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A review of wearable sensors and systems with application in rehabilitation

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Abstract

The aim of this review paper is to summarize recent developments in the field of wearable sensors and systems that are relevant to the field of rehabilitation. The growing body of work focused on the application of wearable technology to monitor older adults and subjects with chronic conditions in the home and community settings justifies the emphasis of this review paper on summarizing clinical applications of wearable technology currently undergoing assessment rather than describing the development of new wearable sensors and systems. A short description of key enabling technologies (i.e. sensor technology, communication technology, and data analysis techniques) that have allowed researchers to implement wearable systems is followed by a detailed description of major areas of application of wearable technology. Applications described in this review paper include those that focus on health and wellness, safety, home rehabilitation, assessment of treatment efficacy, and early detection of disorders. The integration of wearable and ambient sensors is discussed in the context of achieving home monitoring of older adults and subjects with chronic conditions. Future work required to advance the field toward clinical deployment of wearable sensors and systems is discussed.

Keywords: Wearable sensors and systems, Home monitoring, Telemedicine, Smart home

Introduction

The US health care system faces daunting challenges. With the improvements in health care in the last few decades, residents of industrialized countries are now living longer, but with multiple, often complex, health conditions [1-3]. Survival from acute trauma has also improved, but this is associated with an increase in the number of individuals with severe disabilities [4]. From an epidemiological standpoint, the cohort of “baby boomers” in the US is now reaching an age at which they will begin to severely stress the Medicare system. Finally, recent health care reform efforts may add 32 million newly insured patients to the health care system in the next few years [5].

These altered demographics raise some fundamental questions

- How do we care for an increasing number of individuals with complex medical conditions?
- How do we provide quality care to those in areas with reduced access to providers?
- How do we maximize the independence and participation of an increasing number of individuals with disabilities?

Cleary, answers to these questions will be complex and will require changes into how we organize and pay for health care. However, part of the solution may lie in how and to what extent we take advantage of recent advances in information technology and related fields. Currently, there exist technologies that hold great promise to expand the capabilities of the health care system, extending its range into the community, improving diagnostics and monitoring, and maximizing the independence and participation of individuals. This paper will discuss these technologies in depth, with a focus on remote monitoring systems based on wearable technology. We chose to focus on these technologies because recent developments in wearable sensor systems have led to a number of exciting clinical applications.

Wearable sensors have diagnostic, as well as monitoring applications. Their current capabilities include physiological and biochemical sensing, as well as motion sensing [6,7]. It is hard to overstate the magnitude of the problems that these technologies might help solve. Physiological

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monitoring could help in both diagnosis and ongoing treatment of a vast number of individuals with neurological, cardiovascular and pulmonary diseases such as seizures, hypertension, dysrthymias, and asthma. Home based motion sensing might assist in falls prevention and help maximize an individual's independence and community participation.

Remote monitoring systems have the potential to mitigate problematic patient access issues. Nearly 20% of those in the US live in rural areas, but only 9% of physicians work in rural areas [8]. Access may get worse over time as many organizations are predicting a shortfall in primary care providers as health care reform provides insurance to millions of new patients [9]. There is a large body of literature that describes the disparities in care faced by rural residents [8]. Compared to those in urban areas, those in rural areas travel 2 to 3 times farther to see a physician, see fewer specialists, and have worse outcomes for such common conditions as diabetes, and heart attack [9,10]. Wearable sensors and remote monitoring systems have the potential to extend the reach of specialists in urban areas to rural areas and decrease these disparities.

A conceptual representation of a system for remote monitoring is shown in Figure 1. Wearable sensors are used to gather physiological and movement data thus enabling patient's status monitoring. Sensors are deployed according to the clinical application of interest. Sensors to monitor vital signs (e.g. heart rate and respiratory rate) would be deployed, for instance, when monitoring patients with congestive heart failure or patients with chronic obstructive pulmonary disease undergoing clinical intervention. Sensors for movement data capturing would be deployed, for instance, in applications such as monitoring the effectiveness of home-based rehabilitation interventions in stroke survivors or the use of mobility assistive devices in older adults. Wireless communication is relied upon to transmit patient's data to a mobile phone or an access point and relay the information to a remote center via the Internet. Emergency situations (e.g. falls) are detected via data processing implemented throughout the system and an alarm message is sent to an emergency service center to provide immediate assistance to patients. Family members and caregivers are alerted in case of an emergency but could also be notified in other situations when the patient requires assistance with, for instance, taking his/her medications. Clinical personnel can remotely monitor patient's status and be alerted in case a medical decision has to be made.

Despite the potential advantages of a remote monitoring system relying on wearable sensors like the one described above, there are significant challenges ahead before such a system can be utilized on a large scale. These challenges include technological barriers such as limitations of currently available battery technology as well cultural barriers such as the association of a stigma with the use of medical devices for home-based clinical monitoring. In the following section, we discuss key technologies enabling the development and deployment of wearable technologies and remote monitoring systems. The next section describes wearable and ambient sensor technologies that

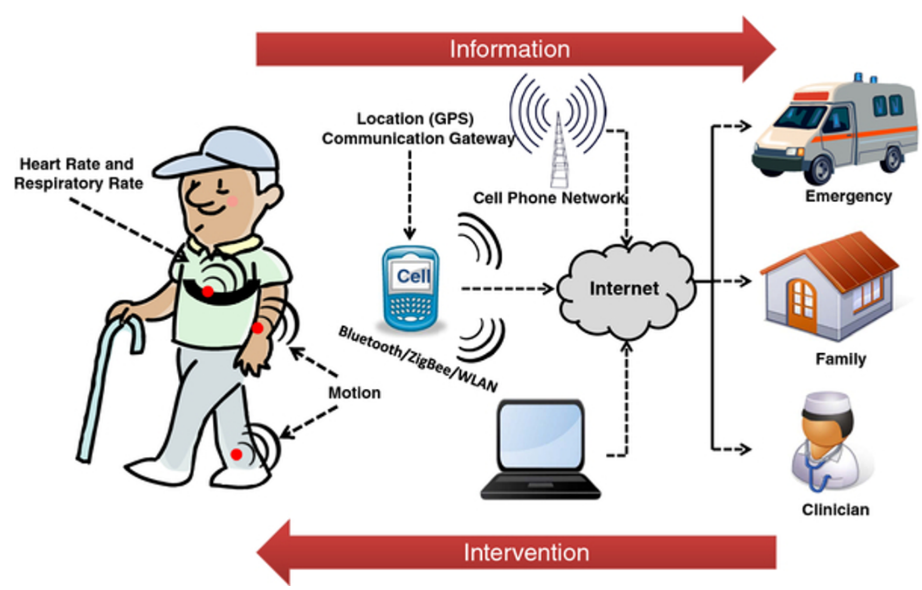

Figure 1 Illustration of a remote health monitoring system based on wearable sensors. Health related information is gathered via body-worn wireless sensors and transmitted to the caregiver via an information gateway such as a mobile phone. Caregivers can use this information to implement interventions as needed.

are essential components of systems to monitor patients in the home and community settings. Examples of applications of these technologies largely taken from a National Science Foundation initiated study of European projects focused on rehabilitation technology [11] are then presented. Conclusions and future developments that we foresee in the field of remote monitoring of patients' status via wearable technology are discussed in the final section.

Key enabling technologies

Wearable systems for patients' remote monitoring consist of three main building blocks: 1) the sensing and data collection hardware to collect physiological and movement data, 2) the communication hardware and software to relay data to a remote center, and 3) the data analysis techniques to extract clinically-relevant information from physiological and movement data. Recent advances in sensor technology, microelectronics, telecommunication, and data analysis techniques have enabled the development and deployment of wearable systems for patients' remote monitoring. Researchers have relied upon advances in the above-mentioned fields to address shortcomings of ambulatory technologies (e.g. Holter monitors) that had previously prevented long-term monitoring of patients' status in the home and community settings.

The miniaturization of sensors and electronic circuits based on the use of microelectronics has played a key role in the development of wearable systems. One of the major hurdles to the adoption of sensing technology, especially for wearable applications, has been the size of the sensors and front-end electronics that, in the past, made the hardware to gather physiological and movement data too obtrusive to be suitable for long-term monitoring applications. Recent developments in the field of microelectronics have allowed researchers to develop miniature circuits entailing sensing capability, front-end amplification, microcontroller functions, and radio transmission. The flexible circuit shown in Figure 2 is an example of such technology and allows one to gather physiological data as well as transmit the data wirelessly to a data logger using a low-power radio. Particularly relevant to applications in the field of rehabilitation are advances in technology to manufacture microelectromechanical systems (MEMS). MEMS technology has enabled the development of miniaturized inertial sensors that have been used in motor activity and other health status monitoring systems. By using batch fabrication techniques, significant reduction in the size and cost of sensors has been achieved. Microelectronics has also been relied upon to integrate other components, such as microprocessors and radio communication circuits, into a single integrated circuit thus resulting in System-on-Chip implementations [12].

Advances in material science have enabled the development of e-textile based systems. These are systems that

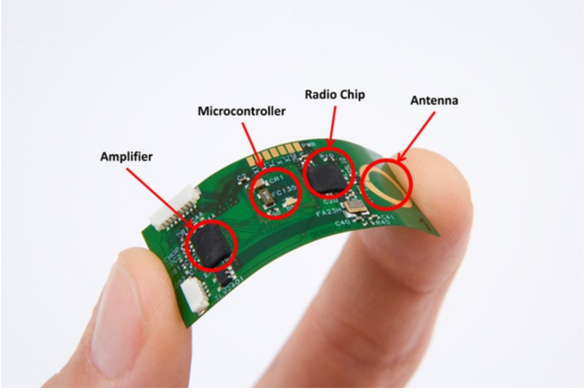

Figure 2 Flexible wireless ECG sensor with a fully functional microcontroller by IMEC. Developments in the field of flexible electronics are expected to lead to the advent of smaller, lighter and more comfortable wearable systems. (Courtesy of IMEC, The Netherlands).

integrate sensing capability into garments. The example shown in Figure 3 demonstrates how sensors can be embedded in a garment to collect, for instance, electrocardiographic and electromyographic data by weaving electrodes into the fabric and to gather movement data by printing conductive elastomer-based components on the fabric and then sensing changes in their resistance associated with stretching of the garment due to subject's movements. Rapid advances in this field promise to deliver technology that will soon allow one to print a full circuit board on fabric.

Health monitoring applications of wearable systems most often employ multiple sensors that are typically integrated into a sensor network either limited to body-worn sensors or integrating body-worn sensors and ambient sensors. In the early days of body-worn sensor networks (often referred to as "body sensor networks"), the integration of wearable sensors was achieved by running "wires" in pockets created in garments for this purpose to connect body-worn sensors. An example of this technology is the MIThril system [13]. Such systems by design were not suitable for long-term health monitoring. Recently developed wearable systems integrate individual sensors into the sensor network by relying on modern wireless communication technology. During the last decade, we have witnessed tremendous progress in this field and the development of numerous communication standards for low-power wireless communication. These standards have been developed keeping in mind three main requirements: 1) low cost, 2) small size of the transmitters and receivers, and 3) low power consumption. With the development of IEEE 802.15.4/ZigBee [14] and Bluetooth, tethered systems have become obsolete. The recently developed IEEE 802.15.4a standard based on

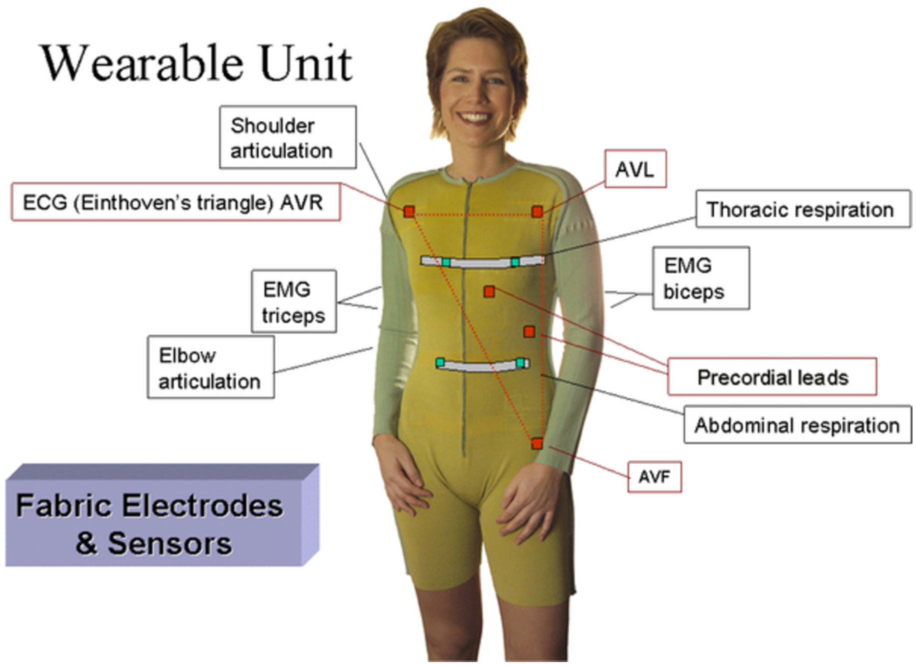

Figure 3 Example of e-textile system for remote, continuous monitoring of physiological and movement data. Embedded sensors provide one with the capability of recording electrocardiographic data (ECG) using different electrode configurations as well as electromyographic (EMG) data. Additional sensors allow one to record thoracic and abdominal signals associated with respiration and movement data related to stretching of the garment with shoulder movements. (Courtesy of Smartex, Italy).

Ultra-wide-band (UWB) impulse radio opens the door for low-power, low-cost but high data rate sensor network applications with the possibility of highly accurate location estimation [15].

Most monitoring applications require that data gathered using sensor networks be transmitted to a remote site such as a hospital server for clinical analysis. This can be achieved by transmitting data from the sensor network to an information gateway such as a mobile phone or personal computer. By now most developed countries have achieved almost universal broadband connectivity. For in-home monitoring, sensor data can be aggregated using a personal computer and transmitted to the remote site over the Internet. Also, the availability of mobile telecommunication standards such as 4 G means that pervasive continuous health monitoring is possible when the patient is outside the home environment.

Mobile phone technology has had a major impact on the development of remote monitoring systems based on wearable sensors. Monitoring applications relying on mobile phones such as the one shown in Figure 4 are becoming commonplace. Smart phones are broadly available. The global smart phone market is growing at an annual rate of 35% with an estimated 220 million units shipped in 2010 [16]. Smart phones are preferable to traditional data loggers because they provide a virtually "ready to use" platform to log data as well as to transmit data to a remote site. Besides being used as information gateways, mobile devices can also function as information processing units. The availability of significant computing power [17] in pocket-sized devices makes it possible to envision ubiquitous health monitoring and intervention applications.

In addition, most mobile devices now include an integrated GPS tracking system thus making it possible to locate patients in case of an emergency. Also, as storage and computation becomes more and more cloud based, health monitoring systems can become low-cost, platform-independent, rapidly deployable and universally accessible [18,19]. Monitoring devices can become simpler and cheaper as the computation is pushed to the cloud. This enables users to buy off-the-shelf devices and access customized monitoring applications via cloud-based services [20]. Cloud-based systems can prove especially useful for bringing health care services to rural areas [21]. In addition, monitoring applications deployed via the cloud can be easily updated without requiring that the patient installs any software on his/her personal monitoring device, thus making system maintenance quick and cost effective.

Finally, the massive amount of data that one can gather using wearable systems for patient's status monitoring has to be managed and processed to derive clinically-relevant information. Data analysis techniques such as

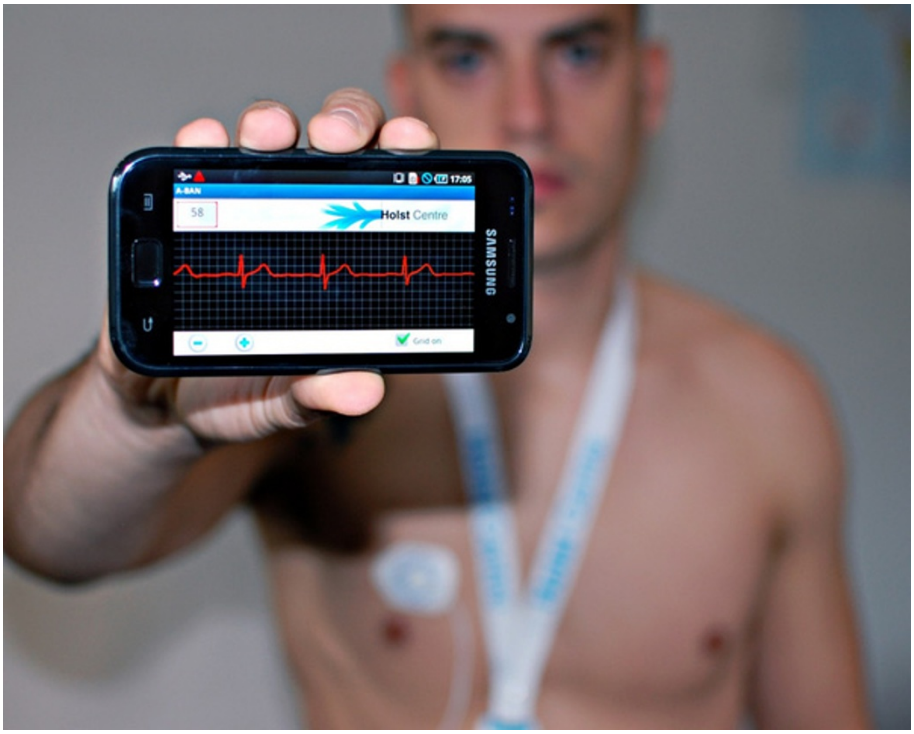

Figure 4 Smart phone based ECG monitoring system by IMEC. The Android based mobile application allows low power ECG sensors to communicate wirelessly with the phone. With increasing computational and storage capacity and ubiquitous connectivity, smart phones are expected to truly enable continuous health monitoring. (Courtesy of IMEC, The Netherlands).

signal processing, pattern recognition, data mining and other artificial intelligence-based methodologies have enabled remote monitoring applications that would have been otherwise impossible. Although a discussion of the various techniques used to process and analyze wearable sensor data is outside the scope of this review paper, one cannot emphasize enough the fact that data processing and analysis techniques are an integral part of the design and development of remote monitoring systems based on wearable technology.

Sensing technology

In this section, we provide information concerning the sensors used in remote monitoring systems. Information gathered using body-worn (i.e. wearable) sensors is collected ubiquitously thanks to the technologies mentioned in the previous section of this review paper. Wearable sensors are often combined with ambient sensors when subjects are monitored in the home environment as schematically shown in Figure 5. The combination of wearable and ambient sensors is of great interest in several applications in the field of rehabilitation. For instance, when monitoring older adults while deploying interventions to improve balance control and reduce falls, one would be interested in using wearable sensors to track motion and vital signs. Specifically-designed data analysis procedures would then be used to detect falls via processing of motion and vital sign data. In this context, ambient sensors could be used in conjunction with wearable sensors to improve the accuracy of falls detection and, most importantly, to enable the detection of falls even at times when subjects do not wear the sensors. This

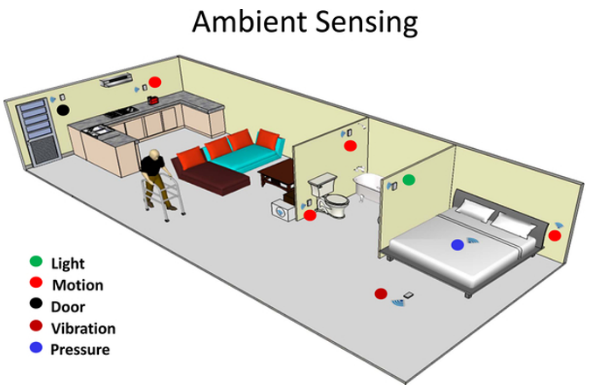

Figure 5 Ambient sensors can unobtrusively monitor individuals in the home environment. Ambient sensors can monitor activity patterns, sleep quality, bathroom visits etc. and provide alerts to caregivers when abnormal patterns are observed. Such sensors are expected to make the home of the future smarter and safer for patients living with chronic conditions.

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