to provide a detailed engineering analysis of wearable computing devices and how they function.

We start by providing an understanding of wearable computing. The concept is relatively straightforward since it generally concerns computing devices that can be worn. However, the existing formal definitions and descriptions of wearable computing tend to refine the concept by emphasizing or deemphasizing certain key characteristics of the devices. An early definition of wearable computing was provided in a July 1996 U.S. Defense Advanced Research Projects Agency workshop on "Wearables in 2005," which aimed to predict the future of wearable ten years into the future. This DARPA workshop defined wearable computing as "data gathering and disseminating devices which enable the user to operate more efficiently. These devices are carried or worn by the user during normal execution of his/her tasks" [1]. The key element in this definition is that wearable computing should be used in a natural, unobtrusive, manner. Steve Mann, an early pioneer in the field who created a personal imaging device with a camera and display built within an ordinary pair of sunglasses, described three key characteristics of what he referred to as "WearComp" [2]. According to Mann, a wearable computer is worn, not carried, in such a way as it can be regarded as being part of the user; it is user controllable, not necessarily involving conscious thought or effort; and it operates in real time and is always on.

Common modern examples of commercial wearable computing devices include: wearable fitness trackers like FitBit, smartwatches such as the Apple Watch and Motorola Moto 360, and wearable cameras like the ones popularized by GoPro. Google glass, which is currently available only for development purposes, is the most ambitious commercial wearable computing product to date. It provides general computer functionality to the user via a tiny projection in front of the user's eye, utilizes voice recognition technology, and includes many of the functions of the very early head-mounted displays. The single most popular wearable computing device is the smartphone, although this is not an ideal example of wearable computing given the definitions just provided—the smartphone often needs to be held in one's hand rather than worn, which means that its use is often obtrusive. However, because it is often "worn" in one's pocket, and in some cases can be controlled by a smartwatch, it is a valid wearable computing device and can sometimes even be used unobtrusively.

2 The History of Wearable Computing

This section provides an overview of the history of wearable computing. This will provide insight into the development path of wearable computing, highlight challenges and issues that can occur, and will allow us to identify several patterns—and lessons—that can help us predict the future path of wearable computing.

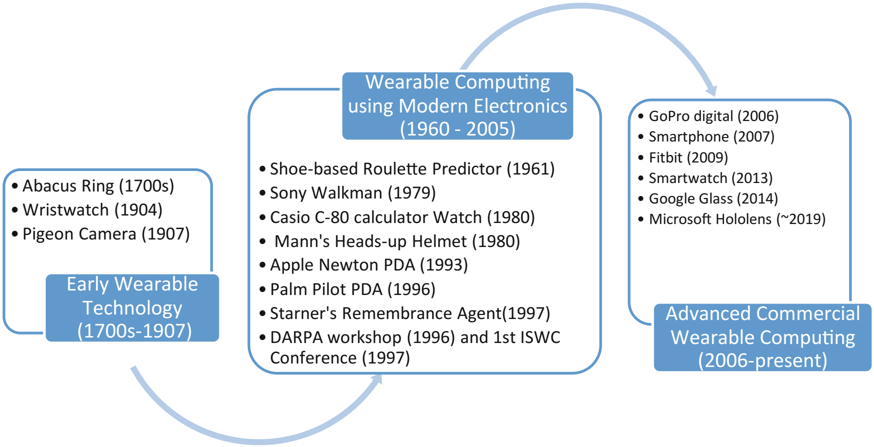

Fig. 1 Timeline of wearable computing products

Interestingly, the history of wearable computing is quite extensive, and even predates the invention of the modern electronic computer. Given the number of wearable devices that have been developed it cannot be comprehensive, so this section instead focuses on breadth—covering wearables from different time periods—and also on the most important and well-known examples of wearable computing. We divide the history of wearable computing devices into three main time periods: Early Wearable Technology (1700–1907s), Wearable Computing using Modern Electronics (1960–2005), and Advanced Commercial Wearable Computing (2006—present). The main distinguishing characteristics between the first and second time periods is the type of technology used, while the main differences between the second and third periods is the level of refinement and commercial success. An overview of all of the products described in this section is provided in Fig. 1.

2.1 Early Wearable Technology (1700–1907s)

The earliest wearable technology had limited computing capabilities and may not have had any electronic components, but nonetheless shared many characteristics with modern wearables. Part of the significance of these early devices is that they were the precursors to more advanced computational devices that were introduced many years later.

2.1.1 Abacus Ring (1700s)

A very early example of wearable computing is the abacus ring from China's Qing Dynasty, which was used by traders in the seventeenth century. The tiny abacus ring was 1.2 cm-long and 0.7 cm-wide, and contained nine wires which each had seven beads. The beads were so small that they could not easily be manipulated by human fingers and instead were manipulated by small pins (it is believed that the rings were often used by women who could use their hairpins for this task). The ring allowed large sums to be quickly tabulated, and hence is an excellent example of non-electronic wearable computing. The abacus ring may be functionally considered a forerunner of or the calculator watches of the 1980s.

2.1.2 Wristwatch (1904)

Another key development in wearable technology had to do with tracking time. As the technology used for making timepieces miniaturized, pocket watches were invented so one could always have a mobile (i.e., portable) timepiece. But removing one's pocket watch to check the time could interfere with important activities, especially in the military, where the synchronization of military maneuvers or actions was often critical. Toward the end of the nineteenth century watches had become sufficiently miniaturized that a German artillery officer was able to strap a pocket watch to his wrist. The first "true" wristwatch was created in 1904 when Alberto Santos-Dumont, an experimenter in heavier-than-air flying machines, commissioned the famous jeweler Louis Cartier to manufacture a small timepiece with a wristband, so that he could check the time on his "wristwatch" while keeping his hands available for flying [3]. While this device did not have any true computing power, it serves as the precursor of the modern smartwatch.

2.1.3 Pigeon Camera (1907)

Around the same time as the invention of the wristwatch, Dr. Julius Neubronner invented a tiny camera, with a timing mechanism, capable of taking a single image (see Fig. 2). The camera was strapped to a pigeon and the resulting aerial images garnered Dr. Neubronner quite a bit of fame. Many of the aerial photographs were turned into postcards. This "pigeon camera" is superficially similar to the popular GoPro camera, because both are "worn." However, there are significant differences, in that the main goal of the GoPro is to take first-person action shots and videos, whereas the pigeon camera was largely designed in order to make it possible to take inexpensive aerial photographs.

Fig. 2 Dr. Neubronner with his pigeon camera

2.2 Wearable Computing Using Modern Electronics (1960–2005)

Electronic programmable computers were introduced in the 1940s, and just a few decades later began to be incorporated into wearable devices. These computers were relatively primitive toward the beginning of this period, but were quite powerful by the end of the period.

2.2.1 Shoe-Based Roulette Predictor (1961)

In 1955 Edward Thorpe conceived of what he considered to be the first wearable computer—a shoe-based device for predicting the outcome of roulette spin. Eventually, in 1960 and 1961, Thorpe built the device with assistance from Claude Shannon, and it was field tested in Las Vegas in 1961 [4]. The device was quite successful and it is expected gain of +44%, determined under laboratory conditions, was validated in Las Vegas and yielded a $10,000 profit. A shoe-based device was used for inputting timing information related to the ball position via toe switches. Based on the physical models that were programmed into the computer, the device would predict which of the eight octants of the roulette wheel that the ball would land in. Two people and devices were involved: one to input the data into one device, while the other would wirelessly receive the prediction via another shoe-based device and place the bet. Thorpe and Shannon kept their invention secret until 1966. The invention was later commercialized by Eudaemonic Enterprises but never generated a huge win [5].

2.2.2 Sony Walkman (1979)

One of the trends that began in this period was the miniaturization of electronic devices. One of the most striking success stories was the Sony Walkman, a 14 oz portable cassette player that was introduced on July 1, 1979. While this was not a computing device—or initially even a digital device—it is very important in the history of wearable computing for two reasons. The first reason is that it was the first electronic device that demonstrated the immense market potential for electronic wearables. More than 400 million Sony portable music players have been sold, and of these 200 million were of the original cassette variety. Thus it anticipated and perhaps suggested the future success of more advanced wearables like the iPhone. The second reason is that the initial Sony Walkman is the predecessor of the portable digital music player, which is a legitimate wearable computing device. While digital music players such as the Apple iPod provided only limited computing capabilities, they ultimately hastened the advent of the smartphone, which included many advanced computing capabilities.

2.2.3 Calculator and Databank Watches (1980)

Simple commercial wearable computing devices began to enter the marketplace in the late 1970s in the form of calculator watches manufactured by Pulsar and HP. However they did not become very popular until the 1980s, when other manufacturers, such as Casio, released their own products. Casio released the C-80 watch with a calculator function in 1980, the T-1500 with a dictionary function in 1982, and the CD-40 with a "databank" function in 1984. The databank could save and recall 10 groups of 16 letters or numerals, eliminating the need to carry a personal phone-number organizer. This watch highlighted the concept of an information device on the wrist. The CD-40 became a major hit, selling six million units in the 5 years after its release [6]. These devices are the predecessors of the modern smartwatch (Fig. 3).

2.2.4 Personal Digital Assistant (1993)

In the early 1990s a new type of commercial portable digital device came out—the personal digital assistant (PDA). These devices included a phone and address book, a calendar, and typically had the ability to take notes using a stylus. These devices also often had handwriting recognition capabilities. The combination of the stylus and handwriting recognition led to a change in user interface and promoted the use of handwriting over keyboarding. Notable PDAs included the Apple Newton, which was introduced in 1993, and Palm Computing's Pilot, which was introduced in 1996. Similar to modern smartphones, these devices were not perfect examples of wearable computing since they normally had to be held in one's hand, but the services that they provided are services that one would want a wearable to provide. Ultimately the functions provided by the PDA were incorporated into the smartphone and hands-

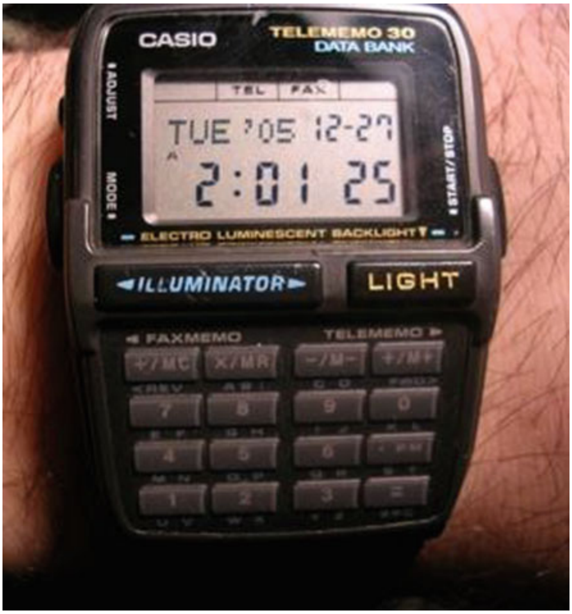

Fig. 3 A casio data bank watch

free wearables like smartwatches that could utilize voice recognition. The use of the stylus—perhaps combined with handwriting recognition—has been almost entirely eliminated from most modern wearable computing devices.

2.2.5 Head-Mounted Displays and Starner's Remembrance Agent (1968–1997)

Much of the most interesting and ambitious work on wearable computing in the late 1960s and the 1970s involved head-mounted displays. The goal for these head-mounted devices was to provide the benefits of traditional computing (e.g., email), but unobtrusively and in a mobile setting, and to also provide new capabilities that are now commonly associated with augmented reality. Ivan Sutherland was involved in very early work in this area, and his head-mounted displays employed partially reflective mirrors to let the wearer see a virtual world superimposed on reality. However, due to the technological limitations of the time, his head-mounted displays had to be tethered in order to obtain the necessary power and computing resources [7]. In 1980, Steve Mann, while still in high school, developed a tetherless helmet with a built-in CRT screen, which allowed one to monitor the screen while walking around [8]. But this system suffered due to the hassle of wearing cumbersome head gear, low-resolution video, eye fatigue, and the requirement for dim lighting conditions. However, over a 16 year span, advances in miniaturization allowed Mann to address many of these issues, and led to the first eyeglass-mounted versions in the late 1980s and, by 1996, an eyeglass version that was virtually indistinguishable from a normal pair of glasses [8]. Computer control was accomplished via a handheld device, which limited the user's ability to interact normally with his environment. Mann envisioned applications such as capturing visual images to form a pictorial diary of one's day, and computationally augmenting the projected images so that the device operates as a personal virtual assistant for the visually challenged.

Research at MIT Media Lab, led by Thad Starner in the 1990s, focused on using head-mounted display technology to function as a personal assistant via augmented reality [9]. The wearable computer would monitor what the user was doing and then would provide relevant information. This information agent was known as the Remembrance Agent [10]. The head-mounted system used finger tracking to replace a computer mouse, an important advance in the area of wearable computing. The system experimented with a variety of important concepts that are still relevant today: providing textual descriptions for physical objects ("physically-based hypertext"), 3D graphics overlaid on physical objects (e.g., for repair instructions), and even using face recognition to identify nearby people. The authors envisioned a prediction component that would ultimately anticipate the user's needs and act accordingly. This system, and systems like it, highlighted the potential value of augmented reality. Google Glass is the descendent of these various systems.

2.2.6 Formation of Dedicated Research Communities (1996)

By the mid-1990s, there was sufficient interest in wearable computing that the main participants could organize and form their own research community. This led to the Defense Advanced Research Projects Agency 1996 workshop on "Wearables in 2005," which attempted to predict the future of wearable computing [1]. The DARPA workshop was attended by representatives from academia, industry, and the military. It was followed a year later by the First International Symposium on Wearable Computers [11], a conference that is still active today. As mentioned earlier in this chapter, papers presented at these meetings helped to define wearable computing and their defining characteristics. Since this 1996 meeting, there has been a research community continuously dedicated to wearable computing, as well as a series of conferences and workshops focused on the topic.

2.3 Advanced Wearable Computing (2006–Present)

The period that we refer to as advanced wearable computing is largely characterized by highly refined products, designed and engineered for the mass market, which typically achieve enormous commercial success. Some of the products, however, are not particularly ambitious in that they are only intended to perform one or a few tasks very well. Only toward the end of this period do we see some products that rival the ambitions of the heads-up displays from the 1980s—and these products have thus far largely failed to catch on (e.g., Google Glass), or are not quite ready for market (Microsoft Hololens).

2.3.1 The GoPro Digital Camera (2006) and Other Lifelogging Wearables

One of the early successes of this period was the GoPro camera. While the first version was introduced in 2004, the first digital version was not introduced until 2006 (that version included the ability to take short videos). As the technology advanced, more storage was available and longer videos could be taken. The distinctive aspect of the GoPro devices was that they were designed to be worn in order to take "first-person" pictures and videos while engaged in active sports, such as skiing or surfing. While these devices performed only limited computing functions, their imaging capabilities were similar to those provided for by the early head-mounted wearables—both were capable of capturing first-person video to help record your life.

More recently, a number of very small wearables have entered the market to help continuously record your life. The Perfect Memory Smart Pro Camera from General Streaming Systems, LLC, is a very small wearable that can be clipped on to your clothes that provides continuous recording [12]. Due to storage limitations not everything can be kept and therefore the product's main goal is to allow you to save interesting events that happen to occur. If something noteworthy occurs, you can manually scroll back and save the footage, or tap the device and it will automatically save the last 5 min of footage. Other lifelogging cameras include the Narrative Clip 2, YoCam, Sony Experia Eye, and ION SnapCam [13]. Most of these devices can use BlueTooth to connect to a smartphone to save the images. The notion of lifelogging has not yet caught on, but could become more attractive and desirable with continued improvements in computer technology.

2.3.2 Smartphones (2007)

The most notable commercial success of this time period is the smartphone. The Apple iPhone and the first Android phone were released in the United States in 2007 and 2008, respectively. These multi-function devices incorporated a large number of services and capabilities, including: phone, camera/video recording, Internet connected web browsing, email, phone/address book, digital music player, GPS-based directions, and video game player. Thus they incorporated all of the functions of cell phones, personal digital assistants, and digital music players. They also were able to serve as cameras, portable gaming systems, and GPS-enable mapping applications. Aside from all of these capabilities, smartphones are also miniature computers with significant processing power and reasonable storage capacity.

The smartphone is not an ideal wearable computing device since many of its functions require that it be retrieved from one's pocket or purse and held in one's hand. The handheld manual operation of the smartphone can interfere with normal daily activities. Thad Starner, who has been wearing heads-up displays for more than two decades, says that it takes about 20s to retrieve a smartphone, and that this delay between intention and action is significant and will reduce smartphone usage [9]. However, the smartphone increasingly serves important roles that do not require it to be held in one's hand. This is because it can connect to other devices wirelessly via Bluetooth, so that its functions can be accessed even when "worn" in one's pocket. Furthermore, it can also serve as a communication hub, providing Internet access to other wearable computing devices. In this sense, the smartphone is currently the most important and ubiquitous wearable computing device available, and at the current time is likely to serve as the central component—for both computing resources and internet access—for other wearable computing devices.

One of the key characteristics of smartphones is that they contain many sensors. Since users often carry their phones on their bodies, this provides the potential for continuous sensing. As smartphones became more technologically advanced, more and more sensors were added. Virtually all smartphones now contain an accelerometer, gyroscope, location sensor (e.g., GPS), light sensor, and magnetometer; some smartphone models also include a barometer, heart rate sensor, and even a dedicated pedometer sensor. The accelerometer is central to many health and fitness applications and allows the smartphone to act as a fitness tracker and step counter.

2.3.3 Fitbit (2009)

The first Fitbit activity tracker was released in 2009, and it accelerated the use of wearables in the health and fitness market. The most basic function of a Fitbit is its pedometer function, and its ability to calculate the distance walked and estimate total calories burned. This basic function is incorporated into the many dozens of Fitbit models. Over time, new models were introduced, which featured sleeker designs and additional functions. The majority of Fitbit products is worn on the wrist or are clipped to one's clothing. The more recent models can connect to your smartphone or computer to upload and analyze data, and there are a variety of social networking features to help motivate the user to become more active. More advanced models can be used to track the duration and quality of your sleep, and you can also use the Fitbit app to log your meals and track your weight. While a smartphone stored in one's pocket can provide many of the same functions via the phone's accelerometer [14], the ease of use and low cost of the activity trackers have proven quite attractive to consumers. Fitbit has been quite successful and experienced rapid growth between 2010 and 2015, when its revenue increased from $5 Million to $1.8 Billion. However, it experienced significant problems in 2016 due to manufacturing problems and unexciting product upgrades, and now is facing competition for Apple and others as consumers gain interest in more sophisticated wearables, like smartwatches, which can provide the same capabilities, as well as additional capabilities.

2.3.4 Smartwatches (2013)

The next major commercial advancement in wearable computing was the introduction of the modern smartwatch. Many earlier digital watches could claim be to "smart" in one sense or the other, but the modern smartwatch did not truly arrive until the introduction of the Pebble in July 2013. The Pebble was funded by an enormously successful Kickstarter campaign, which raised $10.3 Million. By 2014 Pebble sold its one-millionth watch, but it shut down its operations by 2016 due to the flood of more technologically advanced watches entering the market. Some of the notable smartwatches that superseded the Pebble include the Samsung Galaxy Gear (2013), the Motorola Moto 360 (2014), the LG G-Watch (2014), and the Apple Watch (2015). These watches generally could only provide full functionality when paired with a smartwatch, which provided long-range data communication access, including access to the Internet.

Smartwatches have many useful features and can support a variety of applications. One of the key functions of a smartwatch is that it provides improved accessibility to one's smartphone, by eliminating the delay associated with removing a smartphone from one's pocket or purse. By using the smartwatches wireless connection to one's smartphone, one can access common smartphone applications within a few seconds, via simple graphical menus provided by the smartwatch screen, or via voice control. With this capability one can control music play, get travel directions, or send a text message. By providing this improved interface a smartwatch removes many of the barriers that prevented the smartphone from being a true wearable computing device.

Smartwatches also can provide some functions beyond what is provided by smartphones, due to their placement on the body. While smartwatches do not yet contain all of the sensors present on a smartphone, they typically provide an accelerometer and gyroscope, and often include a heart rate monitor. Thus smartwatches can provide pedometer functionality independent of a smartphone and can also recognize more sophisticated activities, including hand-based activities [15]. Smartwatches are especially recognized for their health and fitness applications.

2.3.5 Google Glass (2014)

Google Glass is an optical head-mounted display designed to look like a pair of eyeglasses, but with both of the lenses removed. The user can view the projected image by looking up, as the viewable projection is not directly in front of the eye, so it is less intrusive and does not impair human-to-human interaction. This is perhaps the most ambitious commercial wearable computing product that has ever been released. A prototype of Google Glass started selling in the United States on April 15, 2013 for $1,500, and became available to the general public on May 15, 2014. The product was pulled from the market on January 15, 2015, due to many criticisms about the design. It will not be rereleased until it has been significantly improved, but right now it appears that any new release will first be aimed at industrial users. A number of industrial applications are currently under development.

Google Glass has a number of important features. First, like previous head-mounted displays, it has a camera capable of taking first-person pictures and video, although the limited battery life precludes continuous video recording. It also contains a touchpad, which is located on one outside edge of the frame. The device can also be controlled via voice commands. Responses from the product can be relayed to the user visually or can be relayed via audio using bone conduction through a transducer that sits beside the ear; this setup means that others who happen to be nearby will not be able to hear the audio responses.

Google Glass has the potential to support an enormous number of applications. Navigation is one natural application, and an early Google commercial shows how such an application can help one navigate a city, and how relevant information (e.g., subway information) can be automatically displayed in a context-sensitive way. Google Glass can also be used to provide instructions while assembling a new piece of furniture or following a new recipe, or set a reminder or calendar entry with just a voice command. It can also be used to send texts or email with voice commands, or even make a video call. A smartphone can do many of these functions but, as mentioned earlier, the time it takes to physically access the smartphone is a stumbling block for many tasks—and holding the phone interferes with performing other tasks. There is also an expectation that industry-specific applications will be developed and that Google Glass will be used extensively in industrial settings. For example, an employee in a warehouse could receive a notification of which product to retrieve, and then Google Glass could navigate the employee to the proper location.

Google Glass raised many privacy concerns, which were well publicized and disseminated by the mass media. These concerns are important since they are a barrier to adoption for both Google Glass and potentially other similar future wearables. One concern involved the ability to take pictures of others without their permission and knowledge. This led to some bars and other establishments banning Google Glass [16], and to suggestions that the product not be worn inside of public bathrooms. There was also great concern that facial recognition applications could automatically identify strangers and then display information about them from the Internet. Some experts feel that ultimately people will come to accept the technology and ignore the privacy concerns, just as has happened with other new technologies—but others are not so sure. Because Google Glass sales were quite limited prior to the suspension of sales, the ultimate impact of such concerns is still unknown.

2.3.6 Microsoft Hololens (Estimated 2019)

Hololens is a pair of mixed-reality glasses, developed by Microsoft, which projects 3D objects (“holograms”) into the user’s environment. The current product is not ready for general usage and is intended for developers; there is no product release date but various estimates place a commercial release for 2019. The Hololens is quite different from Google Glass and serves a very different purpose—although there is some overlap. First, the Hololens is much larger than Google Glass and, although tetherless, is primarily intended to be used in a fixed environment. That is because while Google Glass is a perfect example of augmented reality, where the emphasis is on overlaying information on top of the real world, the Hololens is for *mixed* reality, where the emphasis is on the computer generated 3D object(s). The Hololens is not primarily considered a virtual reality system because the 3D image is only viewable in a relatively small section in the center of one's vision—it is designed to allow the user to work in the real world. A sample Hololens application would allow a student to interact with a 3D image of a human heart, show how to trouble-shoot a printer jam, or allow a user to take a tour of a famous site. The Hololens includes 3D sound speakers and can interact via spoken commands or gestures.

2.4 Lessons Learned from the History of Wearable Computing

The history of wearable computing provides many lessons, which can also tell us something about how wearables will continue to evolve in the future. The key lessons are enumerated below, and then discussed and justified in subsequent subsections. Lesson 5 is the only lesson that cannot be fully justified at the present time.

- Lesson 1 Wearable computing devices should fulfill genuine needs.
- Lesson 2 Wearable computing devices are most successful when they satisfy multiple needs.
- Lesson 3 Wearable computing devices should be very quick to access and use—and this should be supported by the device's user interface and placement on the body.
- Lesson 4 Wearable computing devices should be "always on" and available.
- Lesson 5 Wearable computing devices should preserve the privacy of the user and bystanders.

2.4.1 Wearable Computing Devices Should Address Genuine Needs

This is perhaps the most basic lesson and does not require much analysis: wearable computing devices should satisfy real needs of the user. Although this lesson seems trivial, it is not given current consumer perception of wearables: many consumers find wearables to be useless—as well as unattractive and expensive. Most successful wearable devices have a corresponding non-wearable analog, because the need existed prior to the technological advances that enabled a wearable version of the device. As was discussed earlier in this section, the need to track time led to large timepieces (clocks), which were subsequently replaced by their non-digital miniaturized counterparts (wristwatches), which were subsequently replaced by digital watches and then smartwatches. The need to perform calculations led to the abacus, which led to the smaller abacus ring, which then led to the calculator watch—and subsequently to the smartwatch. The need to play recorded music led to the record player, which led to the smaller Sony Walkman (an analog version followed shortly be a digital version), which led to the iPod, and then the iPhone. One way to predict future wearables is then to identify devices that satisfy a need, but cannot be turned into wearables due to technological constraints. Video-based lifelogging is one example of an application that may not yet be feasible, but which may become possible in a few years (i.e., a future version of Google Glass or a competing product may be able to take continuous videos). Similarly, wearable technology that provides high quality monitoring of multiple medical conditions, using sensors deployed over the body (perhaps embedded in clothing), may also become possible over the next decade.

2.4.2 Wearable Computing Devices Are Most Successful When They Satisfy Multiple Needs

Wearable computing devices are often initially developed to satisfy one need—or a narrow range of needs—but history shows us that over time they are often merged into a single device. This occurs even if the merged device does not perform quite as well at satisfying each individual need. Apple Inc. provides perhaps the best example of how a successful wearable device is supplanted by a more powerful, and general, device. For many years Apple produced an incredibly successful series of digital music players, which included the iPod classic, iPod Mini, iPod Nano, and iPod Touch. For a period of several years these music players generated between $5B and $10B in revenue for Apple, with peak worldwide sales of 54 million devices in 2008 and 2009. However, these sales were eventually cannibalized by the introduction of the iPhone and Android smartphones. The smartphones virtually eliminated the market for standalone digital music players. Smartphones also largely replaced other single-purpose wearable computing devices, such as personal digital assistants (PDAs) and handheld GPS trackers; it also seriously impacted the market for portable game players and digital cameras (consumers still purchase digital cameras, but mainly high quality models with powerful optical zooms). Smartwatches, which support multiple applications, have begun to impact the sale of wearable fitness trackers like Fitbit. Based on past history, the future of fitness trackers is not very bright if smartwatches are able to effectively satisfy several user needs—and thus become ubiquitous. But at this moment in time, smartwatches have not yet achieved this status.

Consumers clearly want the convenience of wearable devices that can handle multiple tasks. The merging of these devices yields many benefits. Cost savings is one benefit. The reduction in the number of devices that need frequent charging is another benefit. Each device also places some burden on the user to carry it around, and thus the merging of devices can reduce this burden. The need to merge these devices may be reduced in the future if they can connect wirelessly to share common services (many tasks require the ability to send and receive data). Thus, in the future we may see a reversal of this trend if power requirements drop sufficiently, so that some wearables can be very small and yet communicate with more powerful wearables (e.g., smartphone) via Bluetooth or a body network. But devices will only separate if there is some concrete benefit (e.g., it achieves a more convenient body location).

2.4.3 Wearable Computing Devices Should Be Very Quick to Access and Use—And This Should Be Supported by the Device's User Interface and Placement on the Body

Wearable computing devices should be unobtrusive. That requires a user interface that permits for quick input, while minimizing any loss of focus by the user, and convenient location on the body. The progression seen in many wearables demonstrates this principle. Counting and calculation devices progressed from the abacus ring, which was hard to use since it required a pin to move small beads, to a digital calculator watch with small buttons, to a smartwatch that employs a graphical interface and can also operate via voice recognition. The personal digital assistant also provides a lesson. The PDA relied on a stylus, and partially compensated for this by allowing users to write in cursive, which was optionally converted into printed characters via handwriting recognition. While this interface appeared to be effective and quite advanced at the time, it was cumbersome in that it required the user to first access the stylus—which was both time-consuming and distracting. This interface was subsequently replaced by small physical keyboards, and then, as the PDA functions were subsumed by smartphones, by virtual keyboards on a touchscreen. The voice recognition capabilities of smartphones also represent an improvement in user interface.

Proper location is also important for wearables. Ideally a wearable should be located so that it is easy to access and use. Location was the motivation for the development of a wristwatch and then a smartwatch, as it was important to be able to tell time without going to one's pocket (for a pocketwatch). The smartphone, which is often located in a pocket or purse, is poorly placed for many of its intended purposes, but this is deemed acceptable only because the poor location is counterbalanced by the benefit of combining many devices into a single device. Perhaps the best reason to own a smartwatch right now is not due to the new functions it can provide (e.g., heart rate monitoring), but for its ability to make many smartphone functions available from the user's wrist; thus many smartwatches can be considered extensions of the smartphone. Even Google Glass can be viewed as addressing the location issue, since much of the information that we want is best conveyed visually, and Google Glass places that visual information right in front of our eye. Google Glass can even provide audio information to the user via bone conduction, which has the added benefit that bystanders will not be able to hear the information. While Google Glass did not turn out to be a successful consumer product, it was certainly not due to the convenient location of the wearable.

Based on historical patterns, we can conclude that the user interfaces of wearable computing devices will continue to improve and body placement may also improve as technology makes this more feasible. Voice recognition may be used in more wearable computing devices, even if that means some of them may need to connect to the smartphone to provide this capability. Applications will migrate to more natural body locations as more wearable computing devices are able to connect to the smartphone for computational and data communication resources. Things like email, which are now typically displayed on the smartphone, will more often be accessed on the wrist via a smartwatch, and then made directly accessible via new commercial wearable devices like Google Glass. Health and wellness applications, currently one of the most popular applications areas for wearable computing, will improve as wireless sensors move to more informative body locations. This will eventually occur as wearable sensors are routinely embedded in our clothing and accessories (e.g., belt, shoes).

2.4.4 Wearable Computing Devices Should Be "Always on" and Available

Wearable computing devices should be on continuously and should always be available. Most of the popular wearable computing devices, such as smartphones and smartwatches, essentially meet these criteria since they can operate for an entire working day. There was, and still is, some resistance to smartwatches, because people are not used to charging a watch every evening, and found the task burdensome. But people are adapting to this need, and some smartwatch manufacturers have responded by designing smartwatches that can operate several days on a single charge.

Continuous operation is still an issue for some wearable computing applications. Lifelogging, which entails logging everything that goes on around you, requires continuous recording capabilities. Devices like the GoPro are not capable of lifelogging, so simpler devices were developed, but these have not yet proven to be popular, and often have significant limitations (e.g., video is deleted within a few minutes if not saved). Lifelogging is not supported by Google Glass simply because the device will run out of power within a few hours of continuous video recording. Even some fitness applications, when run continuously on a smartphone, may drain the phone battery prior to the end of the day. As technology advances, lifelogging, and other power-hungry applications, should become capable of continuous operation. It will also allow smaller devices (with smaller batteries) to operate continuously, and this should result in wearable computing devices being incorporated into clothing and accessories.

2.4.5 Wearable Computing Devices Should Support Privacy

The final lesson is that privacy is a concern and may impact the adoption of wearable computing devices. Wearables can yield more concerns about privacy than traditional computing equipment because they are always with the user and can track highly personal information, such as the user's location. Because wearable computing devices move with the user and hence come in proximity to many other people, there is one privacy concern unique to wearables: they threaten the privacy of non-users. There were initially some privacy issues with cellphones and smartphones for this very reason, due to their camera and video-recording capabilities. These concerns focused on their presence in bathrooms and locker rooms. While these concerns still exist, they did not prevent the adoption of these devices, and the issue is largely addressed by the social convention that these devices not be used in environments where people may be unclothed. There are also privacy issues concerning the amount of information that wearables collect about the users (location data, health data, etc.) and potential misuse of this information, but thus far this concern has had not substantial impact on the adoption of these devices.

The privacy issue came to the forefront with the initial introduction of Google Glass. There were two specific privacy concerns that received a great deal of media attention. The first was the ability to surreptitiously record others. Given the placement of Google Glass, this is much bigger issue than for a smartphone. The second issue is far more interesting, since it has to do with the ability the seamlessly access, merge, and display information. Google Glass is capable of supporting face recognition, so it would be possible for the device to identify people in a crowd, collect publically available information about them from the Internet (including from social media), and then display that information to the user. This can all take place without anyone other than the user knowing that it occurred. Even though the devices were never deployed widely, there was tremendous resistance, with some bar owners saying they would not permit the devices into their establishments. Given that devices similar to Google Glass can address many user needs, these privacy issues will likely rise again in the future. If Google Glass had remained on the market as a consumer product, we would have a much better idea if the privacy issues would have been prohibitive, or if people would eventually become accustomed to the devices and inured to the privacy concerns. Since this question has not been resolved, it is difficult to quantify the importance of privacy and its impact on the adoption of new wearable technology. The best we can say is that wearables should address the privacy issue as completely as possible, especially if it has little impact on the functioning of the device.

3 Applications of Wearable Computing

Wearable computing can support a wide variety of applications, as demonstrated by the historical overview provided earlier in this chapter. Nonetheless, past and current technology has focused on a few key industries, and the taxonomy presented in Fig. 4 highlights these industries. Some industries, such as Medicine and the Military, are key users of wearable computing technology because of the tremendous costs associated with performing at anything but peak efficiency. Education, which includes training, has a great deal to gain as wearable computing can provide a more personalized and immersive experience than traditional methods. Wearable computing applications are just beginning to be used in many businesses, but this market should explode in the coming years as specific applications are developed

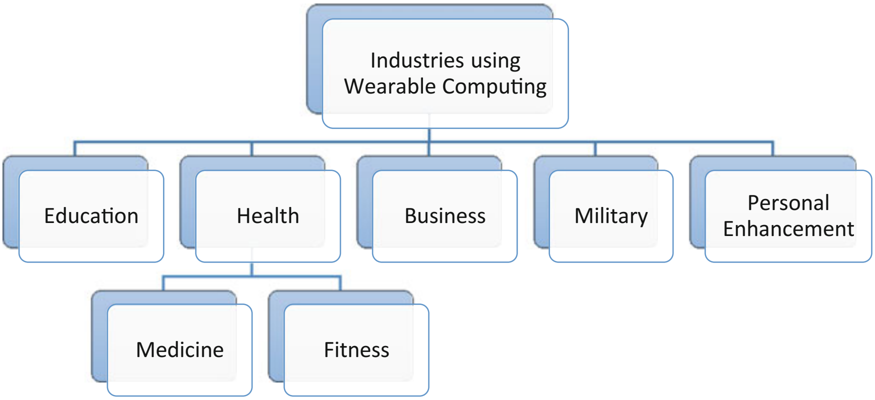

Fig. 4 Major industries employing wearable computing

that enable employees to operate at greater efficiency. The last main entry, "Personal Enhancement," is not what is generally thought of as a major industry, but has been the focus of wearable computing since its inception. This category includes personal assistants and information assistants, and includes any technology that *generally* extends the capabilities of a person that is not tied to a particular industry.

The taxonomy presented in Fig. 4 is not that different than the one provided in a 2014 article on wearable computing applications [17]. That article divided the applications into five categories: health care and medical; fitness and wellness; infotainment; military, and industrial. Most of the applications covered under infotainment are subsumed by the "Education" or "Personal Enhancement" categories.

The industry view is just one way to organize applications of wearable computing. One could also organize them based on the type of capability, or specific technology, that the application provides (the personal enhancement "industry" could fit under this alternative taxonomy scheme). Although the applications described in the remainder of this section are grouped based on industry, it is useful to understand this alternative taxonomy. It is not possible to provide an exhaustive list of the types of capabilities and technologies that wearable computing can provide, but the following list covers the most popular wearable computing capabilities, and also covers all of the applications described in this chapter

- Augmented Reality
- Context Awareness
- Communication and Media
- Sensors and Sensor Mining
- Crowdsourcing
- Social Networking.

Augmented reality provides the user with a view of the real world, but integrates into this view additional information, such as 2D or 3D images, video, text, or audio (this can be contrasted with virtual reality, where the user is placed entirely into a virtual environment). Many of the early heads-up display units provided some form of augmented reality, but were quite cumbersome to wear and often did not even allow a direct view of the world. More recent systems allow a direct view of the world, are much smaller and lighter, and tend to be worn like eyeglasses—like Google Glass. The goal of augmented reality systems it to assist people as they perform real-world tasks [18], which is an example of intelligence amplification [19]. Augmented reality applications span virtually all industries, and specific examples of these applications are described throughout the rest of this section.

Context-awareness is a general capability that provides an understanding of the context in which the wearable computing device is operating. The context awareness can be utilized by various applications so that they behave more intelligently and are responsive to the environment. Context awareness can be used so a smartphone does not put a call through when the user performing an activity that would preclude a conversation, and can even be used by the computing devices themselves to optimize their resource utilization (i.e., by turning off power-consuming capabilities that the user would not use in the current context). Military applications will generally want to be context aware so that the user can respond appropriately based on what is going on around him.

Many wearables are designed to support communication in all of its many forms, including: phone, email, and text. Communication also includes the capability to access the Internet and to retrieve and play media files, such as music and video. Smartphones and smartwatches are the wearables that currently are most directly tied to communication. A much broader range of wearables utilize communication to share the data that they collect.

Wearable computing devices typically contain many sensors, and those sensors are central to many applications. For example, fitness devices use an accelerometer sensor to count steps, medical wearables use sensors to record patient vital signs, and wearables that support navigation use the GPS sensor to establish location. In many cases the ability to collect sensor data is paired with a data analysis tool, or predictive model, which allows the application to make inferences from the data. Crowdsourcing is a related type of capability, since it normally involves sensor data, but in this case the data is collected from a large pool of subjects. An example application is a navigation system that utilizes crowdsourced traffic data to avoid congestion and minimize total travel time. In such cases the traffic information is determined by analyzing the GPS traces of a large number of automobile drivers. Social networking capabilities also use data, but in this case for social reasons. For example, an application may link you to other people that also jog in your neighborhood. The remainder of this section describes applications of wearable computing to the five industries identified in Fig. 4.

3.1 Education

Education and training is an industry that can benefit from wearable computing and, in particular, from augmented reality. One benefit of augmented reality in an educational setting is that text, graphics, and even video, can be superimposed on the student's or trainee's environment. In one example, a publisher in Tokyo released textbooks that revealed augmented educational content when pages of the book were viewed through a smartphone running an augmented reality app [20]. In another example, a product called AR Circuits (arcircuits.com) allows you to experiment with electrical circuits without purchasing any real hardware. Instead, you print out circuit cards on paper, connect them on a flat surface, and then when you bring them into view of smartphone camera running a special app, the circuits come alive on the smartphone screen as working electrical components. There are currently hundreds of education-related augmented reality apps available that allow students to interactively explore the solar system, the human body, historical sites, and other environments in 3D, with educational information superimposed on the structures. The use of augmented reality in education is expected to grow rapidly in the coming decades.

Medical education, especially anatomy, can especially benefit from augmented reality given the high cost of cadavers. One augmented reality system geared toward undergraduate anatomy education integrates a public CAT scan data set with an actual image of the user, so that that user can effectively "see" inside of his body and navigate through the internal structures of the body with hand gestures [21]. The University of Nebraska is betting on this technology as it is opening a $119 million virtual and augmented reality facility to educate the next generation of healthcare workers.

3.2 Health

The healthcare industry has been one of the early adopters of wearable computing technology. It was adopted in the medical domain due to the need for high performance and the cost of errors, and was adopted in the fitness domain because of the relative ease of developing simple and low-cost fitness tracking applications.

3.2.1 Medicine

Wearable computing provides many benefits in medicine, especially since it permits cost-effective continuous monitoring of vital signs and other data when the patient is not in a hospital or doctor's office. This data can then be used to make health decisions. This area has attracted sufficient attention to have its own term: mobile health, or mHealth [22]. While mHealth is not focused solely on wearables, wearables play a central role in the discipline. Many wearable devices are being developed for mHealth, although as of yet these wearables have not had the mainstream success of the activity trackers used for fitness monitoring. The new devices that are being developed exploit the advances in sensing technology, which permit low-power sensors to monitor the functioning of one's body. These sensors are usually placed on the body, but may be inserted into the body. Several representative medical wearables are described in this section.

The VitalPatch® biosensor, produced by VitalConnect (http://vitalconnect.com), measures heart rate, respiratory rate, skin temperature, and single-lead ECGs, and transmits the data in real time to healthcare providers who can intervene if necessary. It can even detect a fall. The data is analyzed using predictive analytics that can identify problems before they become serious. Data can be streamed and stored in the cloud, and from there be shared with both the patient and doctor. The biosensor-based device has a battery life of four days. The MiniMed® 530G System is a wearable device, comprised of a sensor and insulin pump, that monitors glucose levels and automatically dispenses insulin in way that mirrors that of an actual pancreas [23]. Status information can be relayed to your smartphone via a specialized smartphone app. The Zio cardiac monitor is a patch from iRhythm (iRhythm.com) that can comfortably be worn by a patient for two weeks at a time, and can be used to monitor for cardiac abnormalities. A wearable called Quell (www.quellrelief.com) uses an accelerometer to gauge a user's activity level and adjust its stimulation intensity to alleviate pain. The device uses Bluetooth to connect to a smartphone app, where a user can control the device's features and track therapy and sleep results. Finally, WristOx2 by Nonin Medical (www.nonin.com) is a wristwatch-type device for people with asthma who are at risk for congestive heart failure and chronic obstructive pulmonary disease (COPD). This device monitors a user's heart rate and blood oxygen levels. These devices all are similar in that they rely on accurate biosensors and provide for automatic analysis of the data, although the analysis may occur on the person (i.e., on the device or connected smartphone) or at a remote location that receives the data.

Augmented reality also has applications to medicine, beyond the medical education application mentioned earlier. One study demonstrated that Google Glass has many potential benefits for pediatric surgeons, such as making hands-free photo and video recordings [24]. There is also a medical device that has been in use since 2005 that employs augmented reality to identify a vein by using near-infrared light and then projects a green light onto the skin's surface in order to facilitate intravenous injections [25, 26]. Another medical application comes from a company called Brain Power, which develops Google Glass applications and hardware add-ons, to help improve the life of people with autism. The app will help children with autism to focus on the faces of others by presenting exercises as games and providing points for proper behavior; it will also train its subject to identify emotions based on facial expressions [27]. Another company called VA-ST makes wearable "Smart Specs" for partially sighted or legally blind people, which can assist them in navigating the world [28]. An augmented reality-based surgery system has even been used for advanced laparoscopic liver surgery [29].

3.2.2 Fitness

Wearables have been used for several decades to help determine what activities a person is performing, which can serve as the basis for fitness tracking. The initial motivation for determining a user's activity was to simply understand more about the user and their daily activities, or to allow wearables to be "smart" by acting in a context-sensitive manner. Much of this work was research-based and did not necessarily get incorporated into commercial products. Later work focused mainly on fitness activities, such as walking, and focused on quantifying a user's physical activity. This work led to the many commercial fitness tracking devices. The commercial activity trackers that have been developed tend to focus exclusively on basic fitness activities like walking and jogging, while the research-based systems often also include activities of daily living, such as brushing ones teeth, sitting, reading, typing, etc. A relatively exhaustive list of applications for activity tracking technology is provided by Lockhart et al. [30].

Early research into activity tracking utilized custom sensors that were strapped to various parts of the human body [31]. Over time much of the activity recognition research migrated to commercially available mobile devices, which contain accelerometers. One of the earliest studies to use commercial smartphones for activity recognition showed that a smartphone could identify walking, jogging, stair climbing, sitting, and standing activities [14]. This was about the same time that the original Fitbit activity tracker was released. Smartphones are not ideal for activity recognition because of their inconsistent placement, but smartwatches do not suffer from this problem, and hence they are now viable alternatives to dedicated fitness trackers.

Commercial activity tracking wearables that focus exclusively on fitness tracking and related health applications have been a commercial success, led by sales of Fitbit, which sold over 22 Million fitness trackers in 2016. Fitbit devices act as a pedometer, calculate calories burned, measure progress toward goals, allow users to share their fitness results with others, and may even track sleep. Fitbit now sells watch-based fitness trackers, and virtually all brands of smartwatches now include fitness tracking capabilities, most notably the Apple Watch. The Apple watch will track steps taken and calories burned, but will also tell you if you get up to move regularly, and provide a graph that tells you when throughout the day you were active. The fitness market has so dominated the wearables market that they two terms are sometimes used interchangeably.

3.3 Business and Manufacturing

Business and manufacturing have been using wearable computing for a while, although it has not caught on as quickly as in the health and military communities. Wearable computing can have an especially pronounced benefit in manufacturing and other business activities where the worker needs both hands, but also needs to access complex information. Boeing was one of the first businesses to recognize this. In the 1990s, Boeing needed hundreds of workers to assemble wiring harnesses for aircraft. This task required both hands, but also reference to voluminous paper instructions. Boeing deployed head-mounted displays, which removed the need for printed instructions, and this led to improvements in worker productivity.

Google Glass, which is currently discontinued as a consumer device, is in active use for manufacturing. AGCO, a company that makes farm equipment, uses Google Glass to assist in the process of assembling tractor engines. A worker can scan the serial number of a part, and relevant manuals, photos, and videos will appear. Voice commands can also be used to bring up more information. Google Glass is a much better mechanism for obtaining information than the tablet computers that were used previously—and often dropped and broken. Google Glass applications are also being used to efficiently guide warehouse workers to the locations of products that need to be retrieved. In one study using a Dutch logistics company, within its first week of use Google Glass led to a 15% increase in stock picking speed and a 12% decrease in worker errors [32]. More conventional uses of wearable computing can also assist warehouse and retail productivity: a host of companies sell ring barcode scanners that permit workers to scan items and thus free up the worker's hands.

Wearable computing can also improve worker safety. The Reflex wearable from Kinetic (http://wearkinetic.com) automatically detects high-risk postures and notifies the worker of the unsafe position. Over time the device teaches the workers to have good biomechanics, and significantly reduces the number of unsafe postures, which leads to reductions in worker injury. Meanwhile, Life by Smartcap (http://smartcaptech.com) detects when a subject is fatigued and in danger of falling asleep, via EEG readings that are automatically captured by the device. This information is transmitted in real time to a central monitoring station, which can take action. It is employed by industries such as mining and construction, where a lack of alertness can cause serious injury or death.

3.4 Military

The military is often an early user of advanced technology and this holds true for wearable computing. Wearable computing can be particularly beneficial by allowing soldiers to focus on what is happening on the battlefield. As an example, if a soldier needs to "look down" to access certain information, like a map, this can put him at risk in hostile situations. Applied Research Associates ARC4 augmented reality system addresses this issue by overlaying tactical information onto a soldier's field of vision [33]. The system can also display the location of teammates, information about geographical features and buildings (including their distance), and keep the soldier on a predetermined route by displaying a waypoint at a short distance. The soldier can even tag points of interest to share with their teammates.

Wearables also have an important role in the military for monitoring the health of soldiers. There is currently a great deal of concern for traumatic brain injury (TMI). The Defense Advanced Research Projects Agency (DARPA) has developed a wearable blast gauge that measures the impact from an explosion on the solider and automatically notifies medics to respond. The data provides useful information about the severity of the blast and can ensure appropriate treatment. Another issue concerns soldier being pushed beyond their limits, as they are subjected to very high or low temperatures in situations where they must exert themselves. Wearable, chest-based sensors can now determine when soldiers are reaching their physical limits, so they can rest or don protective clothing.

One of the most exciting wearable for the military, which is gaining a great deal of attention lately, is the artificial exoskeleton. The exoskeleton system, known as HULC (Human Universal Load Carrier), allows soldiers to move with less effort, so that they can walk and run for long periods of time without getting tired—even while carrying heavy loads. The units use artificial intelligence to ensure that they are properly amplifying the soldier's intended movements. While these devices can be quite bulky, they meet the definition of wearables provided earlier in the chapter, since they allow the user to operate more efficiently and are used in a natural, unobtrusive, manner.

3.5 Personal Enhancement

A vast number of wearable computing devices aim to generally enhance the effectiveness of the user, without targeting a specific industry. Many examples that fall into this category were described in the historical overview provided earlier in this chapter, and hence will not be repeated here. Perhaps the best examples include the head-mounted displays [8] and Starner's Remembrance Agent [9, 10], which can serve as personal assistants. The personal digital assistants that arrived in 1993 were not nearly as ambitious, but nonetheless supported many of the function of a personal assistant. Smartphones and smartwatches also provide many of the capabilities of a personal assistant, but also provide other capabilities that expand the user's capabilities—from the ability to listen to music to the ability to communicate via email or text. Google Glass, which was described in detail earlier, is capable of providing some of the most advanced applications in this area. In particular, the augmented reality capabilities built into Google Glass extend the capabilities of the human user by seamlessly providing context-appropriate information (e.g., by providing subway information when the user looks at a subway entrance).

4 Case Studies: Activity Recognition and Biometrics

This section describes two research studies related to wearable computing: one involving activity recognition [15] and the other involving biometric identification [34]. These studies only require a commercially available smartphone, which is worn in the pants pocket, and a commercially available smartwatch, which is worn on the dominant wrist. Both the smartphone and smartwatch contain an accelerometer and gyroscope, and the data from both of these sensors is captured while the user performs a variety of activities. This data is then used to build and evaluate a model to identify the physical activity the user is performing (activity recognition), and to build and evaluate a model to identify or authenticate the user's identity (biometrics). The general approach for both case studies is very similar: training data is captured from the devices and then predictive models are generated using common machine learning classification algorithms.

These two case studies demonstrate how future wearable computing technology can progress to better satisfy the needs of users. The case study on activity recognition shows that today's activity tracking applications are quite primitive in what they can track, and that the technology is capable of tracking a much wider set of activities. This example shows the potential for existing wearable computing applications to become smarter through the use of machine learning and data mining methods. Wearable computing devices tend to capture a tremendous amount of data and it does not yet appear that this data is being fully leveraged. The case study on biometrics also shows how data mining and machine learning methods can better exploit data, but it also demonstrates the potential of wearable computing applications to reduce the burden on its users by automating tasks and making them completely unobtrusive. Currently, computer security is accomplished via the use of passwords, which must be manually entered, or via biometric technology such as fingerprint or face recognition. All of these take effort on the part of the user, whereas the proposed application employs the user's motion data to identify them, and hence can be accomplished without any special effort by the user (this assumes the work that is described is extended to include continuous biometrics).

4.1 Data Collection

The activity recognition and biometric models are generated using supervised learning methods and require labeled motion data. The data is also required to evaluate the models. Data was collected from 51 test subjects, each of whom performed 18 routine activities for 3 minutes each, with an Android smartphone in their pocket and an Android-Wear smartwatch on their dominant wrist. A custom-developed Android application sampled the tri-axial accelerometer and gyroscope sensors on the smartphone and smartwatch at 20 Hz. The raw time-series sensor data, for both the accelerometer and gyroscope, was recorded in the following format:

$$< \text{timestamp}, x, y, z >$$

The timestamp is measured in nanoseconds and the x, y, z values correspond to the three spatial axes. The x, y, and z values are measured in m/s^2 for the accelerometer and in rad/s (radians per second) for the gyroscope. The 18 activities included in the study are listed below, organized logically into three categories.

General Activities (non hand-oriented)

- Walking
- Jogging
- Stairs (ascending and descending)
- Sitting
- Standing
- Kicking a Soccer Ball (two people)

General Activities (hand-oriented)

- Dribbling a Basketball
- Catch with a Tennis Ball (two people, underhand)
- Typing
- Writing
- Clapping
- Brushing Teeth
- Folding Clothes

Eating Activities (hand-oriented)

- Eating Pasta
- Eating Soup
- Eating a Sandwich
- Eating Chips
- Drinking from a Cup.

4.2 Data Transformation

Most classification algorithms cannot directly handle time-series data, but rather expect an unordered set of examples. So that these classification algorithms can be used, the time-series data is transformed into examples via a sliding window approach. A 10-s window is moved over the time-series data, without overlap, and the low-level sensor data in each 10-s segment is represented as a single example via the formation of 43 descriptive, high-level features. The features, which are listed below, are used for both the accelerometer and gyroscope sensor data, and are used for both the activity recognition and biometrics tasks. The value in the square brackets indicates the number of features generated. When three features are generated they correspond to the three spatial axes.

- Average [3]: Average sensor value (each axis)
- Standard Deviation [3]: Standard deviation (each axis)
- Average Absolute Difference [3]: Average absolute difference between the 200 values and the mean of these values (each axis)
- Time Between Peaks [3]: Time between peaks in the sinusoidal waves formed by the data as determined by a simple algorithm (each axis)

- Average Resultant Acceleration [1]: For each of the sensor samples in the window, take the square root of the sum of the square of the x, y, z axis values, and then average them.
- Binned Distribution [30]: The range of values is determined (maximum–minimum), 10 equal-sized bins are formed, and the fraction of the 200 values within each bin is recorded (each axis)

After each example is formed, a label is appended that indicates the activity the participant was performing, and a numerical ID is also added that uniquely identifies the subject.

4.3 Activity Recognition Experiments and Results

The activity recognition task is to identify an activity based on 10 s of sensor data. A classification model is built from a subset of the collected data, the training set, and is subsequently evaluated on a separate subset of the collected data, the test set. Two types of models are induced and evaluated: personal models and impersonal models. Personal models are built for each user, using training data *only* from that user. This requires the user to execute a training phase, which can be inconvenient. Impersonal models, also known as universal models, are built using training data from a panel of *other* users, and requires only a single (universal) model to be generated. The test data used to evaluate the impersonal models must *not* include data from any user also present in the training set.

In order to build and evaluate the personal models, data from each of the 51 subjects is separated, and then the data for each subject is partitioned into training and test sets using 10-fold cross validation. The results for personal models are based on the entire population of 51 users, and represent the performance averaged over the 51 users. The impersonal models are generated and evaluated very differently. In this case, the data from one user is separated and placed into the test set, while the data for the remaining 50 users is placed into the training set. A model is then built using the data from the panel of 50 users and is evaluated on the one “test” user; this is repeated 51 times so that all subjects are evaluated once. Based on this procedure, the impersonal models are generated from *much* more training data than the personal models—which is what we expect in realistic applications given the cost of generating personal training data.

Table 1 shows the activity recognition results for the personal models generated using the Random Forest classification algorithm. The accuracy of each of the eighteen activities is shown, for nine different sensor configurations. The first four configurations are for each of the individual sensors: the watch accelerometer, watch gyroscope, phone accelerometer, and phone gyroscope. Then multiple sensors are fused in an attempt to improve performance. These fused sensor configurations are: Watch (watch accelerometer and gyroscope), Phone (phone accelerometer and gyroscope), Accels (phone and watch accelerometers), Gyros (phone and watch gyroscopes), and All (phone and watch accelerometers and phone and watch gyroscopes).

The results show that using all four sensors yields the best overall performance, although using the phone and watch accelerometers yields equivalent performance. Using these fused sensors does better than using any single sensor. Overall performance is quite good since when using all four sensors the average activity recognition performance, for the personal models, is 94.3%.

The results for impersonal models are presented in Table 2. The same nine sensor configurations are evaluated as with the personal models. As before, the best performance is achieved when using all four sensors, which yields an overall accuracy of 66.5%. The results for the impersonal models are much worse than for the personal models, even though the model is trained using much more data. While the overall activity recognition performance is quite low, certain activities, such as jogging, can still be recognized with relatively high accuracy.

The smartwatch sensors are particularly helpful for hand-based activities. To see this, consider the second grouping of activities, for both the personal and impersonal models, which begin with "Dribbling." For these seven activities, if we compare the accuracy results for the watch sensors against the results for the phone sensors, we see that in every case the watch sensors yield higher accuracy.

Based on these results, we can conclude that one can achieve highly accurate activity recognition results using only a smartphone and smartwatch, if personal models are built. The superiority of the personal models means that users move in different ways to perform the various activities, and that by exploiting these differences one can do much better at activity recognition. Personal models require the user to supply labeled training data, which entails some effort on their part, but this can be automated into a "self-training" phase, where the smartphone sequences the user through a set of activities. The results also show that the best results are achieved when the smartphone and smartwatch are both used. These results indicate that much more powerful activity tracking applications can be developed in the future, including some that might be better able to track eating activities.

4.4 Biometrics Experiments and Results

Biometrics can be used to identify or authenticate a person. In the context of this work, the identification task is to uniquely identify a user from a set of users using a sample of their motion sensor data. In contrast, the authentication task is simply to distinguish a user from an imposter. Identification is a multi-class learning problem while authentication is a binary class learning problem. Virtually all prior work on motion-based biometrics is based on gait—walking data is used as a biometric signature. In this study, each of the 18 different activities mentioned earlier are considered as biometric signatures. All experiments use stratified 10-fold cross-validation to build and evaluate the models (the stratification ensures that each fold contains the same distribution of users). Given that each example corresponds to

Table 1 Personal model activity recognition accuracy results

Activity	Watch		Phone		Watch	Phone	Accels	Gyros	All
	Accel	Gyro	Accel	Gyro					
Walking	87.8	85.6	95.8	92.3	89.1	96.6	96.8	94.4	97.0
Jogging	96.9	93.6	95.5	94.3	97.3	98.6	99.3	98.1	99.3
Stairs	85.5	70.4	89.9	84.1	84.0	92.7	93.7	88.3	93.8
Sitting	87.3	62.8	86.7	59.7	84.0	87.0	91.9	70.8	91.8
Standing	90.7	59.0	90.0	68.2	89.7	90.2	94.8	75.1	94.7
Kicking	82.9	72.7	87.8	80.4	84.4	90.6	93.3	86.1	92.7
Dribbling	91.2	90.6	84.9	75.7	96.1	88.2	95.2	94.7	95.6
Catch	90.5	88.7	83.2	73.9	94.4	85.8	94.3	94.2	94.7
Typing	94.1	83.3	90.3	69.2	92.9	92.3	95.8	83.3	95.4
Writing	89.9	77.6	89.7	67.6	91.2	90.8	92.4	81.2	92.9
Clapping	95.0	92.7	88.7	72.6	96.6	91.0	96.8	94.1	97.6
Teeth	91.9	81.6	90.0	69.6	94.8	90.4	96.2	86.1	95.2
Folding	89.8	85.3	88.4	82.9	95.2	92.1	95.9	95.6	96.1
Pasta	83.3	68.3	84.4	48.0	84.1	85.8	92.2	70.4	92.6
Soup	86.6	69.1	86.3	52.6	87.3	85.5	93.0	74.3	93.9
Sandwich	72.7	50.5	86.7	48.1	70.9	84.7	91.1	59.1	90.4
Chips	78.8	60.6	82.9	50.1	80.0	83.0	92.0	69.9	92.4
Drinking	80.9	65.2	85.5	50.0	80.8	85.2	92.7	69.9	92.1
Ave	87.5	75.4	88.2	68.8	88.5	89.5	94.3	82.5	94.3

Table 2 Impersonal model activity recognition accuracy results

Activity	Watch		Phone		Watch	Phone	Accels	Gyros	All
	Accel	Gyro	Accel	Gyro					
Walking	62.3	66.4	35.2	44.7	71.4	58.6	68.4	68.5	73.5
Jogging	92.2	76.3	68.8	64.6	91.6	84.4	97.6	82.3	96.4
Stairs	65.1	47.2	42.8	56.3	66	71.3	72.8	62.3	75.7
Sitting	54.6	50.3	21.2	19.6	58.8	23.4	58.4	52.4	58.1
Standing	73.3	48.4	38.3	37.9	69.7	61	79.2	57.9	80.2
Kicking	70.5	53.1	43.9	50.3	70.4	57.3	78.8	60.8	80.6
Dribbling	59.2	63.2	34.9	31.2	70.7	34.1	70.2	73.8	74.6
Catch	65.1	63.5	37.4	30.1	81.9	35.7	78	74	78.8
Typing	57.7	58.1	23.3	12.5	68.4	12.2	58.8	56.7	64.2
Writing	61.6	58	19.1	10.5	74.4	9.2	69.4	63.9	72.4
Clapping	65.9	66	13.2	13.8	72.6	14.3	78.1	69.3	75.3
Teeth	64.4	52.8	26.3	9.7	71	17.7	69.7	52.5	71.9
Folding	73.9	72.5	22.4	33.3	82.6	33.8	79.5	80	87.2
Pasta	44.1	43.1	17.9	10.1	53.1	10.4	44.1	42.3	48.2
Soup	45.8	33.4	13.9	13.2	53.9	7.5	47.9	33.1	48.2
Sandwich	17.4	10.9	13.4	4.5	17.8	8.2	15.1	11.7	14.3
Chips	39.7	31.9	14.1	10.6	46.1	12.4	40	32.8	44.7
Drinking	46.9	44.8	12.6	7.6	55	5.3	48.5	42.1	52.6
Ave	58.9	52.2	27.7	25.6	65.3	30.9	64.1	56.5	66.5

10 s of data, the most natural application of this work would yield results based on a single 10-s sample. For biometrics, we can assume that the sensor data that is collected from a device is from one person. Thus, we are free to use more than one example for identification or authentication purposes. In the results in this case study, each decision is based on five examples (50 s of data) and a majority voting scheme is used. The majority voting scheme yields significantly improved results.

Table 3 shows the identification results using the majority voting strategy. The random forest algorithm was used to generate the individual classifiers. As with the activity recognition case study, the results are reported for each of the nine sensor configurations—and as before the best results occur when using either all four sensors ("All") or the accelerometers on both the smartphone and smartwatch ("Accels"). The identification accuracies are very high and most activities yield good results. This includes walking, which is the standard activity used for motion-based biometrics. But even the eating activities yield good results, which indicates that people eat in very distinctive ways. Note that these identification results are based on a pool of 51 subjects, so that a strategy of guessing a person's identity would yield an accuracy just under 2%. The performance would undoubtedly degrade with a larger pool of subjects, so it would be interesting to extend this study to include a much larger pool of subjects.

An authentication model must distinguish a specific user from an imposter, which means that each subject must have their own authentication model. The training data must include data from the subject to be authenticated, combined with data from a panel of other subjects, where this panel of other subjects serves as a set of imposters. In real-world situations, we cannot assume that the imposters trying to fool the authentication system would have provided data for training, so in this scenario the test set is made up of data from subjects not represented in the training set. Given that there are 51 total subjects, the 50 "other" subjects are partitioned into two sets, one set to be used in the training set and the other set to be used in the test set. Since authentication is a binary classification problem and the positive class (the user to be authenticated) is rare in comparison to the negative class (imposters that should be rejected), the panel of other subjects was under-sampled to create a training set that is made up of only 75% imposters (several different proportions were evaluated but only had a minimal impact on the results).

Table 4 shows the authentication results. As with the prior identification results, the Random Forest algorithm was used to induce the models and majority voting is used to boost performance. Equal Error Rate (EER) is typically used to assess authentication performance and is used in Table 4. EER is calculated as the point where the False Acceptance Rate (FAR) equals the False Rejection Rate (FRR). FAR is the rate at which the model incorrectly accepts an imposter as a legitimate user, while FRR is the rate at which the model incorrectly rejects a legitimate user. The results in Table 4 again show that the best results are achieved when either all four sensors are used or both accelerometers are used. The results also show that walking is a very good activity for authentication purposes—when using all four sensors, walking yields an equal error rate of 6.8%, which is the second lowest EER (eating pasta appears to give better results but is clearly not the most practical activity).

Table 3 Identification accuracy performance per activity (with voting)

Activity	Watch		Phone		Watch	Phone	Accels	Gyros	All
	Accel	Gyro	Accel	Gyro					
Walking	94.1	80.4	100.0	100.0	90.2	100.0	100.0	100.0	100.0
Jogging	90.0	88.0	100.0	100.0	98.0	100.0	100.0	100.0	100.0
Stairs	70.0	43.8	98.0	90.0	75.0	96.0	100.0	91.7	100.0
Sitting	88.2	33.3	100.0	62.7	86.3	98.0	100.0	64.7	100.0
Standing	82.4	20.0	98.0	39.2	84.0	94.1	100.0	50.0	100.0
Kicking	76.0	32.0	96.1	68.6	82.0	100.0	100.0	80.0	98.0
Dribbling	98.0	90.2	96.1	68.6	86.3	98.0	96.1	96.1	100.0
Catch	78.0	85.7	98.0	70.0	91.8	100.0	100.0	91.8	100.0
Typing	94.0	50.0	100.0	89.8	100.0	100.0	100.0	95.9	100.0
Writing	94.1	58.8	96.1	80.0	98.0	100.0	100.0	90.0	100.0
Clapping	96.1	90.2	100.0	86.3	98.0	100.0	100.0	100.0	98.0
Teeth	94.1	62.7	98.0	82.4	96.1	100.0	100.0	94.1	100.0
Folding	64.7	39.2	100.0	76.5	86.3	96.1	100.0	78.4	100.0
Pasta	84.0	48.0	100.0	56.0	84.0	100.0	100.0	71.4	98.0
Soup	88.2	62.0	100.0	66.7	88.0	100.0	100.0	80.0	100.0
Sandwich	84.0	38.0	98.0	68.0	82.0	100.0	100.0	73.5	98.0
Chips	82.4	41.2	100.0	76.0	82.4	98.0	98.0	80.0	100.0
Drinking	86.3	41.2	100.0	58.8	80.4	100.0	100.0	60.8	100.0
Ave	85.8	55.8	98.8	74.4	88.3	98.9	99.7	83.2	99.6

An activity like clapping yields fairly good results, and since it could reasonably be performed in most environments, perhaps should be considered for authentication.

The biometric results, for both identification and authentication, have been presented in terms of individual activities. A long term goal is to build a system that performs continuous biometrics—that continuously validates a person's identity in the background, as the person goes about their normal tasks, without requiring the user to perform any specific activity. Thus, in the next set of identification experiments, we move a step closer to continuous biometrics by using the set of all 18 activities—without explicitly labeling each activity. Thus, the question becomes whether we can identify someone based on the sensor data generated from a diverse set of unlabeled activities. This is only a step towards continuous biometrics, since only eighteen activities are considered, rather than all activities a person might perform during their daily activities.

Three variations of the basic experiment are conducted. The first is the basic experiment: activity labels are not provided. The second experiment provides the activity labels and is provided for comparison purposes, to assess the impact of not having the activity labels. The third experiment does not include any activity labels, but uses an activity recognition model to predict the activity. Thus, this is a two stage approach, where the activity label is predicted and then is used in the biometric identification process. Table 5 provides the results for all three variations of the experiment, and also includes the results when the majority voting strategy is not used and is used, corresponding to the situation of making an identification using a 10 s sample of data or a 50 s sample of data, respectively.

The results in Table 5 demonstrate that good performance is possible even without the activity labels, at least when the voting strategy is used. Specifically, the results indicate that identification accuracy is 99.1% when all sensors are used and majority voting is used, even when no labels are provided. In fact, the results show that including the labels in this situation yields the same accuracy. Somewhat surprisingly, in this case predicting the activity label yields slightly worse performance than not having it. The key conclusion from Table 5 is that it is possible to achieve good identification accuracy when the input is only an unlabeled stream of activity data.

Based on the results in this section, motion-based biometrics using a smartphone and/or smartwatch can be effective. Wearable computing applications that perform much more granular activity recognition should arrive over the next decade, as should applications that use a person's motion to passively perform biometric identification.

5 Summary and Future Directions

This chapter provides a basic overview of wearable computing. It began by defining wearable computing and emphasized key characteristics, including that wearable computing technology should be easy to utilize without much conscious effort. It then provided a tour through the history of wearable computing devices, and in doing so demonstrated the diversity of wearable computing and wearable computing

Table 4 Authentication equal error rate per activity (with voting)

Activity	Watch		Phone		Watch	Phone	Accels	Gyros	All
	Accel	Gyro	Accel	Gyro					
Walking	13.2	17.2	9.4	9.8	13.9	8.8	11.3	10.0	6.8
Jogging	16.2	15.2	7.8	10.8	12.7	9.7	9.0	11.2	8.3
Stairs	19.3	23.9	13.4	12.5	18.9	9.3	8.4	14.1	6.9
Sitting	14.5	32.1	10.4	23.7	17.0	8.8	10.0	21.1	10.2
Standing	16.7	31.6	12.1	22.1	15.2	10.9	10.0	21.5	7.7
Kicking	21.0	24.1	10.6	19.4	16.6	11.0	10.1	18.8	11.0
Dribbling	16.4	16.1	10.3	21.0	14.5	9.7	10.0	11.8	11.5
Catch	16.3	15.5	9.7	19.3	14.9	10.0	9.3	13.9	10.0
Typing	13.0	20.7	8.3	15.4	14.0	8.9	8.6	13.3	8.8
Writing	10.7	21.3	8.7	15.7	11.6	9.2	9.0	16.0	10.1
Clapping	12.9	17.2	9.4	13.4	13.2	10.1	8.1	14.8	8.5
Teeth	13.3	20.0	10.1	14.0	14.4	10.2	10.8	14.9	8.2
Folding	17.0	23.4	7.9	18.6	17.3	10.0	8.1	16.2	7.1
Pasta	14.3	26.6	8.0	23.7	18.5	8.9	9.0	19.6	5.4
Soup	17.0	22.3	7.3	19.2	13.3	6.1	7.8	17.5	8.0
Sandwich	17.5	25.7	9.9	17.9	17.7	11.4	8.2	16.2	9.3
Chips	14.7	25.9	9.9	21.5	18.1	10.3	8.5	17.2	8.0
Drinking	16.6	25.1	11.3	19.2	13.9	10.2	10.9	19.9	8.1
Ave	15.6	22.4	9.7	17.6	15.3	9.6	9.3	16.0	9.3

Table 5 Identification accuracy using all eighteen activities

Sensors used	Without label		With label		Predicted label	
	voting?		voting?		voting?	
	No	Yes	No	Yes	No	Yes
Phone accel	58.0	96.8	58.5	97.6	30.3	96.0
Phone gyro	27.4	61.6	28.6	65.1	27.0	63.1
Watch accel	27.8	76.0	28.6	77.3	62.7	75.4
Watch gyro	12.4	39.8	13.2	43.9	51.8	42.4
Phone	61.2	97.0	62.1	97.5	32.7	96.2
Watch	28.6	77.1	29.3	77.9	66.6	80.6
Accel	64.0	99.2	63.9	99.3	64.0	98.9
Gyro	30.3	72.3	30.6	73.0	56.3	72.9
All	64.7	99.1	65.1	99.1	67.0	98.9
Ave	41.6	79.9	42.2	81.2	43.8	80.5

applications. The history also demonstrated that many of the more recent wearables have their roots in wearables that were developed decades ago. Lessons learned from the history of wearables were presented and used to predict future trends in wearable computing. The chapter then described several wearable common application areas, and the industries that are currently benefitting most from this technology. Case studies on activity recognition and biometrics were provided to demonstrate how some wearable computing applications are implemented, and highlight how data science methods can lead to more powerful future wearable computing applications.

Wearable computing has entered the mainstream over the last few years, first with the introduction of activity trackers and then with smartwatches. These devices have only begun to tap the potential of wearable computing and even they have not yet completely proven themselves. For example, activity trackers are quite popular, but have not been around quite long enough to prove that they are not a fad—and there are signs that even the commercial success of Fitbit may be fading. In fact, there are even studies that indicate that the benefits of fitness tracking may be overblown. One study showed that adding fitness tracking to a standard behavioral intervention for weight loss resulted in a *reduction* in weight loss [35]. Similarly, many users find the benefits of using a smartwatch to be minimal, and the growth of the smartwatch market has thus far been rather disappointing. More ambitious wearable computing devices, like Google Glass, still face an uncertain future—Google Glass itself was withdrawn from the commercial market until the product can be improved. It is still unclear whether augmented reality devices will ever enter the mainstream.

However, there is reason for optimism. There is still great interest in wearable computing and devices like Google Glass may simply have been released prematurely. After all, the Apple Newton PDA was a flop, but ultimately Apple released the iPhone, which includes much of the PDA functionality, and it was a tremendous success. Furthermore as the electronics continue to shrink and power requirements are reduced, wearable computing devices will become cheaper and less cumbersome. This is especially true for wearable sensors, which could ultimately be embedded on our clothing. Medical applications of wearable computing could alone turn out to have enormous benefits. Thus, there is great potential for growth in wearable computing technology, but such technology must provide substantial and concrete benefits to the user.

References

1. DARPA: Proceedings of the Wearables in 2005 Workshop (1996)
2. Mann, S.: An historical account of the 'WearComp' and 'WearCam' inventions developed for applications in 'personal imaging'. In: First International Symposium on Wearable Computers, 13–14 Oct, 1997. IEEE. Cambridge, MA, USA (1997)
3. Hayes, J.: XII things you (Probably) didn't know. Eng. Technol. **8**(12), 39–42 (2013)
4. Thorpe, E.O.: The invention of the first wearable computer. In: Proceedings of the Second International Symposium on Wearable Computers (SWC), pp. 4–8 (1998)
5. Bass, T.A.: The Eudaemonic Pie. Houghton Mifflin (1985)
6. Casio: Casio History 1980. Web (2017). http://world.casio.com/corporate/history/chapter02/. Accessed 13 June 2017
7. Sutherland, I.: A head-mounted three dimensional display. In: Proceedings of the Fall Joint Computer Conference, pp. 757–764. IEEE CS Press, Los Alamitos, California (1968)
8. Mann, S.: Wearable computing: a first step toward personal imaging. Computer **30**(2) (1997)
9. Starner, T.: Project glass: an extension of the self. IEEE Pervasive Comput. **12**(2), 14–16 (2013)
10. Rhodes, B., Starner, T.: Remembrance agent: a continuously running automated information retrieval system. In: The Proceedings of the First International Conference on the Practical Application of Intelligent Agents and Multi Agent Technology (PAAM), pp. 487–495 (1996)
11. IEEE Computer Society: Digest of Papers from the First International Symposium on Wearable Computers, 13–14 Oct (1997). IEEE Computer Society (1997)
12. Edwards, F.: Introducing the Tiny, Wearable 12MP Perfect Memory Camera. DigitalRev, Web (2016)
13. D'Cruze-Sharpe, R.: Best cameras for lifelogging: how to livestream your life on the move. In: Wearable (2016). www.wareable.com/cameras/best-wearable-lifelogging-cameras. Accessed 3 July 2017
14. Kwapisz, J.R., Weiss, G.M., Moore, S.A.: Activity recognition using cell phone accelerometers. ACM SIGKDD Explor. **12**(2), 74–82 (2010)
15. Weiss, G.M., Timko, J.L., Gallagher, C.M., Yoneda, K., Schreiber, A.J.: Smartwatch-based activity recognition: a machine learning approach. In: Proceedings of the 2016 IEEE International Conference on Biomedical and Health Informatics, Las Vegas, NV, pp. 426–429 (2016)
16. Streitfeld, D.: Google Glass picks up early signal: keep out. The New York Times. Retrieved June 26, 2013
17. Jhajharia, S., Pal, S.K., Verma, S.: Wearable computing and its application. Int. J. Comput. Sci. Inf. Technol. **5**(4), 5700–5704 (2014)
18. Azuma, R.T.: A survey of augmented reality. Presence: Teleoperators Virtual Environ. **6**(4), 355–385 (1997)
19. Brooks, F.P.: The computer scientist as toolsmith II. CACM **39**(3), 61–68 (1996)
20. Stewart-Smith, H.: Education with augmented reality: AR textbooks released in Japan, ZDNet Apr. 4, 2012. http://www.zdnet.com/article/education-with-augmented-reality-ar-textbooks-released-in-japan-video
21. Blum, T., Kleeberger, V., Bichlmeier, C., Navab, N.: Mirracle: an augmented reality magic mirror system for anatomy education. In: Proceedings of the 2012 IEEE Virtual Reality, pp. 115–116. IEEE Computer Society (2012)

22. Kay, M., Santos, J.: Takane M (2011) mHealth: new horizons for health through mobile technologies. World Health Organ. **64**(7), 66–71 (2011)
23. MiniMed 530G System: Medtronic, July 1, 2017. http://www.medtronicdiabetes.com/products/minimed-530 g-diabetes-system-with-enlite
24. Muensterer, O.J., Lacher, M., Zoeller, C., Bronstein, M., Kübler, J.: Google Glass in pediatric surgery: an exploratory study. Int. J. Surg. **4**, 281–289 (2014)
25. Kaddoum, R., et al.: A randomized controlled trial comparing the AccuVein AV300 device to standard insertion technique for intravenous cannulation of anesthetized children. Pediatr. Anesth. **22**(9), 884–889 (2012)
26. Miyake, R.K., Zeman, H.D., Duarte, F.H., Kikuchi, R., Ramacciotti, E., Lovhoiden, G., Vrancken, C.: Vein imaging: a new method of near infrared imaging, where a processed image is projected onto the skin for the enhancement of vein treatment. Dermatol. Surg. **32**, 1031–1038 (2006)
27. Shu, C.: Startup brain power uses Google Glass to develop apps for kids with autism. TechCrunch Dec. 23, 2014. Accessed June 30 2017
28. Metz, R.: Augmented-reality glasses could help legally blind navigate. MIT Technology Review, June 15, 2015. www.technologyreview.com/s/538491/augmented-reality-glasses-could-help-legally-blind-navigate
29. Conrad, C., Fusaglia, M., Peterhans, M., Lu, H., Weber, S., Gayet, B.: Augmented reality navigation surgery facilitates laparoscopic rescue of failed portal vein embolization. J. Am. Coll. Surg. **223**(4), e31–e34 (2016)
30. Lockhart, J.W., Pulickal, T., Weiss, G.M.: Applications of mobile activity recognition. In: Proceedings of the ACM UbiComp International Workshop on Situation, Activity, and Goal Awareness, Pittsburgh, PA (2012)
31. Bao, L., Intille, S.: Activity recognition from user-annotated acceleration data. Lecture Notes Computer Science 3001, pp. 1–17 (2004)
32. Google Glass: Wearable Tech in the Warehouse: Harvard Business School, Nov 7, 2017 (2017). https://rctom.hbs.org/submission/google-glass-wearable-tech-in-the-warehouse/
33. Gans, E., Roberts, D., Bennett, M., Towles, H., Menozzi, A., Cook, J., Sherrill, T.: Augmented reality technology for day/night situational awareness for the dismounted soldier. In: Proceedings of the SPIE 9470, Display Technologies and Applications for Defense, Security, and Avionics IX; and Head- and Helmet-Mounted Displays (2015)
34. Yoneda, K., Weiss, G.M.: Mobile sensor-based biometrics using common daily activities. In: Proceedings of the 8th IEEE Annual Ubiquitous Computing, Electronics & Mobile Communication Conference, New York, NY, pp. 584–590 (2017)
35. Jakicic, J.M., Davis, K.K., Rogers, R.J., King, W.C., Marcus, M.D., Helsel, D., Rickman, A.D., Wahed, A.S., Belle, S.H.: Effect of wearable technology combined with a lifestyle intervention on long-term weight loss: the IDEA randomized clinical trial. JAMA **316**(11), 1161–1171 (2016)