



## Smart wearable systems: Current status and future challenges

Marie Chan<sup>a,b,\*</sup>, Daniel Estève<sup>a,b</sup>, Jean-Yves Fourniols<sup>a,b</sup>, Christophe Escriba<sup>a,b</sup>, Eric Campo<sup>a,b</sup>

<sup>a</sup> Laboratory for Analysis and Architecture of Systems, National Center for Scientific Research, 7 avenue du Colonel Roche, F-31400 Toulouse, France

<sup>b</sup> University of Toulouse, F-31400 Toulouse, France

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### ABSTRACT

**Objective:** Extensive efforts have been made in both academia and industry in the research and development of smart wearable systems (SWS) for health monitoring (HM). Primarily influenced by skyrocketing healthcare costs and supported by recent technological advances in micro- and nanotechnologies, miniaturisation of sensors, and smart fabrics, the continuous advances in SWS will progressively change the landscape of healthcare by allowing individual management and continuous monitoring of a patient's health status. Consisting of various components and devices, ranging from sensors and actuators to multimedia devices, these systems support complex healthcare applications and enable low-cost wearable, non-invasive alternatives for continuous 24-h monitoring of health, activity, mobility, and mental status, both indoors and outdoors. Our objective has been to examine the current research in wearable to serve as references for researchers and provide perspectives for future research.

**Methods:** Herein, we review the current research and development of and the challenges facing SWS for HM, focusing on multi-parameter physiological sensor systems and activity and mobility measurement system designs that reliably measure mobility or vital signs and integrate real-time decision support processing for disease prevention, symptom detection, and diagnosis. For this literature review, we have chosen specific selection criteria to include papers in which wearable systems or devices are covered.

**Results:** We describe the state of the art in SWS and provide a survey of recent implementations of wearable health-care systems. We describe current issues, challenges, and prospects of SWS.

**Conclusion:** We conclude by identifying the future challenges facing SWS for HM.

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## 1. Introduction

Efforts to research and develop smart wearable systems (SWS) have been increasing in both academia and industry [1–3]. The world population is ageing, and the proportion of young workers in developed countries has been shrinking [4,5]. Elderly people have a greater level of disability due to age-related diseases, a greater need for care and assistance, and are more likely to be admitted to a hospital or nursing home. Permanent admission to a care home is an expensive way of providing care for elderly, most of whom would prefer to remain in their own home [6–8]. Currently, between 2 and 5% of elderly people reside in nursing homes [9]. Data on health from 30 countries of the Organization for Economic Cooperation and Development (OECD) show that health care expenditures as a proportion of gross domestic product (GDP) are at an all-time high, due to both increased expenditures and to a general economic slow-down [10]. France spent 11.8% of its

GDP on healthcare delivery in 2009 according to OECD statistics. France was second among the OECD countries, behind the USA (17.4%), Germany (11.6%), Canada (11.4%), Switzerland (11.4%) and Austria (11.0%) [11]. Telecare, telehealth and telemedicine are new models of care already in use, bringing solutions to healthcare issues [12,13]. A large variety of laboratory prototypes, test beds and industrial products have already been produced. The role of SWS is to match the living environment with the physical and cognitive abilities and limitations of those suffering from disabilities or diseases, thereby enhancing performance and minimising the risk of illness, injury, and inconvenience. These systems support independent living for the elderly, postoperative rehabilitation for patients to expedite recovery, and assessment or enhancement of individual sportive or technical abilities [14,15].

For monitoring health, an SWS may include a wide range of wearable or implantable devices, including sensors, actuators, smart fabrics, power supplies, wireless communication networks (WCNs), processing units, multimedia devices, user interfaces, software, and algorithms for data capture, processing, and decision support. These systems are able to measure vital signs, such as body and skin temperature, heart rate, arterial blood pressure, blood oxygen saturation (SpO<sub>2</sub>), electrocardiograms (ECGs), electroen-

\* Corresponding author at: Laboratory for Analysis and Architecture of Systems, National Center for Scientific Research, 7 avenue du Colonel Roche, F-31400 Toulouse, France. Tel.: +33 5 61 33 69 51; fax: +33 5 61 33 62 08.

E-mail address: [chan@laas.fr](mailto:chan@laas.fr) (M. Chan).

cephalograms (EEGs), and respiration rate. The measurements are forwarded via a wireless sensor network (WSN) either to a central connection node, such as a personal digital assistant (PDA), or directly to a medical centre. A physician can then manage the patient based on the transmitted data. An increasingly important type of wearable system is an intelligent medical monitoring device capable of providing real-time processing and feedback to medical staff, patients, athletes, and healthy subjects. A subject can wear the device during normal daily life while medical professionals monitor the patient in real-time for longer periods than are possible during a hospital stay or a visit to a physician's office. The system can even issue alerts in the event of an emergency. For example, when a subject living alone suffers a stroke, an ambulance can be sent as soon as the stroke occurs. Advances in the field of micro-electromechanical systems (MEMS) have addressed a number of clinical indications, such as drug release [16] and biosensors for point-of-care testing [17]. Electrical stimulation by implantable or transcutaneous electronic devices or electrodes is often used for motor and sensory function recovery in the treatment of patients during the acute and subacute phase of paralysis induced by a central nervous system lesion [18]. However, there are a number of obstacles that must be overcome to fully implement the use of SWS, including high costs, size and weight limitations, energy consumption, sensor implementation and connectivity, ethics, laws, privacy, freedom, autonomy, reliability, security, and service issues [19–21].

This paper provides a review of SWS, describing the current status of research and development of wearable systems for HM by reporting the salient characteristics of the most promising projects being developed and the future challenges in this area. The paper is organised as follows. Section 2 describes the common materials and methods used in SWS, and Section 3 describes the current features of wearable systems, the sensor technologies, the wearable systems developed in academia and industry and our own on-going laboratory research in the field. Section 4 presents current issues surrounding SWS, and Section 5 discusses the challenges and the future perspectives. Section 6 draws the review to a close.

## 2. Materials and methods

SWS have the potential to monitor and respond to both the patient and the patient's environment, and the advances in the technology behind the development of SWS are steadily increasing. SWS are commonly recognised as one of the technological cornerstones for HM. Intelligent, low-cost, ultra-low-power sensor networks are designed to help provide services to dependent persons and can collect a huge amount of biomedical information from dependent individuals [22]. They offer new resources and bring new challenges as a result of the data that they provide rapidly, dependably, and safely. As wireless technologies and ubiquitous and pervasive computing [23] continue to develop, so will wireless network sensors [24], mobile devices, intelligent wearable devices [25–27], SWS, and data communication networks [28]. These technologies will create an intelligent environment and help with long-distance health care [26,27]. Their current abilities include physiological, biochemical, and motion sensing. SWS are used in areas ranging from 'telehealth', 'telehealthcare', 'telemedicine', 'telecare', 'telehomecare', 'e-health', 'p-health', 'm-health', 'assistive technology', or 'gerontechnology'. Issues related to connectivity have introduced terms such as 'WSN', 'body area network (BAN)', 'body sensor network (BSN)', 'wide area network (WAN)', and 'personal area network (PAN)'. Important concerns include 'user needs', 'user acceptance', 'privacy', 'ethics', 'legality', 'effectiveness', 'cost', 'psychological and social issues', 'hardware and software', 'implantation site', and 'unobtrusiveness'. For this

literature review, we have chosen specific selection criteria to include papers in which wearable systems or devices are covered.

### 2.1. Inclusion criteria for wearable systems search

1. Most research projects in SWS have focused on smart devices and intelligent environments that encompass wearable computing, which displace the interface for computational surroundings from the home (the smart home) onto our bodies (implantable, swallowable) [29] and into our clothes (smart clothing) [30] and by extension as portable accessories (jewelry), in patch form, etc. Systems that have the following features are included:
  - Wearable, portable, implantable, swallowable capsule, in vivo.
  - 'Patch', 'biosensor', 'sensor'.
  - 'Fabric', 'clothing', 'textile', 'fibre'.
  - Mobile, stationary, ambulatory, at home, at work.
2. Recent developments in micro- and nanotechnology, the use of lightweight devices, WSNs, and data processing have led to the resurgence of noninvasive SWS that improve HM systems [3]. SWS detect the state of the user in his or her vicinity. Projects in SWS concentrate on detecting the physical state of the user (physiological parameters, activity, mobility, location) [25]. Driven by fast progress in mobile sensing and computing, wearable computing has developed powerful methods to recognise, classify, and label human health states, actions, and behaviours automatically [31]. SWS have monitoring as well as diagnostic applications. Systems that are intelligent, ubiquitous, and pervasive or context-aware are included.
3. Automatic integration of collected data and user input into research databases can provide the medical community or the formal or informal caregiver with an opportunity to search for personalised trends, enabling insights into illness evolution, the effects of drug therapy, the rehabilitation process, and support for people with disabilities. Systems may either require user intervention or may not rely on the active participation of the user; empowered patients suffering chronic disease are more likely to feel in control of their health [32–35].
4. Advances in wireless sensor networking and ubiquitous computing have paved the way for new possibilities in health-care systems. In the home, pervasive networks can assist residents by providing memory support, remote control of household appliances, medical data look-up, automatic medication dispensing, and emergency communications and services. It is time to break through the physical boundaries of hospitals and to take health-care facilities into the home. In nursing homes and hospitals, SWS and ubiquitous computing for nursing and medical staff constitute a solution both for reducing medical costs and for enhancing patient safety while better supporting clinical processes [36,37]. Projects that involve SWS and ubiquitous computing in the home, in nursing homes, or in hospitals are included.
5. Recent technological advances in integration and miniaturisation of sensors, embedded microcontrollers, and radio interfaces on a single chip and in wireless networks have led to a new generation of WSNs for HM. A number of physiological sensors that supervise vital signs, environmental sensors (temperature, light, humidity), and a location sensor can all be inserted into a WSN, BAN, BSN, WAN, or PAN. Descriptions of networks that include the words WSN, BAN, BSN, WAN, or PAN are included.

### 2.2. Inclusion criteria for study area search

We included projects, pilot studies, case studies, prototypes, test beds, test sites, and research conducted in nursing homes, laboratories, health care settings, e-health care settings, or systems

**Table 1**  
Keywords used for the literature search.

|                      |                       |
|----------------------|-----------------------|
| Assistive technology | Smart home            |
| E-health             | Smart textile         |
| Home healthcare      | Socio-economic impact |
| Implantable device   | Telecare              |
| In vivo device       | Telehealth            |
| M-health Patch       | Telemedicine          |
| Obtrusiveness        | Telemonitoring        |
| Patch                | User acceptance       |
| Portable             | User needs            |
| Smart clothing       | User satisfaction     |
| Smart fabric         | Wearable              |

involving healthcare stakeholders, providers, caregivers, and end users.

### 2.3. Search methods and strategy

This literature review is not a systematic review and does not report an exhaustive search of scientific publications. Rather, cited reports are intended to give some illustrative examples of SWS. Our study includes published works that have undergone peer review. Our search was limited to papers in journals, chapters of periodicals and congress proceedings written between 1993 and 2012. Some web sites describing systems, devices, prototypes, and projects were included when the published literature did not offer adequate presentations of the projects. Searches using keywords were conducted either in Scopus, Elsevier, IEEE Xplore, Springer, PubMed, PubMed Central or using the Google search engine.

### 2.4. Results

Scopus gives hits from the period between 2007 and 2012. In this initial search, we attempted to find articles and abstracts, websites with the keywords listed in Table 1. The keywords are used alone or in combination and/or. The article should report a clear description of the systems, the recipients or the users in need of those systems, and the issues related to the SWS, including measured parameters, WSN, user needs, and user acceptance. Because of the large number of papers and abstracts retrieved, a decision was made to include only papers published after 1989. Since this review is not an exhaustive presentation of the scientific literature of the SWS field, only some representative SWS research and development projects or products from academia or industry are presented.

The number of hits in the SWS research area is shown in Table 2.

## 3. Current features of wearable systems

Non-invasive sensor systems allow monitoring of physiological functions, daily activities, and individual behaviours. Wearable HM systems may include various types of miniature wearable, implantable or in vivo sensors. These biosensors can measure physiological parameters such as body and skin temperature, heart rate, ECGs, EEGs, electromyograms (EMGs), or SpO<sub>2</sub>. Smart devices can provide real-time processing. Data transmission via wireless body communication networks enable patient monitoring by healthcare providers that can be alerted as soon as a dangerous event occurs. The aim of this section is to review wearable systems capable of monitoring individuals such as the elderly, the handicapped, those suffering from chronic diseases, and the injured with special needs.

### 3.1. Assessable parameters and users of SWS

#### 3.1.1. When, where and how SWS can be used

There is a growing interest in finding new healthcare solutions to provide care, or manage and support patients or individuals

**Table 2**  
Number of hits in the smart wearable systems research area.

|                                 | Scopus | PubMed | PubMedCentral |
|---------------------------------|--------|--------|---------------|
| SWS                             | 454    | 540    | 80            |
| Telemedicine                    | 15,116 | 13,462 | 2148          |
| Telehealth                      | 1981   | 1194   | 624           |
| Telecare                        | 1981   | 331    | 228           |
| Telemonitoring                  | 1063   | 432    | 253           |
| e-Health                        | 2221   | 936    | 1069          |
| M-health                        | 176    | 862    | 1063          |
| Telemedicine and wearable       | 256    | 140    | 49            |
| User needs                      | 77,409 | 3414   | 18,908        |
| User needs and wearable         | 241    | 11     | 116           |
| Medicine skin patch             | 455    | 1346   | 107           |
| Implantable device              | 11,115 | 18,306 | 3083          |
| Smart fabrics                   | 1010   | 68     | 46            |
| Smart clothing                  | 491    | 88     | 416           |
| User acceptance                 | 8724   | 1244   | 4888          |
| User acceptance wearable        | 43     | 10     | 30            |
| Efficiency wearable             | 311    | 36     | 114           |
| Obtrusive wearable              | 20     | 10     | 7             |
| Rehabilitation wearable         | 409    | 231    | 128           |
| Electrical stimulation wearable | 40     | 28     | 34            |
| Socio-economic and wearable     | 2      | 0      | 6             |
| Wireless sensor network         | 44,389 | 167    | 232           |
| Wireless sensor network         | 577    | 34     | 68            |
| Body area network               | 4945   | 1195   | 31,366        |
| Body area network wearable      | 270    | 21     | 93            |
| BSN                             | 2484   | 119    | 3227          |
| BSN wearable                    | 417    | 24     | 78            |
| Personal area network           | 6760   | 1001   | 16,922        |
| Personal area network wearable  | 116    | 8      | 74            |
| Economic analyse telemedicine   | 5      | 7      | 31            |

anywhere at any time. Innovative portable and wearable systems offer solutions to accessible and good quality individualised HM services.

- SWS are used to monitor patients 24 h a day, in their own home and outdoors, according to preventive medicine protocols. The monitoring system is connected to an assistance centre where the measured parameters are continuously or intermittently transmitted. The centre can also provide help if needed. The activities or motions of elderly individuals can be monitored, and when their life habits suddenly change, such as the propensity to remain at home or reduction of mobility, appetite, and social activities, these dangerous conditions can be foreseen based on analysis of the activities of daily living. During extreme climatic conditions (excessively cold or hot weather), elderly people are more prone to lung infections, dehydration, or other diseases [38]. This can be avoided if the changes in the patient's behaviour as a result of disease, infection, or dehydration are collected early and adequate therapy or rehydration is initiated before the situation becomes dangerous.
- Recent studies have developed diagnostic devices for point-of-care testing. Easy-to-use features of point-of-care diagnostics allow patient-side clinical analysis (e.g., outside of the hospital, in the field). Enabled by microfabrication and microfluidics, a wide variety of medical situations using point-of-care diagnostics have been explored, including disease markers, assessing therapies, detecting chemical and biological hazards, and identifying infectious people during pandemics. Microfluidic devices are able to electrochemically analyse a wide variety of biochemical compounds, such as glucose, cholesterol, lactate and alcohol [39,40].
- MEMS devices, including microreservoir drug depots, micropumps, valves, and sensors, have been developed for the delivery of microgram quantities of drugs. The usefulness of MEMS for biomedical applications lies in their ability to behave in a continuous or discrete fashion which may mimic the metastability of a living organ. A microchip for drug delivery is capable of releasing

drugs by opening various reservoirs on command. Pulsing or discontinuous performance may also be achieved in a MEMS using components such as valves or pumps. Adding hydrogels, biosensors, and other features that are responsive to the local device environment can enable a MEMS to function in an integrated manner with its biological surroundings. Combining new disciplines such as biomimetics and new biocompatible polymeric materials into microfabricated devices for tissue engineering and drug delivery and new techniques for patterning living cells may lead to fully integrated smart MEMS-based devices. These devices could replace entire biological systems and be responsible for delivering the right stimulus, such as a drug or an electrical impulse, at the right time [41].

- Capsule endoscopy, involving a miniaturised video-camera, represents an appealing alternative to traditional techniques. Traditional clinical products are passive devices whose locomotion is driven by natural peristalsis, which has the drawback of failing to collect images from important regions of the gastrointestinal tract because the physician is unable to control the capsule's motion and orientation. Active locomotion devices could enable capsule endoscopy to be performed in a totally controlled manner. The physician would be able to steer the capsule towards interesting pathological areas and to accomplish medical tasks. Capsule endoscopy offers new possibilities for screening, diagnostic, and therapeutic endoscopic procedures [29].
- Progress in sensor technologies and innovation in wearable computing have spawned numerous new devices which are now ready to revolutionise medical and professional applications, including diagnostics, surgery, remote patient monitoring, and indoor and outdoor positioning. Wireless medical instruments provide new dimensions for these applications. Biosensors combined with wireless devices in a 'smart instrument' can remotely monitor an elderly person at home or a patient in the operating room. Multiple pieces of medical equipment can be controlled and monitored wirelessly by a single device for each patient during and after surgical operations [42] or childbirth or during their transport to a hospital. In nursing homes or geriatric home-care facilities, SWS can improve residents' quality of life [37]. An individual injured during a catastrophic event (e.g., a plane or car crash, a natural disaster) can be supervised during transport or at the hospital and tethered to wearable devices or systems. The monitoring can range from intensive (every 15 min or less) to discontinuously invasive or non-invasive. In disaster situations (e.g., fire, earthquake), SWS can protect workers [43,44]. In extreme working conditions, for example for difficult mass transportation in dangerous sectors such as mines or oil platforms [45,46] or during catastrophic events (bus, plane, or boating accidents), SWS can send an alarm to a management centre.

The vital parameters that can be monitored by SWS are listed in Table 3.

### 3.1.2. Diseases, handicaps or disabilities that can be monitored by SWS

Ongoing cutting-edge multidisciplinary research in micro- and nanotechnologies, biosensors, and wireless and mobile information communication technologies has given rise to multi-parameter vital sign monitoring:

- Cardiovascular diseases – heart disease has become one of the leading causes of death world-wide. The World Health Organization (WHO) states that cardiovascular diseases are the world's greatest killers, claiming 17.3 million lives a year in events like heart attack and stroke [47]. Angina, atherosclerosis, cardiac dysrhythmia, congestive heart failure, coronary artery disease, heart attack, and tachycardia are the main cardiovascular diseases.

**Table 3**

List of vital parameters assessed using wearable systems.

| Type of vital signals      | Type of sensor                      | Signal source                                  |
|----------------------------|-------------------------------------|--|
| Electromyogram (EMG)       | Skin electrodes                     | Electrical activity of a muscle                |
| Electroencephalogram (EEG) | Scalp-placed electrodes             | Electrical activity of brain, Brain potentials |
| Activity, mobility, fall   | Accelerometer                       | Gesture posture/limb movements                 |
| Respiration rate           | Piezoelectric/piezoresistive sensor | Inspiration and expiration per unit time       |
| Heart sounds               | Phonograph                          | Record of heart sounds, with a microphone      |
| Blood glucose              | Glucose meter                       | Assessment of the amount of glucose in blood   |
| Oxygen saturation          | Pulse oximeter                      | Oxy-hemoglobin in blood                        |
| Body or skin temperature   | Temperature probe or skin patch     | Body or skin                                   |
| Galvanic skin response     | Woven metal electrodes              | Skin electrical conductivity                   |

These can be diagnosed by analysing changes in ECG patterns [48–50].

- Diabetes mellitus is a disorder of glucose metabolism and one of the most challenging diseases both from a medical and an economic perspective. Patients suffering from the disease can benefit from frequent, even continuous, monitoring of their blood glucose concentration to receive the right quantity of insulin to prevent hypoglycaemia complications [51]. The development of an 'artificial pancreas' may be one of the solutions for better management and monitoring of glucose level and the infusion of insulin [52].
- Renal diseases – patients suffering kidney failure depend on dialysis treatments. Ideally, the wearable artificial kidney (WAK) would closely approximate the function of a real kidney by providing round-the-clock dialysis. However, despite years of research, a WAK hemodialysis system remains elusive [53]. Recent advances in MEMS-based membrane technology promise to enable the development of continuous implantable renal replacement therapy [54].
- Respiratory diseases – patients suffering from dyspnea, sleep apnea syndrome, chronic obstructive pulmonary disease, or asthma can be monitored for early detection of symptoms and administration of treatments [55]. Respiration-rate assessment for children suffering pulmonary disease can be undertaken using textile sensors and electronics for interfacing, data handling, storage, and transmission. Such a system would enable continuous, long-term monitoring of children in a hospital environment [56].
- Cancer is a leading cause of death worldwide and accounted for 7.6 million deaths (approximately 13% of all deaths) in 2008 according to the WHO [47]. Some cancer tumours can be detected by WNS by studying the blood flow in the area surrounding a tumour using sensors placed on a needle (because cancer cells exude nitric oxide), enabling physicians to diagnose tumours without performing a biopsy [57]. Patients suffering from cancer are monitored to support their wellness [58].
- Posture, motion control – particularly interesting for those who have undergone hip surgeries. A wearable accelerometer embedded in a waist belt and attached to the lumbo-sacral region could enable assessment of motor recovery and of physical effectiveness therapy for post-stroke hemiplegic patients [59]. Postures and gestures can be monitored using accelerometers and magnetometer-based devices which can be micro-electromechanical or textile-based transducers [60]. A gyroscope, compass, accelerometer [61], magnetometer, piezoelectric sensor, and GPS in miniaturised and wearable forms can be combined to detect complex movement patterns [62].



- Neurological disorders and brain stimulation – epilepsy is a neurological disorder characterised by spontaneous seizures. Over one-third of patients receive insufficient oral anti-epileptic drug (AED) and experience seizures while on medication. New generations of AED are delivered directly to the seizure focus in the brain to provide more effective doses while by-passing the remainder of the brain and body to prevent side effects. The devices are polymer-based implants loaded with AED to achieve gradual, continuous release of AED directly into the brain region responsible for seizures [63,64]. Recent advances in nanotechnology have provided promising solutions for the effective non-invasive treatment of central nervous system (CNS) diseases. Many nanomedicines can be transported across various in vitro and in vivo blood–brain barrier models by endocytosis, transcytosis, or both and have demonstrated early pre-clinical success for the management of CNS conditions such as brain tumours, HIV encephalopathy, Alzheimer's disease, and acute ischemic stroke [65].
  - Rehabilitation – movement and muscle activity pattern recordings can be associated with a given set of functional motor tasks and muscle stimulation [66]. In the case of post-stroke rehabilitation, upper-limb kinematic variables can be assessed using sensor-equipped garments. Using this technology, both sensors and interconnection wires can be deposited in a single printing and manufacturing process. The patients benefit from the comfort provided by the device because no metallic wires are necessary to connect them to the electronic data acquisition system. No rigid constraints are present in the wearable system, and movements are unrestricted [67].
  - Parkinson's disease, quadriplegia, and paralysis – Parkinson's disease is a neuro-degenerative disorder that induces characteristic motor symptoms: rigidity, tremor, bradykinesia, and hypokinesia. A quantifiable, objective, continuous data acquisition system providing information on the characteristic movement disorders for evaluation of the disease could improve diagnosis and monitoring. A 'bionic glove' can be used to provide functional electrical stimulation of muscles, either to produce a hand-grasp motion or to open the hand. The glove is designed to improve the function of the paralyzed hand after spinal-cord injury or stroke [68–70]. Implantable devices can restore function after paralysis by by-passing damaged regions of the nervous system, giving the patients the ability to live with greater independence and enhancing their quality of life [71].
  - In sport sciences – in the context of highly competitive teams, the discrepancy in performance among competitive athletes is becoming smaller and smaller. Wearing high-tech textiles in the form of compression garments, smart textiles, and wearable technologies could help to achieve an advantage over competitors [72]. Wearable sensors could enable coaches and athletes to assess physiological signs and body kinematics during exercise performance, to understand how an athlete's body responds to exercise, and to track improvements in sport performance or how a race car driver responds during simulated conditions [73,74]. As for bodily fluids such as tears, sweat, urine, and blood, wearable chemical sensors have been developed for real-time ambulatory monitoring of sweat. This has enormous implications for the field of sports and human performance and opens a new field of research in the clinical setting [75]. Measuring sweat makes it possible to collect rich information about the physiological condition of the subject because sweat contains a matrix of essential ions and molecules. Sweat analysis is known to be used to identify pathological disorders such as cystic fibrosis [76].
  - Stress is a leading cause of illness and disease and is so pervasive that there is an inherent need to be able to supervise stress in real time over long periods. A real-time personal stress monitor could provide subjects with continuous feedback about their stress levels. Their physicians could thus objectively evaluate stress exposure between visits. The system could be used as part of a psycho-physiological evaluation of members of the military undergoing intense training. The system uses measures of heart-rate variability to quantify stress levels before and during training as well as to predict stress resistance [77].
  - The ability to recognize emotions is one of the characteristics of emotional intelligence, which is an important aspect of human intelligence. It is well known that too much emotion is bad for rational thinking; much less well known is that neuro-scientific studies of patients who have essentially had their emotions disconnected reveal that these patients have strong impairments in intelligent day-to-day functioning, suggesting that too little emotion can impair rational thinking and behaviour. Emotional data are collected using sensors of physiological signs (facial muscle tension, blood volume pressure, skin conductance which measures electro-dermal activity, Hall effect respiration) to enable classification of affect [78].
  - Sudden infant death syndrome (SIDS) is a phenomenon in which apparently healthy new-borns die during sleep in their cradles. The exact cause is not yet fully understood, whence the term syndrome. However, various symptoms can be identified that show an elevated high risk for SIDS. The physiological signs include ECG, oxygen saturation in the blood, temperature, breathing rhythm, and blood pressure and should be monitored for risky new-born patients. For a great number of new-borns, evaluation of the patient's risk for SIDS is performed using a polysomnographic test (PSG) in a dedicated sleep clinic. This test, however, has poor reliability. A textile-integrated system monitoring vital signs after childbirth would provide a low-cost, reliable, and easy-to-use early alert for potential SIDS as well as recognition of the development or progression of diseases at an early stage [79]. A 'BBA bootee' has been developed to supervise vital signs in infants at special risk due to factors such as prematurity, chronic lung diseases, and malformation syndromes [80].
- ### 3.2. Location of sensing technology systems
- The sensing systems can be:
- Worn by an individual as an accessory:
    - o Piece of jewelry, wristwatch [81], wristband measuring pulse, body temperature, galvanic skin response (GSR), and EMG data [82], or ring [83]. These can also be a necklace, brooch, pin, earring, or belt buckle.
    - o Electronic patch [84] or skin [85].
    - o Armband worn on the back of the upper arm with sensors that assess movement, heat flow, near-body ambient temperature, heart rate, skin temperature, and GSR [86].
    - o Chest belt or shirt for measuring vital signs [87].
    - o Pyjamas and shoes for detection of sudden infant death syndrome [79,80].
    - o Shoes for monitoring motion or analysing gait [88].
    - o Glasses with mountable microphones or video cameras that can function as augmented reality glasses for navigation. The glasses wirelessly provide virtual information to the user, describing local cultural interests, shops, restaurants, and convenient transportation near the wearer's location, while also providing regular optical correction [89].
    - o Gloves for recording hand posture while individuals perform activities such as eating, dressing, or while they manipulate objects [90].
  - Implantable, in vivo:
    - o Miniaturised video camera [91], pills, gastric pressure measurement [92], gastric pH measurement.

- Continuous glucose-monitoring biosensors [93],
- Continuous implantable renal replacement therapy [54],
- Gradual, continuous-release implantable devices for drug delivery [63,64],
- Implantable devices for functional electrical stimulation of muscles [66],
- Capsule for endoscopy [29].
- Portable:
  - Multimedia devices or systems,
  - video camera,
  - microphone,
  - PDA.
- Embedded in the user's outfit as part of clothing [94]:
  - Passive smart textiles act as sensors,
  - Active smart textiles sense and also react to stimuli from the environment, exhibiting both sensor and actuator functions,
  - Very smart textiles adapt their behaviour to particular circumstances.
- Embedded in pieces of object, furniture, or the floor of a house:
  - Several applications use contextual information derived from load-sensing techniques. The weight of a subject, object position, and interaction events on a given surface can be obtained [95],
  - RFID tags deployed on an item such as a cup could detect when an individual is close to the cup [96]. Such a system could assess how many times an individual uses his or her preferred items. These habits could provide a good measure of the patient's activities.
  - A reminder system deployed on an item could remind elderly people to take their medication. Pill-bottle caps could change colour to indicate that a medication should be taken and could be equipped with ambient technology [97].

### 3.3. Sensor system networks

With the recent progress in network infrastructure, wireless systems have supplanted wired systems, whereas past sensors had to be directly connected to a wearable computer by cables. Researchers have developed WSNs to embed sensors in clothing or to allow sensors to be worn as accessories by the user. Two networks are deployed with the objective of monitoring, for example, vital signs that produce an alert for centralised medical monitoring services. The first is a wireless body area network (BAN) that is deployed on the body of the patient. This system includes all the wearable sensors and a PDA as a wearable computer [98]. The second network, the personal area network (PAN) platform, completes the first system wireless body area network (WBAN) and can include a smart phone sensor, video sensor, and environmental sensors. A gateway operates via a wireless wide area network (WAN) and connects a distant end-user to a healthcare-monitoring centre to manage all of the assistive services. A wide variety of available wireless technologies allow data transmission or long-range information communication between the SWS and the assistance centre. These technologies include WLAN, GSM, GPRS, UMTS, and WIMAX that can provide extensive network access. Fourth-generation (LTE-Advanced) are expected to be operational soon [99]. M-health is the term used to define 'unwired e-med', introducing 'mobile computing, medical sensors, and communication technologies for healthcare' [100]. In future cities, satellite networks and ultra-mobile devices could be deployed and lead to access of ubiquitous broadband connections, individual mobility and could be used as the main platform for personal e-health applications and services [101].

### 3.4. Smart biomedical wearable systems: current status and ongoing research

The diversity of applicable fields for SWS corresponds with the various system architectures and components, from wristwatches [102] to smart clothing for professionals [43,44]. We have selected representative SWS that have been developed in academia or industry or that have been commercialised. The SWS are presented according to their main features (e.g., electronic components, smart fabric, implantable).

#### 3.4.1. Research prototypes

**3.4.1.1. Based on microcontroller or other electronic device platforms.** Amon [81] is a wearable monitor developed under grants from the European Union FP5 IST program. The wearable monitor consists of a wrist-worn device, which measures skin temperature, blood pressure, SpO<sub>2</sub>, and one-lead ECG. A two-axis accelerometer correlates user mobility with the measured vital signs. In a supervision centre, a physician can analyse data transmitted from the wrist-worn device thanks to a GSM-based cellular communication link. The aim of the wearable Amon is to enable high-risk cardiac/respiratory patients to live independently. Data are classified according to the risk for serious cardiac/respiratory problems and appropriate actions are taken by the device, such as initialisation of additional measurements, risk alerts, or transmission of information to an assistance centre.

The Lifeguard system has been developed by a team of researchers at NASA and Stanford for extreme environments, space and terrestrial conditions. It includes physiological sensors (e.g., ECG/respiration electrode patch via impedance plethysmography, heart rate, SpO<sub>2</sub>, body temperature, blood pressure monitor and body movement), a wearable box the size of a cigarette pack, and a base station where data are sent via Bluetooth. The authors conducted a series of validation tests in extreme environments, and the results for data transmitted to remote locations with satellite connection were acceptably accurate [103].

LiveNet has been developed by the MIT Media Lab for long-term HM. It is composed of three major components, a PDA based on a mobile wearable platform, a software network and resource discovery application program interface (API), and a real-time machine learning inference architecture. The platform is composed of a 3-D accelerometer, ECG, EMG, and galvanic skin conductance sensors which can interface with a wide range of commercially available sensors. A three-layer software architecture allows communication between the applications, the distribution and processing of digital signals, and the implementation of real-time classifiers for wearable applications [104].

A portable wireless system capable of measuring phonocardiography (PCG), electrocardiography, and body temperature has been developed in Tainan, Taiwan. The proposed prototype system successfully uses Bluetooth technology to invisibly transmit and receive physical signals through the air. The system consists of a capacitor-type microphone inserted on a stethoscope for PCG detection, a three-lead ECG, a temperature sensor, a measuring board including a CPU, a Bluetooth transceiver, an A/D module and a PDA with an external memory unit. The PDA controls the system by issuing commands to the measuring circuit [105].

A shoe has been developed to identify the characteristics of human gait. The system consists of force-sensitive resistors (FSR), accelerometers and gyroscopes. The raw sensor data are processed by data fusion algorithms within a microprocessor [106].

Auranet is the University of Oregon's Wearable Computing group's implementation of a wearable community. The Auranet is the network of computing devices that exists in a person's social space or "Aura". The Auranet is where people and their personal computing devices have face-to-face encounters. Developing

a wearable assistant for those with cognitive impairments (e.g., traumatic brain injury, dementia), the assistant will have access to GPS information to track a user's location. It will have Internet access to alert a caregiver when help is needed. Finally, it will be able to establish point-to-point connections with local good Samaritans for assistance [107].

The INTREPID project has the objective of developing a multi-sensor context-aware wearable for the treatment of anxiety-related disorders and testing its clinical efficacy in reducing anxiety-related symptoms. The system uses biofeedback-enhanced virtual reality to facilitate the relaxation process. The virtual reality relaxation experience is strengthened by the use of a mobile phone capable of tracking and visualising the outpatient setting. The physiological data of the patient are recorded by biosensors so that they can control clinical protocols for the treatment of generalised anxiety disorder and during rest conditions [108].

The Aubade project is a wearable platform designed to analyse emotional states in real time, using signals obtained from the face. Aubade uses a variety of healthcare-related applications mainly from the fields of neurology and psychology. Those include facial pain, facial muscle disorders, speech disorders, depression and stress assessment. The wearable platform includes a mask that wirelessly collects and transmits signals (e.g., EMG, heart rate, skin conductivity and respiration rate) obtained from appropriate sensors placed on the face of the user to centralised systems. It uses efficient methods to process multisensorial signals based on sensor management and data fusion techniques. Clinical trials have been conducted to study the validity of the wearable platform [109].

A portable long-term physiological signal recorder has been developed at the University of Technology, Tampere, Finland. The system includes a bio-impedance block, an electrocardiography block, an acceleration sensor, a control and storage device, a radio communication interface, a rechargeable battery and a user interface. The system measures bio-impedance, ECG and the user's activity. The bio-impedance measures dynamic changes in impedance, the main application being to monitor a user's respiration. Activity is assessed with a three-axis acceleration sensor. Special attention has been paid to the power consumption of the device, with the system functioning 24 h a day. The system has been proven to be operational with both commercial Ag/AgCl gel-paste electrodes and custom-made textile electrodes [110].

*3.4.1.2. Systems based on smart clothes.* MyHeart is a personal health assistant developed within the framework of the European Commission Research Program. The system aims to detect early atrial fibrillation, enabling prevention and immediate treatment with medication. The sensing modules are either integrated into the garment or simply embedded on a piece of clothing. The underlying concept relies on the use of tiny conductive wires knitted like normal yarn, which increases the comfort of the wearable system. The size of the overall system is decreased, the sensors (ECG and activity) do not need wireless modules and the system relies on a centralised wearable power supply. One main device controls the on-garment bus and is responsible for the synchronisation and the power supply for all of the wearable components. Associated software has been developed to classify activity into resting, lying down, walking, running, and going up or downstairs with very high accuracy. The MyHeart project developed heart belts as well, that could be worn across the chest or attached to a standard bra or to the waistband of standard underwear [111].

The MagIC project has been developed in Milan, Italy, using a textile-based system for the unobtrusive measurement of vital signs. A washable, sensorised vest incorporates fully woven textile sensors for monitoring ECG and respiration rate and a portable electronic board, which measures the user's motion level and is

responsible for signal pre-processing and information transmission through Bluetooth to a local PC or PDA. The system includes skin temperature measurements for elderly or cardiac patients at home for daily life HM. The data gathered from the evaluation tests showed very good acquired signal quality except in cases of maximal physical activity and that the system is also capable of identifying atrial fibrillation episodes and atrial and ventricular ectopic beats [112].

The Biotex is an EU-funded project that aims to develop textile sensors to measure physiological signs and the chemical composition of body fluids, with a particular focus on sweat. A wearable sensing system has been developed that integrates a textile-based fluid handling system for sample collection and transport with a number of sensors including sodium, conductivity, and pH sensors. Sensors for sweat rate, ECG, respiration, and blood oxygenation have also been developed. With the current design, the sensors respond well provided that there is an adequate supply of sweat [75].

The ProeTEX project financed by the European Commission, a consortium of 23 European universities, research institutions, and organisations in the field of emergency management, has developed a new generation of 'smart' garments for emergency-disaster personnel. ProeTEX Garments include portable sensors and devices in order to continuously monitor risks endangering the lives of rescuers. The smart system allows detection of a wearer's vital signs (e.g., heart rate, breathing rate, body temperature, SpO<sub>2</sub>, position, activity, and posture) and environmental parameters (e.g., presence of toxic gases, such as carbon monoxide and carbon dioxide (CO<sub>2</sub>), external temperature, and heat flux passing through the garments), to process data and remotely transmit useful data to the operation manager. Three ProeTEX prototypes have been built according to specific requirements for law enforcement officers as well as urban and forest fire-fighters. The core system is an electronic box that collects data from the sensors and sends the data to a local operation coordinator by means of a remote transmission system with a Wi-Fi protocol. Software running on the local coordinator's workstation visualises the data extracted from information in real-time and automatically activates alarms when dangerous events are detected. The results obtained using ProeTEX systems show the potential of smart garments developed by the consortium in order to monitor the vital signs of rescuers and environmental variables (e.g., external temperature, presence of toxic gases, and heat flux passing through the garments) [43,44].

Meremoth, the Medical Remote Monitoring of Clothes is a European IST FP6 project and part of six other European projects involved in the development of smart fabrics and interactive textiles. The garment includes conductive and electrostrictive fabrics and yarn and dry electrodes, enabling the measurement of ECG, respiratory inductance plethysmography, skin temperature and activity through accelerometers. A PDA is connected to a microcontroller which is used as an interface for the sensors on the garment, and provides an RF link to a local PC for display and assessment of data [113].

The VTAM project aims at developing generic clothing technology, embedding fabric biosensors and bio actuators. The garment includes smooth, dry ECG electrodes, a GPS receiver, and several sensors (e.g., shock/fall, breathing-rate, temperatures) [114].

The US Army is working on developing the Land Warrior System that enables soldiers to view computer generated graphical data and maps, engages targets at night without exposing soldiers to hostile fire, shares intelligence information and video images, and coordinates and synchronises actions with peer groups via mobile networks [115].

SensVest was designed for use in the Lab of Tomorrow project. The system has been developed for use by sciences teachers and students elaborating on the users' requirements that needed to be

met. It measures, records, and transmits vital signs such as movement, energy expenditure, heart rate, and body temperature. The trials carried out by students using SensVest proved the wearable system to be promising. They were able to carry out activities with no apparent inhibition to movement and little discomfort, and the data were reliable [116].

The Smart-Clothing project combines research in textiles, wireless sensors, and actuator networks in the context of human body monitoring with statistical methods for data analysis and treatment. The project aims to aid in the monitoring of foetal movement in the last 4 weeks of pregnancy [117].

Mithrill is a next-generation research platform aiming to develop context-aware wearable computing projects at the MIT Media Lab. The Mithrill architecture includes a multi-protocol body bus and body network, integrating a range of sensors, interfaces, and computing cores. The aim of Mithrill has been to develop a wearable system using context aware applications, supporting daily use functions such as recording grocery lists and movie recommendations, conversational note taking, messaging and e-mail [118].

Smart Vest has been developed in Bangalore, India. The system is able to monitor a number of vital signs, such as ECG, photoplethysmogram (PPG), heart rate, systolic and diastolic blood pressure; body temperature and GSR, in a single device without the attention of the wearer. The physiological information is transmitted using a RF link to a remote monitoring and analysis station along with the geo-location of the user where analysis of all the measurements are carried out in real time and presented in an appropriate form for transmission. Smart vest prototypes with varying degrees of success were obtained through clinical validation involving 25 healthy subjects [119].

**3.4.1.3. Mote-based body area network.** A wide range of projects are involved in the use of motes, or wireless-enabled tiny nodes, to constitute a body area network. CodeBlue is a project at Harvard University. A sensor network platform for multipatient monitoring environments has been developed based on Zigbee compatible MicaZ and Telos motes, including sensors for pulse oximetry, three-lead ECG, EMG, and mobility activity. The project enables data communication between medical sensors, receivers (e.g., PDAs carried by nurses and physicians). Software allows end users to dynamically request information from a specified network node. An RF-based localisation system tracks the location of patients and caregivers. The system was validated in a 30-node test bed [120].

A u-healthcare system has also been developed. u-Healthcare pursues new types of solutions, to effect changes in prevention and to develop more focused medical care systems, centering on individuals and the concept of well-being. The communication layer performs bi-directional data or command exchange via 802.15.04 network and code division multiple access (CDMA) to connect ECG and blood pressure sensors to a basic mobile phone device for information display and signal feature extraction. As a result, only abnormal vital signs (ECG, blood pressure patterns) are transmitted to the hospital. This is achieved by first extracting simple ECG features, such as QRS duration, RR interval, or R magnitude, and then making a decision based on pre-specified criteria. Blood pressure measurements are obtained from chest belt and wrist band devices. The project includes the use of accelerometers and SpO<sub>2</sub> sensors [121].

BASUMA systems have been developed to measure ECGs, air and blood content of the thorax (i.e., thoracic impedance), body temperature, respiration rate and cough control, blood pressure, pulse rate, SpO<sub>2</sub>, lung functions, reactive oxygen species (ROS) (i.e., exhaled H<sub>2</sub>O<sub>2</sub>), and lactate in breath condensate. The project uses sensors equipped with the ZigBee compliant Philips AquisGrain platform. It aims for long-term monitoring of chronically ill patients [122].

A MicaZ mote-based platform has been developed at the University of New South Wales, Sydney, Australia. The project investigates the opportunities and challenges in the use of dynamic radio transmit power control for prolonging the life time of body-wearable sensor devices used in continuous HM. MicaZ motes from Crossbow Technologies have been tested using the device strapped around a patient's chest, simulating monitoring of heartbeat and ECG. The authors conducted several experiments in which the device was strapped around a patient's arm (i.e., for monitoring blood pH and glucose). Several applications have been tested, including walking back and forth in a room for a few minutes at a normal walking pace or slow walking, as in the case of an elderly or disabled person with restricted mobility, and resting. The system shows the potential benefits and limitations of adaptive radio transmit power control as a means of saving energy in body-wearable sensor devices used for healthcare [123].

A BSN-based vital signs routine monitoring system has been developed at the National University of Singapore. The system comprises a wireless mote, amplifier circuit board and arterial SpO<sub>2</sub> probe. It is able to measure physiological signs in real time with only minimal disturbance to quality of life. The device is easy to wear and convenient to use. Using a dock with a ZigBee adapter, a PDA phone can communicate with the mote and then display the ECG/PPG data as well as the heart rate, SpO<sub>2</sub> value and the systolic blood pressure [124].

Patients recovering from surgery are at risk of complications due to reduced mobility as a result of postoperative pain. Continuous monitoring of these patients has encouraged research on wireless medical monitoring solutions that realise the vision of a wireless hospital. A patient station consists of a mote device that receives data from the sensors recording the vital signs (e.g., ECG, respiration and activity level) and is responsible for the first stage of data processing. The received signals are sent to a central server for analysis. This analysis is done using moteView software and generates alerts for medical professionals, caretakers and emergency medical department personnel [125].

**3.4.1.4. Implantable devices.** A wide range of devices can be used to identify people and to provide personal information. One of the most well-known is an implantable identification device (IID), a RFID tag developed by VeriChip Corp. that was approved for human implantation by the U.S. Food and Drug Administration in 2004. The VeriChip is usually implanted in the upper arm. Authorised medical professionals can use the serial number emitted by a VeriChip to access a patient's medical information in a database called VeriMed. This enables rapid retrieval of vital data even if the patient is unconscious or unresponsive during a medical emergency. The aim of VeriChip is to access medical records, but it can have other healthcare applications as well. Physicians and other medical professionals can use it to access sensitive hospital areas or certain patient records. The system may be used to verify a patient's identity before performing a surgical operation or administering a drug [126].

Other systems enable patients suffering chronic diseases to live independently. An implantable kidney has been developed jointly in Ohio and California, USA. The system uses highly efficient membranes and cell-based bioreactors. The authors have used MEMS to create biocompatible silicon membranes with nanometer-sized pores that can mimic the filtering capacity of the human kidney through cloning. Between the conventional thrice-weekly and the quotidian dialysis, this is a third alternative to dialysis and transplantation based on demonstrated technologies, sound science, and measurable milestones [54].

Other classes of implantable devices include sensors for nerve stimulation capable of alleviating acute pain in patients suffering



from cancer or trembling caused by Parkinson's disease, and to restore the grasp function in tetraplegic patients [127].

An implantable telemetry platform system allows in vivo monitoring of physiological parameters. The small size of the electronic circuit makes the system suitable for minimally invasive diagnostic tests, e.g., for gastro-oesophageal pressure, pH, glucose monitoring, according to the different sensor used [128].

A capsule endoscopy system allows patients to be examined from data collected by the camera. The system is composed of the capsule itself, a portable image receiver/recorder unit and battery pack, and a computer workstation. The patients undergoing capsule endoscopy wear an antenna array including eight leads that are connected by wires to the recording unit, worn in standard locations over the abdomen. The recording device to which the leads are attached is able to record the images transmitted by the camera in the capsule and received by the antenna array. The capsule system is useful for diagnosing gastrointestinal bleeding, inflammatory bowel diseases, taking small bowel radiography and monitoring postsurgical small bowel transplantation [129].

A robust and precise medical device has been developed for regulating blood glucose. It is composed of four subsystems: sensors, a pump, a controller and a power system. An insulin controller is suggested for the prototype device as well as a proportional derivative (PD) controller of insulin secretion by the pancreas. The authors demonstrated through results of their preliminary experiments the potential to achieve robust regulation of blood glucose using the artificial pancreas. Further improvements on control algorithms and electromechanical hardware are needed for a clinically viable solution [52].

**3.4.1.5. Skin devices.** Glucowatch Biographer is a minimally invasive self-monitoring system to measure blood glucose levels through extraction of transdermal fluid. The watch uses reverse iontophoresis to non-invasively extract glucose across the skin. The device has to be calibrated with an invasive "finger-stick", and this has been perceived as a disadvantage. The urea component was extracted simultaneously in an attempt to render the technique completely non-invasive. As a result, the extraction flux and concentration of urea both remained relatively constant, but the normalised, transdermal, iontophoretic flux of glucose showed inter-individual variability due to mechanisms that were not entirely governed by electrotransport. More specifically, despite good qualitative tracking of blood levels, biochemical and metabolic factors, as well as contamination, affect the quantitative results. Due to complaints that the device provoked skin allergies, the US Food and Drug Administration has since banned the use of the device [130].

A microwave sensor has been developed as a non-invasive monitor of blood glucose levels. The sensor is based on the microstrip ring-resonator. The sensor output is an amplitude measurement of the standing wave versus frequency sampled at a fixed point on an open-terminated spiral-shaped microstrip line. The patient presses his thumb against the line and applies contact pressure that falls within a narrow pressure range. A single-spiral microstrip sensor has been shown to exhibit significant changes in its response corresponding to changes in the measured blood glucose level of several test subjects. Microwave sensors are robust and economical and are elegant solutions to the problem of non-invasive glucose testing [131]. After being used in hospitals, glucose sensors are now offered to patients for ambulatory use. The patient, however, must be taught how to use the glucose sensor properly and wear the device regularly. An insulin pump with an integrated continuous subcutaneous glucose monitoring device improves the patient's therapeutic management.

A Danish laboratory has developed a textile-based, wearable electronic patch that can assess vital signs (e.g., EMG, SpO<sub>2</sub>, ECG, body temperature) [84].

'Electronic second skin' has been developed at the University of Wisconsin. This electronic skin consists of pressure-sensing materials and associated electronic devices for pressure readings. The electronic skin uses thin single-crystal silicon that has superior flexibility and mobility properties. Using a printing method called 'inking and printing', a thin silicon layer is bonded to a silicon dioxide release layer. The silicon layer is cut into a lattice of micrometer-scale "chipllets", and a transfer stamp layer is attached to the top of the divided silicon. The transfer layer and "chipllets" are then lifted and transferred to a flexible substrate. The support layer of the electronic skin is elastomeric polyester. The circuitry part consists of two protection layers that sandwich a multifunctional middle layer. The middle layer consists of the metal, semiconductor, and insulator components needed for sensors, electronics, power supplies, and light-emitting components, all of which are in serpentine shapes comprising a stretchable net. The system can be simply mounted onto or peeled off natural skin like bandage tape. Vital signs from heart, brain, and skeletal muscles similar to those measure using bulky electrodes and hardware have been obtained using the electronic skin. Other forms of physiological data can also be collected using this skin. The system has proved to be viable and inexpensive [85].

**3.4.1.6. Other wearable devices or biosensors.** Nanowires and nanotubes have been used for analytical applications. The most common use is in the modification of a bulk electrode such as gold or glassy carbon electrode with nanowires. They are able to detect biochemical components, viruses, etc. in body fluids. Carbon nanotube (CNT) arrays have been utilised to develop advanced nano- and microdevices. A novel type of cupric oxide (CuO) nanoparticle-modified multi-walled CNT array electrode for sensitive nonenzymatic glucose detection has been developed. CNTs have been used as electrode material due to their high surface area, unique structures, excellent electrical conductivity, ultra-strong mechanical properties and high stability. The electrode is used to analyse glucose concentration in human serum samples, and is promising for the development of nonenzymatic glucose sensors [132].

CNT-based sensors have been used to detect viruses. The CNT biosensors were assembled using a layer-by-layer technique exploiting the chemical functionalisation on nanotubes to tailor their interactions with viruses and antiviral antibodies [133]. At Toyohashi University of Technology in Japan, a penetrating Si microprobe array, with each probe only a few microns in diameter, has been developed. Development of the microprobe array employed a standard integrated circuit process followed by selective growth of silicon (Si) probes based on vapour-liquid-solid growth. The device is used for neural recordings as well as neuronal stimulation [134].

An enzyme-free glucose sensor prepared by the electrodeposition of gold nanowires within an anodic alumina oxide (AAO) template and subsequent transfer of the obtained array onto a glass substrate has been developed at Sungkyunkwan University in Korea. Electrochemical oxidation of glucose in 0.1 M NaOH solution was investigated using cyclic voltammetry. The voltammetry and amperometric detection of glucose was explored [135].

An alternative non-contact method to collect cardiopulmonary signs, including respiration and heartbeat signals, is via Doppler radar. However, the heartbeat signal cannot be distinguished when the subject does not hold his or her breath. To resolve the problem, adaptive noise cancellation based on a recursive-least squares algorithm showed that the heartbeat signal can be extracted and that the heart rate is strongly correlated with that derived from the ECG [136,137].

Advances in low-power and high-performance readout circuit design for the acquisition of biopotential signals enable the implementation of miniaturised and comfortable systems for acquisition of biopotential signals, such as EEGs, ECGs, and EMGs in the case of wearable and implantable systems [138]

Measuring pulse oximetry is based on spectral analysis, the detection and quantification of components in solution by their unique light absorption characteristics. A two-LED pulse oximeter is able to isolate the absorbance of arterial blood components from that of venous blood, connective tissue and other absorbers [139,140].

Sudden cardiac death is a public health issue. A wearable defibrillator or automatic external defibrillator is frequently used in cases of sudden cardiac death. Both devices are able to restore sinus rhythms in patients with ventricular tachyarrhythmia [141].

#### 3.4.2. Ongoing research on smart biomedical wearable systems in our laboratory

LAAS-CNRS has been conducting research on elderly monitoring systems since 1990 [142,143] and has followed the evolution of the development of elderly monitoring systems. Initially, in the 1990s, one of the important features in the concept of people-monitoring systems was the study of elderly behaviour and activity using monitoring systems and electronic devices embedded in their homes. The development of monitoring systems was based on a home environment where sensors collected spatiotemporal information about human activity [144]. A multisensory monitoring platform included the use of satellite communication to link the medical centre to a rural institution for retired individuals within the Ourses project [145]. This supervision system operates whenever the subject is alone in his or her home:

- (1) As soon as there are several people in the apartment or in the hallways and living rooms of the environment, continuous data gathering is corrupted or interrupted. In new projects (Homecare and BéA), wearable identification and location systems have been chosen to ensure continuous data collection and thus achieve 24-h monitoring of elderly people [146,147]. These systems include identification and location devices in a body area sensor network. In Homecare, a wearable electronic tag, such as those developed in a study by Haahr et al. [84] is used to identify and locate the subject. For the BéA project, a geographic tracking instrument worn by the individuals (e.g., elderly suffering from dementia, handicapped people) allows data collection and communication with a centre to detect and report cases of probable dangerous events. The system is composed of a waist belt connected to a wearable PDA that includes GPS, Wi-Fi location devices and software to detect safe areas or deviations from usual displacement trajectories for the subject. In the Respect project, the sole of a shoe, as shown in [88], is under development. The system includes identification and location functions in a body sensor area network. Using the Zigbee standard for wireless communication systems enables data transmission to a service centre that can provide assistance to the wearer.
- (2) Chronic mental stress is perceived as a risk factor for cardiovascular diseases [148]. Thus, it can be considered as one element determining an individual's health and self-esteem. Cardiac frequency may be one parameter related to stress. The objective is to find states far from equilibrium and to classify them as stress indicators. Heart rate variability (HRV) is a non-invasive method for measuring and detecting changes in cardiac frequency. Moreover, HRV serves as a marker of sympathovagal balance of the autonomic nervous system (ANS). In fact, perceived mental stress strongly affects ANS homeostasis [149]. There are numerous papers reporting changes in HRV due to mental stress [150]. Mainly low frequency and high

frequency components of HRV (LF/HF), standard deviation of all normal heart periods (SDNN) and root mean square successive difference in a heart period series (RMSSD) are significantly affected. Unfortunately, these investigations provide only tendencies, rather than threshold values for stress assessment. Our goal is to create a method that enables us to perform broad time-domain analysis, which, unlike standard HRV methods, will provide an insight into the evolution of the signal. The method permits us to establish symptoms of stress and finally create a SCORE stress index. We have actually introduced two statistical parameters that satisfy our criteria. We have also used microtechnologies to create a non-invasive ECG analyser combining a programmable analogue chip and accelerometer to measure ECG and human activities. We have used inexpensive commercially available off-the-shelf (COTS) accelerometers driven by microcontrollers with embedded signal processing algorithms and a smart power management system. The system uses on/off power consumption and is under patent, ADXL330 accelerometers from Analog Devices and LIS3DN accelerometers from STMicroelectronics are also used. We have developed ECG sensors where the electrodes are in kapton with Au deposit and the system is based on an amplifier designed in our laboratory. The system communicates with a microcontroller PIC from Microchip and has been developed under soft electronics technology.

Current LAAS-CNRS research is shown in Fig. 1.

#### 3.4.3. Commercial products

Bodymedia health wear armband is worn on the back of the upper right arm. This device is an armband composed of polyurethane with an accelerometer, a thermal conductivity sensor, a skin and ambient temperature sensor and a skin electrical conductivity sensor. It can also be connected to a wireless heart-rate sensor. The system focuses on weight management and assesses movement, heat flux, skin temperature, and GSR, allowing accurate measurements of energy expenditure. It can be connected wirelessly to external sensors based on a GSM transceiver. A PC connected to the transceiver records the raw data and transmits it to a help centre [151].

Vivago WristCare is a wireless wellness monitor which aims to support ubiquitous computing applications for wellness management and home automation. A wrist-worn device monitors skin temperature, skin conductivity and movement [102].

Vivometrics developed a LifeShirt System to continuously measure pulmonary, cardiac, and other vital signs. Accelerometers and sensors for respiratory measurement are embedded in an under-shirt garment; an external PDA stores the data and extracts the vital signs [152].

Micropaq Monitor has been developed by WelchAllyn. The system is a wearable device worn in a carrying pouch. It assesses pulse oximetry and up to five-lead ECG [153]. The SmartShirt developed by Sensatex is designed to measure ECG, respiration rate, and blood pressure. It is based on conductive smartfibres and nanotechnologies [154].

Cardionet is a mobile cardiac patient telemetry system. It monitors ECG and helps physicians diagnose and support patients suffering from arrhythmias [155].

Medtronic's CGMS<sup>®</sup> and Guardian<sup>®</sup> systems are 'minimally invasive' continuous blood glucose-level monitoring systems. A disposable bio-sensor needle is inserted under the skin of the abdomen and the blood glucose level is assessed from the interstitial tissue fluid [156].

A. Menarini Diagnostics's Glucoday<sup>®</sup> is a portable instrument provided with a micropump and a biosensor, coupled to a microdialysis system capable of recording the subcutaneous glucose

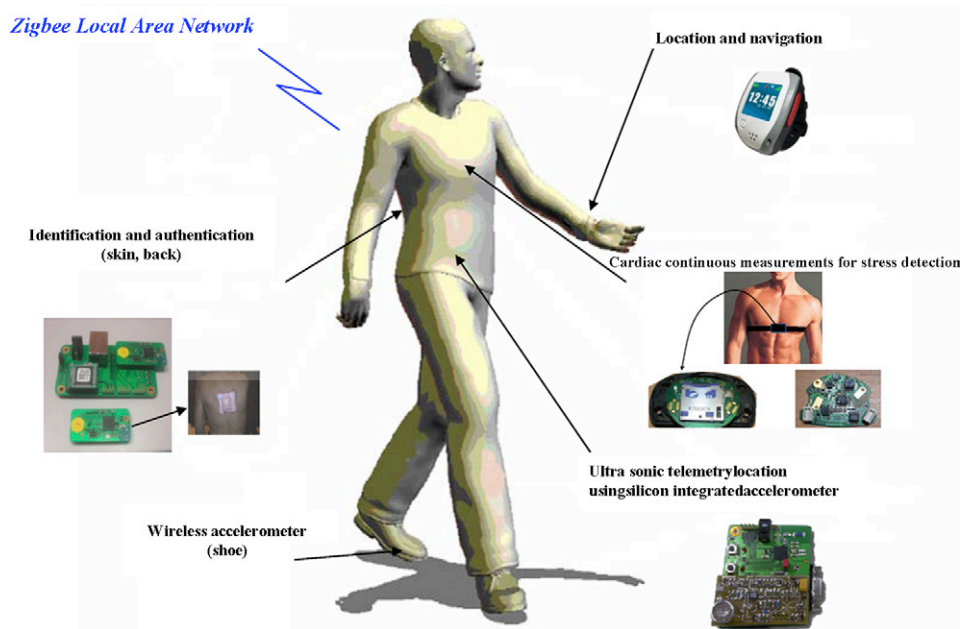


Fig. 1. Wearable systems developed at our laboratory.

level every 3 min [157,158]. Abbott Diabetes care's FreeStyle Navigator<sup>®</sup> uses a glucose oxidase-based electrochemical sensor that is inserted subcutaneously and measures interstitial glucose in a range of 20–500 mg/dL every 1 min (or 1440 readings a day) [159].

A list of wearable systems with the authors, the system descriptions and their applications is presented in Table 4.

#### 4. Current issues with wearable systems

##### 4.1. User needs, perception and acceptance

User preferences for use of SWS in their daily life need to be studied before actual use of these devices becomes more widespread. In order to explore the relationship between the perceived emotions factor and the use of science technology, Davis [160] developed the Technology Acceptance Model (TAM) that shows how users come to accept and use a technology, which is based on important features related to the perceptions, concerns and attitudes of elderly individuals towards SWS and their independence. In an Australian research study, the authors claim that any system or technology that can prolong independence tends to be highly considered and accepted. Their findings indicate that participants' attitudes towards the idea of WSN for HM are generally positive. Moreover, the WSN-based systems (i.e., mote systems having the capability to facilitate the gathering of a range of environmental and structural sensory data such as weight, blood sugar, blood oxygen level, ECG information, EEG information, sound, temperature, humidity, light-intensity, vibration and acceleration) are still under development, and most elderly participants have difficulty fully understanding the benefits that motes can provide. The authors conclude that current acceptance models such as TAM or UTAUT may need to be extended or modified due to the uniqueness of a WSN-based healthcare system designed for elderly users. Furthermore, their study is limited to the area of Sydney, Australia [161]. In [37], researchers found that 93% of patients in a geriatric care facility accepted a wearable system, because it was minimally invasive and did not interfere with their normal daily life. The EPSRC SMART Consortium presented a study in which user feedback was used to

change the design of their devices. User preferences were monitored to improve prototype devices for training stroke patients. New user issues were identified as the system was being developed. Changing a wired version to an unwired one created more complex system management and upkeep from the user. It was also noted that user tolerance of certain systems was reduced when their confidence in the devices decreased, with a key confidence factor being the correct use of the equipment. Data output were affected, and compliance and confidence levels were reduced when patients were unsure how to use the system correctly. Problems were raised in initial and second prototypes, such as correct garment placement. The Consortium discovered the properties of their equipment that needed to be taken into account; namely, compact size, simple to operate and maintain, and usable by stroke patients preferably without the help of the caregiver. The users preferred to receive encouraging feedback data, from the health professionals and quantifiable, objective data about their performance, instead of praise from a physiotherapist [162,163]. Both patients and practitioners using ECG devices were aware of usability and performance issues, including stigmatisation, size and weight of the system, altering normal functional performance, sensors becoming unattached from the patient, and the number of related hospital visits that were needed [164]. In the case of a glove providing functional electrical stimulation of muscles controlling the fingers, the users identified reliability, difficulty in manipulating and placing the electrodes, as well as drying out of electrodes as issues. Some patients found it difficult to set stimulus parameters on the device. Users who were more familiar with consumer electronic devices seemed to have less trouble setting the parameters. Other issues concerned the fit of the device on the arm, and the weight and the size of the system which could limit the type of clothing that the user could wear over the glove [68–70]. In [165], the authors study all questions related to improving the quality of life using wearable systems. They concluded that more investigations with interviews, questionnaires and experiments are needed and that prototypes should be developed with industrial partners and tested in real-world, everyday life settings. Easy-to-use and unobtrusive wearable systems could more easily contribute to user acceptance of these devices in their daily life [166].

**Table 4**  
List of wearable systems.

| Author                    | System description  | Applications  |
|---------------------------|---|---|
| Santini et al. [41]       | Microchip   | Autonomous controlled release implant ('Pharmacy-on-a-chip') or controllable tablet ('smart tablet') for oral drug delivery                                       |
| Curone et al. [43,44]     | 'ProeTEX' smart garment                                       | Health-state parameters, environmental variables  |
| Kario et al. [45]         | Multifunctional device  | Heart rate, physical activity   |
| Gómez et al. [52]         | Pumping, controller and power system                          | Insulin controller to achieve regulation of blood glucose   |
| Fissel et al. [54]        | Unique technology toolkit, MEMS system                        | Membrane prototyped for renal replacement   |
| Okubo et al. [55]         | Home care sensor system                                       | Respiratory diseases  |
| Islam et al. [58]         | Wellness monitor  | Wellness for patients suffering cancer  |
| Akay et al. [59]          | Accelerometer unit  | Body motion in healthy subjects, patients with Parkinson's disease and post stroke hemiplegic patients  |
| Prochazka et al. [68]     | Electrical stimulator garment (glove)                         | Controlled grasp and hand opening in quadriplegia   |
| Lorussi et al. [69]       | Strain sensors integrated in garments (gloves, leotards etc.) | Hand posture and gesture monitoring   |
| Niazmand et al. [70]      | Sensor based smart glove                                      | Parkinson's disease evaluation  |
| Coyle et al. [73]         | Textile-based sensor ('Biotex')                               | Measuring sweat   |
| Katsis et al. [74]        | 'Aubade' sensor system  | EMG, ECG, respiration, skin conductivity (EDR)  |
| Jovanov et al. [77]       | Wireless intelligent sensor system                            | Heart rate variability for stress measuring   |
| Jourand et al. [79]       | Wearable textile garment                                      | Sudden infant death syndrome  |
| Rimet et al. [80]         | Bootee  | Wearable multiparameter monitor   |
| Anliker et al. [81]       | 'Amon' portable telemedical monitor                           | High-risk cardiac/respiratory patients  |
| Wu et al. [83]            | RFID ring-type pulse sensor, optical sensor                   | Pulse and temperature signals, heart rate measures  |
| Haar et al. [84]          | Electronic patch  | EMG, arterial oxygen saturation   |
| Ma et al. [85]            | Electronic second skin  | Antenna, LED, strain gauge, temperature sensor, ECG, EMG, Wireless power coil, RF coil, RF diode  |
| Miwa et al. [86]          | Wearable sensor   | Roll-over detection, sleep quality  |
| Lanata et al. [87]        | Wearable system   | Several vital signs and physiological variables to determine the cardiopulmonary activity during emergencies  |
| Bamberg et al. [88]       | Shoe  | Gait analysis   |
| Simone et al. [90]        | Glove   | Monitoring and functional hand assessment   |
| Beach et al. [91]         | In vivo telemetry system                                      | Improvement of the function of an implant evaluated in situ, in blood vessel growth (angiogenesis), reduced inflammation, reduction of foreign body encapsulation |
| Maqbool et al. [92]       | Smart pill  | Monitoring system with scintigraphy for measuring whole gut transit   |
| Chaudhary et al. [93]     | Biosensor   | Glucose measures  |
| Giorgino et al. [94]      | Sensorized cloth  | Remote monitoring and control of motor rehabilitation   |
| Vivago [102]              | 'Vivago' (Wellness monitoring)                                | Vital signs   |
| Lifeguard [103]           | 'Lifeguard' cigarette pack size box                           | Physiological signs   |
| Sung et al. [104]         | 'LiveNet' mobile platform                                     | Accelerometer, ECG, EMG, galvanic skin conductance  |
| Chang et al. [105]        | Portable system   | PCG, electrocardiography, body temperature, Bluetooth   |
| Jagos et al. [106]        | Shoe  | Human gait  |
| Auranet [107]             | 'Auranet' personal computing devices                          | Cognitive impairments   |
| Riva et al. [108]         | 'Intrepid' multi-sensor context-aware wearable                | Anxiety   |
| Vuorela et al. [110]      | Portable signal recorder                                      | Electrocardiography, bioimpedance and user's activity   |
| MyHeart [111]             | 'MyHeart' clothing  | Atrial fibrillation, ECG, activity  |
| Di Rienzo et al. [112]    | 'MagIC' vest  | Atrial fibrillation, atrial and ventricular ectopic beat, ECG, respiration rate, skin temperature   |
| Luprano et al. [113]      | 'Mer moth' clothes  | ECG, respiratory inductance plethysmography, skin, temperature, activity  |
| Weber et al. [114]        | VTAM clothing   | ECG, GPS, biosensors and bioactuators   |
| Warrior garment [115]     | Warrior garment   | Vital signs   |
| Knight et al. [116]       | 'SensVest'  | Vital signs: movement, energy expenditure, heart rate, body temperature   |
| Borges et al. [117]       | 'Smart-Clothing'  | Fetal movement in the last 4 weeks of the pregnancy   |
| Mithrill [118]            | 'Mithrill'  | Supporting daily use functions: grocery list, messaging, e-mail, conversational note taking, and movie recommendations  |
| Pandian et al. [119]      | 'Smart Vest'  | ECG, PPG, heart rate, systolic and diastolic blood pressure,  |
| Shnayder et al. [120]     | CodeBlue' mote based system                                   | Pulse oximetry, ECG, EMG, mobility activity   |
| Chung et al. [121]        | A u-healthcare system   | ECG, blood pressure patterns transmitted to the hospital  |
| Loew et al. [122]         | 'BASUMA'  | Chronically ill patients  |
| Xiao et al. [123]         | 'MicaZ' mote based system                                     | Heartbeat, ECG, blood pH, glucose, mobility, walking  |
| Guo et al. [124]          | BSN based system  | Vital signs   |
| Oliver et al. [125]       | Wireless medical monitoring system                            | Surgery recovering patients   |
| Verichip [126]            | 'Verichip'  | Patient identity  |
| Schneider et al. [127]    | Implantable sensor  | Nerve stimulation capable of alleviating acute pain in patients suffering cancer or Parkinson's disease   |
| Valdastri et al. [128]    | Implantable telemetry platform system                         | Gastro oesophagus pressure, pH, glucose monitoring  |
| Adler et al. [129]        | Wireless capsule  | Endoscopy   |
| Sieg et al. [130]         | 'Glucowatch Biographer'                                       | Blood glucose measure   |
| Jean et al. [131]         | Microwave sensor  | Blood glucose measure   |
| Jiang et al. [132]        | Carbon nanotube electrode                                     | Glucose concentration in human serum  |
| Bhattacharya et al. [133] | Carbon nanotube based sensor                                  | Detection of viruses  |
| Kawano et al. [134]       | Si microprobe electrode                                       | Neural recording, stimulation of neurons  |
| Cherevko et al. [135]     | Gold nanowire array electrode                                 | Glucose detection   |
| Lu et al. [136]           | Doppler radar system  | Heartbeat measures  |
| Morgan et al. [137]       | Doppler radar system  | Cardiopulmonary sensing   |
| Yazicioglu et al. [138]   | Ultra-low-power biopotential interfaces                       | EEG measure   |
| Hayes et al. [140]        | Probe   | Pulse oximetry, Photoplethysmographic signal or blood volume pulse  |
| Lee et al. [141]          | Wearable or automatic defibrillator                           | Sudden cardiac death  |



Table 4 (Continued)

| Author                  | System description                                  | Applications                                     |
|-------------------------|---|--|
| Bourennane et al. [147] | Identification, location                            | Dangerous events detection                       |
| Bodymedia [151]         | 'Bodymedia' health wear armband                     | Vital signs                                      |
| Vivometrics [152]       | 'LifeShirt'   | Vital signs                                      |
| WelchAllyn [153]        | 'Micropaq' wearable device worn in a carrying pouch | Pulse oximetry, ECG                              |
| Sensatex [154]          | 'SmartShirt'  | Vital signs                                      |
| Cardionet [155]         | 'Cardionet'   | Cardiac patient telemetry system                 |
| Medtronic [156]         | 'CGMS'  | Glucose concentration variation                  |
|                         | 'Guardian'  | Hypo and hyper glucose concentration measurement |
| Poscia et al. [157,158] | 'Glucoday'  | Subcutaneous glucose level measurements          |
| DirecNet [159]          | 'FreeStyle Navigator'                               | Interstitial glucose measurements                |

#### 4.2. Effectiveness

In terms of medical issues and therapeutic effectiveness, there is some evidence regarding telemonitoring using WHMS. In [35], the authors claim that home telemonitoring requires the active participation of the patients. It allows for closer monitoring of each patient's health condition, as well as early detection of warning signs that a patient's health is deteriorating. Their findings suggest that better glycaemic, asthma, and blood pressure control are possible. However, larger randomised trials are needed to confirm the benefits regarding hospitalisations, quality of life, functional capacity, self-monitoring ability and to thoroughly test the efficacy of this technology in home monitoring in the context of patients suffering heart failure. In [48], the authors include therapeutic effects, increased efficiencies in health services, and technical usability. In the case of implantable biosensors, the reliability is often undermined by factors like bio-fouling, material-tissue interaction that results from sensor implantation that is one of the major obstacles in developing viable, long-term implantable biosensors [167,168], and foreign body response [169] in addition to sensor drifts and lack of temporal resolution [170]. Sensors provide excellent temporal and spatial resolution for in vivo monitoring. Advances in applications to measure catecholamines, indoleamines, and amino acids have been important. Improvements in stability, sensitivity, and selectivity of the sensors have been of paramount interest [171]. Several types of interventions were found to be therapeutically effective in programmes for patients suffering from chronic heart failure [172], those needing control of respiratory conditions [173], and patients with diabetes, heart diseases and chronic obstructive pulmonary disease [174]. Both wearable defibrillators and external automatic defibrillators have been shown in a small series of trials to be highly effective at restoring sinus rhythms in patients with ventricular tachyarrhythmia. Most patients enrolled in a trial with pre-specified safety and effectiveness guidelines had been met, with 75% of defibrillation attempts being successful. Only a few inappropriate shock episodes occurred and few deaths (12) occurred during the study, none of these patients died while correctly wearing the device (6 nonsudden deaths, 5 sudden deaths occurred in patients not wearing the device and 1 sudden death occurred in a patient who reversed the leads [175].

#### 4.3. Interoperability

Wearable medical devices such as blood pressure monitors, glucose meters, pulse oximeters, ECG monitors, and implantable cardiovascular electronic devices are essential to healthcare. Interest in these devices will increase if clinical software applications can seamlessly collect the medical data. Industry has already recognised a viable format for clinical applications. The solution proposed involves bilateral mappings from the ISO/IEEE 11073 Domain Information Model (DIM) to HL7 Personal Health Monitoring

Report (PHMR) document format [176]. Some wearable prototypes have begun to use PHMR draft standard to store and transmit training data to health professionals and to maximise interoperability with their information systems [177].

#### 4.4. Hardware and software

The weight of wearable devices is one of the causes of discomfort for users [178]. Other discomfort could be caused by displacement and interruption of monitoring systems due to electrodes using gel-coated adhesive pads. The patients have to wear a bulky monitor for prolonged periods to collect the rare abnormal cardiac events. Moreover, individuals with sensitive skin may develop rashes. The contact resistance between electrodes and skin also changes with time, thereby degrading the quality of the signal collected [119]. Some data are difficult to process due to the devices used. In the case of monitoring user location using infrared sensors, the location data collected are noisy, which affects accuracy [142]. In physiological measurement devices, using textile electrodes does not guarantee that they stay in place firmly during a user's movements. An elastic band and Velcro allow proper pressure between the electrode and the skin so that the impedance block remains stable and low enough to measure bio-impedance [110]. Using Doppler radar signals, estimation of respiration and heart rates is possible when the subject is at rest. However, with dynamic movements, such as when the subject is walking or jogging, the large body movements overwhelm the small respiration and heartbeat signals, making reliable estimation of rates extremely difficult [136,137]. The limitations of the device range from calibration assumptions, optical interference, and signal artefacts which are essentially due to movement of the oximeter probe in relation to the skin. Other sources of errors, such as anaemia or skin pigmentation, are also possible [139]. A new approach for pulse oximetry has been developed to be less sensitive to motion artefacts. The artefacts in the underlying photoplethysmographic signals are reduced in real time, using an electronic processing methodology that is based on inversion of a physical artefact model. The approach provides uninterrupted output and superior accuracy under conditions of sustained subject motion, and widens the clinical scope of the measurement [140]. Wearable devices or systems have to be calibrated and maintained. During the maintenance phase, it is important to properly calibrate the devices or systems. This phase may affect device or system safety and performance. External factors such as energy supply failure, failures due to medical gas and vacuum supplies, environmental parameters (e.g., temperature, humidity, and light) and radio frequency interference can also affect safety. Potential sources of error in the lifecycle of a medical device include pre-purchase evaluation, poor incident reporting, lack of incident investigation, accident investigation, lack or incomplete training, inappropriate use of wearable devices, and improper cleaning, re-use errors (poor sterilization, poor maintenance) [179].

#### 4.5. Medical, wellness, quality of life benefits

The use of intelligent biomedical clothing could reduce the incidence of cardiac diseases by predicting the acute phase of the disease with long-term trend analysis; this can overcome infrequent clinical visits that may fail to detect transient events foreseeing dangerous future events. Early diagnosis through long-term trend analysis reduces the potential severity of a disease. These analyses could provide instant diagnosis of acute events, issue alerts to health care professionals and reduce the time to intervention by telediagnosis and teletherapy. Elderly people can live at home safely. Rehabilitation at home could also be supported [180]. Rehabilitation wearable systems have the potential to monitor the recovery process and to detect improvements or complications as they arise. Patients suffering diabetes could be better managed by continuous non-invasive blood glucose monitoring and insulin delivery [181,182]. Individuals suffering kidney failure need to undergo dialysis in a specialised centre for 3–5 h, three times a week, and exhibit a propensity for cardiovascular disease and infections. Alternatively, they could receive treatment for 6–8 h every day with better outcomes, but this would overwhelm the dialysis centre and severely limit patient activity and mobility. With recent advances in membrane and MEMS technology, patients could benefit from implantable dialysis systems. Wearable and portable artificial kidneys allow patients to have a better quality of life [183]. Patients suffering from respiratory diseases, such as asthma, dyspnea, sleep apnea syndrome, or chronic obstructive pulmonary disease could be monitored for early signs of dangerous symptoms and be treated with mild medicines [55]. The next generation of drug delivery systems is expected to be 'intelligent' and allow therapies that are responsive to specific patient needs. Controlled delivery of appropriate and effective amounts of a drug might be calculated and released or manufactured at an appropriate time [184]. SWS enable individuals suffering from chronic diseases to live at home instead of a nursing home or hospital, satisfying a major desire of elderly people. Healthcare costs are also lower than those accrued by staying in a hospital, institution, or nursing home. Furthermore, it is more practical to measure physiological signs with wearable miniaturised systems during normal life, such as during rest, when sleeping, or during daily activities.

#### 4.6. Cost, psycho-, socio-economic barriers

Wireless pendants, bracelets, or other pieces of jewellery that connect an elderly person to formal or informal caregivers or a call centre, which then can notify ambulance services in the case of an emergency, are affordable and disposable. The technology has been available for 30 years, yet despite its affordability [185], adoption in nearly every country is minimal. Wearing permanent healthcare mobile devices and systems have psychological effects on patients. Significant barriers limit the widespread use of these systems due to lack of studies on smart wearable system tests by end-users providing their feedback and preferences [186]. The high cost of current wearable system services limits their expansion. Wireless networking is another barrier to the deployment of such technology. In France for example, high-speed networks are not available everywhere, and many consumers do not have access to broadband Internet. Therefore, accessing services via the Internet is not a commodity that is always available. Individuals suffering from diseases or injuries could experience problems finding adequate wearable devices and services to support their treatment and healing. Economic and social issues also have to be addressed to ensure the opening of the market to these new technological systems to support people in their efforts to overcome their functional limitations. Some studies provide rough estimates, such as references to the participation of business or to an expected large market for the

systems [187]. A robust analysis of the costs and benefits of wearable systems has not been conducted. Some projects only mention the costs of system components, claiming that a regular widespread operation would shift the costs [188]. The science of sociotechnical design should be taken into consideration so that health care will meet the needs of society. Ultimately, the author in [189] argues that it is our culture's beliefs and values that shape what we will create and what we will dream. Four rules govern the design of health services: (1) Technical systems have strong social consequences. (2) Social systems have technical consequences. (3) We do not design technology; designing sociotechnical systems does not signify designing technology only. (4) The design of sociotechnical systems must consider how individuals and technologies interact.

#### 4.7. Privacy, ethics, and legal barriers

Informational privacy is connected with the confidentiality of patient data, which means that this aspect is going to take on increasing importance in the future with the on-going growth of data processing. The main areas of privacy concern in healthcare delivery are related to data protection and the prevention of information inaccuracies, with people not necessarily having much confidence in the current system [190]. Moreover, records of conversations, location tracking, and monitoring aspects of SWS could have a negative effect on the privacy of the user. The provision of personal communication and security or healthcare assistance through telematic or wearable systems is frequently accompanied by a reduction of direct contact with family members, friends and care personnel. For instance, the provision of remote services via wearable systems and devices could lead to situations of social exclusion of the user if he is prevented or discouraged from performing activities such as work or shopping, because similar activities could be performed in other ways, i.e., remote health assistance, telework, or shopping via the Internet. Ethical considerations have been identified as a major barrier to the delivery of remote healthcare and it is suggested that clear guidelines are needed for providing the privacy, confidentiality and proper user of electronic medical information. Similar issues arise when a large range of wearable system implants and prostheses are used to detect, monitor, and stimulate physiological parameters (e.g., electric brain signals, blood pressure, blood glucose, heart rate, pulmonary rate). They could limit the freedom of the user who might find it difficult to decide what data he or she wants to give to the machine in charge of the monitoring [191]. In [192], the author observes that with a densely populated world of smart and intelligent but invisible communication and computation devices, no single part of our lives will be able to seclude itself from digitisation. Everything we say, do, or even feel, could be digitised, stored, and retrieved anytime later. Smart devices have the alleged ability to create a Big Brother society in which every individual activity is memorised and smart devices attempt to anticipate human thought. The task of lawmakers should be to facilitate and develop approaches that do not obstruct what telemedicine, robotics [193], and SWS have to offer. The authors in [193] claim that working across jurisdictional boundaries can afford the best of diagnostic, therapeutic and surgical treatments to patients in the most remote locations. Without leaving their own workplaces, physicians can make their skills available in other countries and continents. The European Union has harmonised laws in matters of trade in goods and services. From this perspective, 'Rome II' in the same spirit of 'The Rome Convention' promotes the free movement of persons, goods and services [193]. In [194], the authors give an overview of legal and ethico-legal issues in e-healthcare research projects in the UK. They provide data concerning legal hurdles and issues faced by the analysed projects and consider some of the proposals put forward to overcome them. In [195], the authors consider

that the barriers greatly impeding the potential of eHealth to help solve the healthcare crisis can only be removed in a timely manner by a comprehensive national framework. In this way, the legal, operational, and economic landscape for eHealth is reshaped. The failure of the health information technology market is preventing U.S. health care from delivering high quality care to all Americans at reasonable cost [196]. Judicious and gently applied government intervention can give the extra assistance needed to boost HIT adoption nationwide [197].

#### 4.8. Impact of wearable systems on society

Wearable health systems are thought to have the potential to improve health in a cost-efficient manner. Research on the use of wearable health care systems has recognised several functional and technological requirements, but relatively little is known about factors that affect their commercialisation, market penetration, and adoption by users. Little has been done in clinical validation and in thorough analysis of user requirements of wearable systems that may have a significant impact on user acceptance, on health professionals' community, and on the decision makers. Personal monitoring systems on the market today provide mainly instantaneous single-parameter assessment and transmission. Wearable systems capable of continuously monitoring vital signs are limited ('Lifeshirt' [152], 'Vivago WristCare' [102]) or under development (i.e., 'Biotex' [75], 'ProeTEX' [43,44]). There is currently no smart wearable system on the market integrating several biosensors, intelligent processing and alerts to support medical applications while interacting with health providers. In the case of dialysis, the use of a wearable artificial kidney may decrease the expense of uraemia therapy [198]. The impact on societies such as China of using wearable systems and body area networks may contribute to lower healthcare costs by introducing preventive healthcare strategies, developing advanced technologies to cut equipment and labour costs, inventing new techniques for precise diagnosis and targeted therapy, streamlining diagnostic procedures, introducing a balanced contribution system for relevant parties, and eliminating unnecessary health services [199]. An important feature of wearable systems is the enhancement of the quality of life of the elderly, handicapped, or those suffering from chronic diseases [200]. Expected economic benefits from the implementation of wearable and pervasive health care systems have been predicted that would have a considerable impact on the finances of societies with a shortage of personnel for taking care of the elderly or chronically ill [201]. Authors in [202] claim that telehomecare may improve patients outcomes through timely intervention and health crises prevention, thus cutting visits to physicians' offices and hospitals. However, better understanding of the conditions for their integration, wide spread and judicious adoption into existing practices are needed. The success of implementing telehomecare depends on local context in which the technology emerges.

### 5. Challenges and future perspectives

To fully realise the health and wellness benefits of smart wearable technologies, researchers and providers have to work towards adoption of these technologies by studying user requirements and developing a comprehensive approach to health and wellness services, instead of devices and applications that monitor only single diseases. At the same time, researchers and providers have to deliver health services using a wide variety of sources from traditional health providers to commercial providers in close contact with users. Wireless, phone, and cable providers, and other communications companies could provide access to the home and provide

billing for services (e.g., social alarms, HM or other distant care giving services). Employers could become potential financial partners for SWS as they face increasing employee absences to care for elderly family members. In Europe, the United States, and Japan, people are more aware of their wellness and vitality. Product offers and user demands are low for devices promoting disease prevention, and consequently, penetration into the public market is low. Developing an integrated architecture of intelligent home services with wearable systems and devices for home comfort, health and wellness are without a doubt one of the key solutions to maintain and boost research and development [89]. Academic research must tackle issues such as:

- System efficiency, reliability, and unobtrusiveness: These are essential for the widespread use of devices and technologies. Wearable systems and devices must have efficient software and hardware and be unobtrusive [203].
- User needs and privacy: At times, there is tension between assistance and autonomy, or privacy and independence that characterises the individual's judgment in using telehealth technology [204].
- User perception and acceptance: Elderly users perceive independence and autonomy as crucial for their everyday life, so that any systems or technology that can prolong that independence tends to be highly considered, and the privacy of WSN health data might not be as important as typically understood [161].
- Legislation [193]: Complex situations may occur in telehealth practice when health care professionals begin to render services through electronic technology, such as over the Internet; the impact of those services may be felt in whatever state or country the individual resides. The regulation affects the health care professional and the recipient of the services. The situation becomes more complex when those individuals do not live in the same country, for example; licensure, certification, and protection must be standardised in terms of laws inside the European Communities [205].
- Interoperability: As health care develops from an organisation-centred via service-centred towards an individual-centred system, information systems involved must be semantically interoperable, process-related, decision-supportive, context-sensitive, user-oriented, and trustworthy [206].
- Services: Integrating sustainable and beneficial telehomecare services require key internal and external stakeholders involved in the beginning of the project of the delivery of services to the elderly [207].
- Reimbursement or cost: This may be the most prominent determinant influencing elderly acceptance of technology, such as telemedicine that has been available for 30 years [208]. Private insurance companies may partially support health care costs. As in the case of telemedicine, economic evaluation of wearable systems still has room for improvement [209].
- End-user training to use wearable systems: As in Telemedicine, addressing technological barriers is one of the necessary conditions for its diffusion [210].
- Social inclusion: The authors in [211] consider that telecare introduces risks of increased isolation of users and healthcare professionals and providers through decreased physical face-to-face interaction with caregivers and physicians.
- Ethical issues: Overcoming the barriers will be difficult and could require subsidies and performance incentives by payers (i.e., purchasers including physicians, health plans, employers) and the government (national social insurance program) [212].
- Technological capabilities of wearable systems: They must meet healthcare professionals and end-users requirements in disease management and general remote HM.



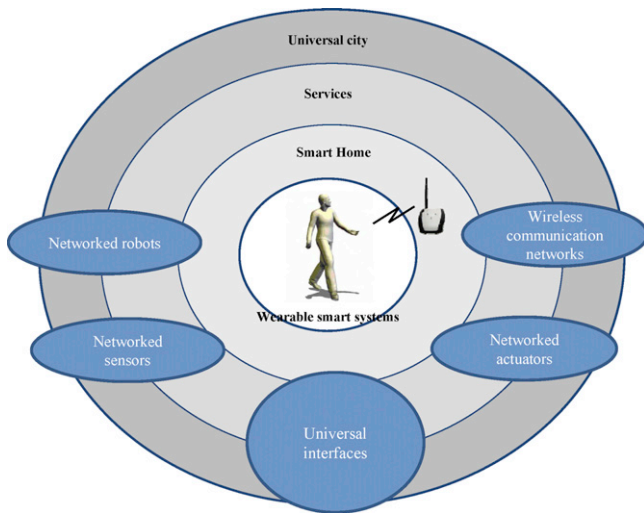


Fig. 2. Key technologies for organization of healthcare in a city.

- Interactive relationship: Research focusing on relationship between patients, professionals and healthcare providers are needed [202].
- Wearable system market penetration: The government may need to intervene to address the failure of the health information technology market [213].
- The global vision of key technologies for healthcare organisation for elderly and handicapped people in a universal city is shown in Fig. 2.

Wireless networks are now available in most urban areas. Every building, from a school to a coffee house now has an antenna, even most children have a cell phone to keep in touch with their family. In a digital city, with the advances in MEMS devices, smart phones and smart wearable health systems, an individual living at home would be surrounded by a lot of information to be shared, have access to usable information, and could be monitored and be rescued in case of health emergencies [214].

## 6. Conclusions

The aim of this study was to provide an overview of the current status and future perspectives in research and development of wearable systems related to healthcare. For this goal, it was necessary to define the field of wearable systems. These systems may include anything from monitoring the elderly or patients undergoing surgical operations to advanced sensor supervision in the case of infant respiratory disorders or soldiers on the battlefield. Pharmaceutical companies are now undergoing a sort of revolution of their practice. In the past, they used to produce revolutionary molecules to treat diseases (i.e., cardiovascular disease, diabetes, respiratory diseases, and renal diseases). With recent advances in new materials (i.e., membrane, textile, fabrics), electronics and telecommunication information technology, treatment with pharmaceutical products has become more accurate with continuous automatic processes to dispense an effective dose of drug to treat disease or in vivo, implantable wearable devices to replace defective organs. Wearable systems feature a broad and heterogeneous range of devices, WSN standards, applications, and involve the efforts or numerable researchers, developers and users. Due to its interdisciplinary nature, a number of applications related to health care integrate biomedical engineering and medical informatics. Other knowledge in the fields of medicine, social sciences, psychology, economics, ethics, and law must be taken into account and

be integrated into the development and deployment of wearable healthcare systems. Most systems are still in their prototype stages, and developers have not yet faced deployment issues. Information technology and electronics are mature fields and can provide viable, disposable, and affordable wearable systems. Identifying the lack of deployment issues such as service organisation, privacy, user needs, acceptance, system security and safety, and economic and financial issues presents the paramount research focus over the next few decades. Systematic evaluations of the effectiveness and efficiency of wearable health care systems are considered crucial to ensure potential user acceptance. Along with these perspectives, several technical as well as medical issues have to be solved before definite clinical trials can be conducted. The most important challenges are the development of smart signal processing, data analysis and interpretation, communication standards interoperability, electronic components efficiency, and energy supply.

## Conflict of interest

The authors state no conflict of interest.

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## References

- [1] Lukowicz P, Kirstein T, Tröster G. Wearable systems for health care applications. *Methods of Information in Medicine* 2004;43:232–8.
- [2] Konstantas D. An overview of wearable and implantable medical sensors. In: IMIA year book of medical informatics; 2007 p. 66–9.
- [3] Lymberis A, Dittmar A. Advanced wearable health systems and applications, research and development efforts in the European Union. *IEEE Engineering in Medicine and Biology Magazine* 2007;May/June:29–33.
- [4] Muir Gray JA. Better value healthcare – the 21st century agenda. *Zeitschrift für ärztliche Fortbildung und Qualität im Gesundheitswesen – German Journal for Quality in Health Care* 2007;101(5):344–6.
- [5] Kalache A. Ageing worldwide. In: Ebrahim S, Kalche A, editors. *Epidemiology in old age*. London: BMJ; 1996. p. 22–31.
- [6] Hedda Agüero-Torres H, von Strauss E, Viitanen M, Winblad B, Fratiglioni L. Institutionalization in the elderly: the role of chronic diseases and dementia. Cross-sectional and longitudinal data from a population-based study. *Journal of Clinical Epidemiology* 2001;54:795–801.
- [7] McCann M, Donnelly M, O'Reilly D. Living arrangements, relationship to people in the household and admission to care homes for older people. *Age and Ageing* 2011;40:358–63.
- [8] Eloranta S, Arve S, Isoaho H, Routasalo P. Home care from the perspective of older clients and their professional carers. *Archives of Gerontology and Geriatrics* 2010;51(10):180–4.
- [9] Ribbe MW, Ljunggren G, Steel K, Topinková E, Hawes C, Ikegami N, et al. Nursing homes in 10 nations: a comparison between countries and settings. *Age and Ageing* 1997;26(S2):3–12.
- [10] Huber M, Orsz E. Health expenditure trends in OECD countries, 1990–2001. *Health Care Financing Review* 2003;25(Fall (1)):1–22. <http://www.oecd-ilibrary.org/> [accessed 06.03.12].
- [11] Stowe S, Harding S. Technology applied to geriatric medicine, telecare, telehealth and telemedicine. *European Geriatric Medicine* 2010;1:193–7.
- [12] Moehr JR, Schaafsma J, Anglin C, Pantazi SV, Grimm NA, Anglin S. Success factors for telehealth—a case study. *International Journal of Medical Informatics* 2006;75:755–63.
- [13] Gatzoulis L, Iakovidis I. Wearable and portable eHealth systems. *IEEE Engineering in Medicine and Biology Magazine* 2007;September/October:51–6.
- [14] Tröster G. The agenda of wearable healthcare. In: Haux R, Kulikowski C, editors. *IMIA yearbook of medical informatics 2005: ubiquitous health care systems*. Stuttgart: Schattauer; 2004. p. 125–38.
- [15] Richards Grayson AC, Scheidt Shawgo R, Li Y, Cima MJ. Electronics MEMS for triggered delivery. *Advanced Drug Delivery Reviews* 2004;56:173–84.
- [16] Lee TMH. Over-the-counter biosensors: past, present and future. *Sensors* 2008;8:5535–59.
- [17] Micera S, Keller Lawrence M, Morari M, Popovic DB. Wearable neural prostheses, restoration of sensory-motor function by transcutaneous electrical stimulation. *IEEE Engineering in Medicine and Biology Magazine* 2010;29(3):64–9.



- [19] Kluge EHW. Ethical and legal challenges for health telematics in a global world: telehealth and the technological imperative. *International Journal of Medical Informatics* 2011;80(2):1–5.
- [20] Brey P. Freedom and privacy in ambient intelligence. *Ethics and Information Technology* 2006;7(3):157–66.
- [21] Stanberry B. Legal ethical and risk issues in telemedicine. *Computer Methods and Programs in Biomedicine* 2001;1:225–33.
- [22] Giroux S, Pigot H, editors. From smart homes to smart care: ICOST 2005. Assistive technology and research series. Fairfax, VA: IOS Press; 2005.
- [23] Abowd GD, Hayes GR, Iachello G, Kientz JA, Patel SN, Stevens MM, et al. Prototypes and paratypes: designing mobile and ubiquitous computing applications. *IEEE Pervasive Computing* 2005;4(May/June (4)):67–73.
- [24] Rhodes B, Mase K. Wearable in 2005. *IEEE Pervasive Computing* 2006;5(January/March (1)):92–5.
- [25] Paradiso J, Borriello G, Bonito P. Implantable electronics. *IEEE Pervasive Computing* 2008;7(January/March (1)):12–3.
- [26] Yang GZ, editor. Body sensor networks. London, UK: Springer-Verlag; 2006.
- [27] ESTO. Science and technology roadmapping: ambient intelligence in everyday life (Aml@Life). Seville, Spain: Joint Research Fraunhofer Institute Systems and Innovation Research/Institute Prospective Technology Studies; 2003.
- [28] Baronti P, Pillai P, Chook VWC, Chessa S, Gotta A, Fu YF. Wireless sensor networks: a survey on the state of the art and the 802.15.4 and ZigBee standards. *Computer Communication* 2007;30:1655–95.
- [29] Ciuti G, Mencassi A, Dario P. Capsule endoscopy: from current achievements to open challenges. *IEEE Reviews in Biomedical Engineering* 2001;4:59–72.
- [30] Smith D. Smart clothes and wearable technology. *AI & Society* 2007;22:1–3.
- [31] Roggen D, Magnenat S, Waibel M, Tröster G. Wearable computing. *IEEE Robotics & Automation Magazine* 2011;18(June (2)):83–95.
- [32] Holmström I, Röing M. The relation between patient-centeredness and patient empowerment: a discussion on concepts. *Patient Education and Counseling* 2010;79:167–72.
- [33] Suter P, Suter WN, Jonston D. Theory-based telehealth and patient empowerment. *Population Health Management* 2011;14(2):87–92.
- [34] Paget T, Jones C, Davies M, Evered C, Lewis C. Using home telehealth to empower patients to monitor and manage long term conditions. *Nursing Times* 2010;106(45):17–9.
- [35] Paré G, Moqadem K, Pineau G, St-Hilaire C. Effets du télémonitorage dans la prise en charge du diabète. *Médecine des Maladies Métaboliques* 2010;4:257–62.
- [36] Della Vecchia G, Gallo L, Esposito M. An infrastructure for smart hospitals. *Multimedia Tools and Applications* 2012;59:341–62.
- [37] Fraile JA, Corchado JM, Abraham A. Applying wearable solutions in dependent environments. *IEEE Transactions on Information Technology in Biomedicine* 2010;14(6):1459–67.
- [38] Oudin Åström D, Forsberg B, Rocklöv J. Heat wave impact on morbidity and mortality in the elderly population: a review of recent studies. *Maturitas* 2011;69:99–105.
- [39] Malic L, Brassard D, Veres T, Tabrizian M. Integration and detection of biochemical assays in digital microfluidic LOC devices. *Lab on Chip* 2010;10:418–31.
- [40] Ronkainen NJ, Halsall HB, Heineman WR. Electrochemical biosensors. *Chemical Society Reviews* 2010;39:1747–63.
- [41] Santini JT, Cima MJ, Langer R. A controlled-release microchip. *Nature* 1999;397:335–8.
- [42] Mahfouz MR, To G, Kuhn MJ. Smart instruments: wireless technology invades the operating room. In: Proc IEEE topical conference on biomedical wireless technologies, networks, and sensing systems. 2012. p. 33–6.
- [43] Curone D, Dudnik G, Loriga J, Luprano G, Magenes R, Paradiso A, et al. Smart garments for safety improvements of emergency/disaster operators. In: Proc 29th annual international conference of the IEEE EMBS. 2007. p. 3962–5.
- [44] Curone D, Secco EL, Tognetti A, Loriga G, Dudnik G, Risatti M, et al. Smart garments for emergency operators: the Proetex project. *IEEE Transactions on Information Technology in Biomedicine* 2010;14(3):694–701.
- [45] Kario K, Yasui N, Yokoi H. Ambulatory blood pressure monitoring for cardiovascular medicine. *IEEE Engineering in Medicine and Biology Magazine* 2003;May/June:81–8.
- [46] Hudson LR, Brent Hamar G, Orr P, Johnson JH, Neftzger A, Chung RS, et al. Remote physiological monitoring: clinical, financial, and behavioral outcomes in a heart failure population. *Disease Management* 2005;8(6):372–81.
- [47] <http://www.who.int/> [accessed 05.07.12].
- [48] Maric B, Kaan A, Ignaszewski A, Lear SA. A systematic review of telemonitoring technologies in heart failure. *European Journal of Heart Failure* 2009;11:506–7.
- [49] Grange EF, Warren V, Khemka S, Theodorou AN, Vallance-Owen AJ. The role of telemedicine in helping to manage hypertension – a review of health outcomes and cost benefit. In: Proc international conference on eHealth, telemedicine, and social medicine. 2009. p. 204–8.
- [50] Kappiarukudil KJ, Vinodini Ramesh M. Real-time monitoring and detection of “heart attack” using wireless sensor networks. In: Proc 4th international conference on sensor technologies and applications, SENSORCOMM. 2010. p. 632–6.
- [51] Guerci B, Böhm P, Halter C, Bourgeois C. Capteurs de glucose et mesure continue du glucose. *Médecine des Maladies Métaboliques* 2010;4(2):157–68.
- [52] Gómez EJ, Hernando Pérez ME, Vering T, Rigla Cros M, Bott O, García-Sáez G, et al. The INCA system: a further step towards a telemedical artificial pancreas. *IEEE Transactions on Information Technology in Biomedicine* 2008;12(4):470–9.
- [53] The D&T report. In: MacReady N. (Section Ed.) The future of renal replacement therapy. *Dialysis & Transplantation* 2010;39(5):178–81.
- [54] Fissell WH, Fleischman AJ, Humes HD, Roy S. Development of continuous implantable renal replacement: past and future. *Translational Research* 2007;150(6):327–36.
- [55] Okubo M, Imai Y, Ishikawa T, Hayasaka T, Ueno S, Yamaguchi T. Development of automatic respiration monitoring for home-care patients of respiratory diseases with therapeutic aids. In: Proc ECIFMBE 2008, IFMBE proceedings, vol. 22. Berlin Heidelberg: Springer-Verlag; 2008. p. 1117–20.
- [56] Catrysse M, Puers R, Hertleer C, Van Langenhove L, van Egmond MD. Towards the integration of textile sensors in a wireless monitoring suit. *Sensors and Actuators A* 2004;114:302–11.
- [57] Schwiebert L, Gupta SKS, Weinmann J. Research challenges in wireless networks of biomedical sensors. In: Proc international conference on mobile computing and networking (MOBICOM 2001). 2001. p. 151–65.
- [58] Islam R, Ahamed SI, Talukder N, Obermiller I. Usability of mobile computing technologies to assist cancer patients. In: Holzinger A, editor. *USAB 2007. Lecture notes in computer science (including subseries Lecture notes in artificial intelligence and lecture notes in bioinformatics)*, LNCS, vol. 4799. Berlin, Heidelberg: Springer-Verlag; 2007. p. 217–24.
- [59] Akay M, Tamura T, Higashi Y, Fujimoto S. Unconstrained monitoring of body motion during walking. *IEEE Engineering in Medicine and Biology Magazine* 2003;22(3):104–9.
- [60] Lorusi F, Galatolo S, De Rossi DE. Textile-based electrogoniometers for wearable posture and gesture systems. *IEEE Sensors Journals* 2009;9(9):1014–24.
- [61] Culhane KM, O'Connor M, Lyons D, Lyons GM. Accelerometers in rehabilitation medicine for older adults. *Age and Ageing* 2005;34:556–60.
- [62] Gabaglio V, Merminod B. Using satellite positioning systems and inertial sensors for human navigation. In: Proc European symposium on global navigation satellite systems. 2000.
- [63] Halliday AJ, Mouton SE, Wallace GC, Cook MJ. Novel methods of antiepileptic drug delivery – polymer-based implants. *Advanced Drug Delivery Reviews* 2012. <http://dx.doi.org/10.1016/j.addr.2012.04.004>.
- [64] Pathan SA, Jain GK, Akhter S, Vohora D, Ahmad FJ, Khar RK. Insights into the novel three ‘D’s of epilepsy treatments: drugs, delivery systems, and devices. *Drug Discovery Today* 2010;15(17/18):717–32.
- [65] Wong HL, Wu XY, Bendayan R. Nanotechnological advances for the delivery of CNS therapeutics. *Advanced Drug Delivery Reviews* 2012;64:686–700.
- [66] Oskeoei MA, Hu H. Myoelectric control systems—a survey. *Biomedical Signal Processing and Control* 2007;2:275–94.
- [67] Tognetti A, Lorusi F, Bartalesi R, Quaglioni S, Tesconi M, Zupone G, et al. Wearable kinesthetic system for capturing and classifying upper limb gesture in post-stroke rehabilitation. *Journal of NeuroEngineering and Rehabilitation* 2005;2(8). <http://dx.doi.org/10.1186/1743-0003-2-8>.
- [68] Prochazka A, Gauthier M, Wieler M, Kenwell Z. The bionic glove: an electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia. *Archives of Physical Medicine and Rehabilitation* 1997;78(6):608–14.
- [69] Lorusi F, Scilingo EP, Tesconi M, Tognetti A, De Rossi D. Strain sensing fabric for hand posture and gesture monitoring. *IEEE Transactions on Information Technology and Biomedicine* 2005;9(3):372–81.
- [70] Niazmand K, Tonn K, Kalaras A, Fietzek UM, Mehrkenn JH, Lueth TC. Quantitative evaluation of Parkinson’s disease using sensor based smart glove. In: Proc 24th international symposium on computer-based medical systems (CBMC 2011). 2011.
- [71] Pancrazio JJ, Hunter Peckham P. Neuroprosthetic devices: how far are we from recovering movement in paralyzed patients? *Expert Review of Neurotherapeutics* 2009;9(4):427–30.
- [72] Nusser M, Senner V. High-tech – textiles in competition sports. *Procedia Engineering* 2010;2:2845–50.
- [73] Coyle S, Morris D, Lau KT, Diamond D, Moyna N. Textile-based wearable sensors for assisting sports performance. In: Proc BSN 2009 – body sensor networks. 2009.
- [74] Katsis CD, Goletsis Y, Rigas G, Fotiadis DI. A wearable system for the affective monitoring of car racing drivers during simulated conditions. *Transportation Research Part C* 2011;19:541–51.
- [75] Coyle S, Lau KT, Moyna N, O’Gorman D, Diamond D, Di Francesco F, et al. BIOTEX—biosensing textiles for personalized healthcare management. *IEEE Transactions on Information Technology in Biomedicine* 2010;14(2):364–70.
- [76] Morris D, Coyle S, Wu YZ, Lau KT, Wallace G, Diamond D. Bio-sensing textile based patch with integrated optical detection system for sweat monitoring. *Sensors and Actuators B: Chemical* 2009;139:231–6.
- [77] Jovanov E, O’Donnell Lords A, Raskovic D, Cox PG, Adhami R, Andrasik F. Stress monitoring using a distributed wireless intelligent sensor system. *IEEE Engineering in Medicine and Biology Magazine* 2003;May/June:49–55.
- [78] Picard RW, Vyzas E, Healey J. Toward machine emotional intelligence: analysis of affective physiological state. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 2001;23(10):1175–91.
- [79] Jourand P, De Clerc H, Puers R. Robust monitoring of vital signs integrated in textile. *Sensors and Actuators A: Physical* 2010;161:288–96.

- [80] Rimet Y, Brusquet Y, Ronayette D, Dageville C, Lubrano M, Mallet E, et al. Surveillance of infants at risk of apparent life threatening events (ALTE) with the BBA bootee: a wearable multiparameter monitor. In: Proc 29th annual international conference of the IEEE EMBS. 2007. p. 4997–5000.
- [81] Anliker U, Ward JA, Lukowicz P, Tröster G, Dolveck F, Baer M, et al. Amon: a wearable multiparameter medical monitoring and alert system. IEEE Transactions on Information Technology in Biomedicine 2004;8(4): 415–27.
- [82] Loseu V, Ghasemzadeh H, Ostadabbas S, Raveendranathan N, Malan J, Jafari R. Applications of sensing platforms with wearable computers. In: Proc 3rd international conference on pervasive technologies related to assistive environments, PETRA 2010. 2010.
- [83] Wu YC, Chen PF, Hu ZH, Chang CH, Lee GC, Yu WC. A mobile health monitoring system using RFID ring-type pulse sensor. In: Proc 8th IEEE international conference on dependable, autonomic and secure computing. 2009.
- [84] Haahr RG, Duun S, Thomsen EV, Hoppe K, Branebjerg J. A wearable “electronic patch” for wireless continuous monitoring of chronically diseased patients. In: Proc 5th international workshop on wearable and implantable body sensor networks, in conjunction with the 5th international summer school and symposium on medical devices and biosensors. 2008.
- [85] Ma Z. An electronic second skin. Science 2011;333:830–1.
- [86] Miwa H, Sasahara SI, Matsui T. Roll-over detection and sleep quality measurement using a wearable sensor. In: Proc 29th annual international conference of the IEEE EMBS. 2007. p. 1507–10.
- [87] Lanatà A, Scilingo EP, De Rossi D. A multimodal transducer for cardiopulmonary activity monitoring in emergency. IEEE Transactions on Information Technology in Biomedicine 2010;14(3):817–25.
- [88] Bamberg SJM, Benhasat AY, Scarborough DM, Krebs DE, Paradiso JA. Gait analysis using a shoe-integrated wireless sensor system. IEEE Transactions on Information Technology in Biomedicine 2008;12(4):413–23.
- [89] Coughlin JF. Disruptive demographics, design and the future of everyday environments. Design Management Review 2007;18(2):53.
- [90] Simone LK, Sundararajan N, Luo X, Jia Y, Kamper DG. A low cost instrumented glove for extended monitoring and functional hand assessment. Journal of Neuroscience Methods 2007;160:335–48.
- [91] Beach RD, Moussy F. Totally implantable real-time *in vivo* video telemetry monitoring system for implant biocompatibility studies. IEEE Transactions on Instrumentation and Measurement 2001;50(3):716–23.
- [92] Maqbool S, Parkman HP, Friedenbergh FK. Wireless capsule motility: comparison of the SmartPill® GI monitoring system with scintigraphy for measuring whole gut transit. Digestive Diseases and Sciences 2009;54(10):2167–74.
- [93] Chaudhary A, McShane MJ, Srivastava R. Glucose response of dissolved-core alginate microspheres: towards a continuous glucose biosensor. Analyst 2010;135(10):2620–80.
- [94] Giorgino T, Tormene P, Lorussi F, De Rossi D, Quaglini S. Sensor evaluation for wearable strain gauges in neurological rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering 2009;17(4):409–15.
- [95] Schmidt A, Strohbach M, van Laerhoven K, Friday A, Gellersen H-W. Context acquisition based on load sensing. In: Borriello G, Holmquist LE, editors. Ubiquitous computing. Proc of Ubicomp 2002. LNCS, vol. 2498. Heidelberg: Springer-Verlag; 2002. p. 333–51.
- [96] Cook DJ, Augusto JC, Jakkula VR. Ambient intelligence: technologies, applications, and opportunities. Pervasive and Mobile Computing 2009;5: 277–98.
- [97] Coughlin JF, Pope J. Innovations in health, wellness, and aging-in-place. IEEE Engineering in Medicine and Biology Magazine 2008;July/August:47–52.
- [98] Singh D, Lee HJ, Chung WY. An energy consumption technique for global healthcare monitoring applications. In: Proc 2nd international conference on interaction sciences: information technology, culture and human. 2009. p. 539–42.
- [99] Kumar RM, Singh AN, Vasanthi V, Bharati B, Hemalatha M. 4G – fourth generation wireless systems requirements and technical challenges. Journal of Theoretical and Applied Information Technology 2011;31(1): 29–35.
- [100] Istepanian RSH, Jovanov E, Zhang TY. Beyond seamless mobility and global wireless health-care connectivity. IEEE Transactions on Information Technology in Biomedicine 2004;8(4):405–14.
- [101] Cova G, Xiong H, Gao Q, Guerrero E, Ricardo R. A perspective of state-of-the-art wireless technologies for e-health applications. In: Proc international IEEE symposium on IT in medicine and education (ITME 09). 2009. p. 76–81.
- [102] <http://www.vivago.fr/> [accessed 05.07.12].
- [103] <http://simson.net/ref/2004/csci.e-170/handouts/final/sanj1-spargos.1.paper.pdf> [accessed 05.07.12].
- [104] Sung M, Marci C, Pentland A. Wearable feedback systems for rehabilitation. Journal of Neuroengineering and Rehabilitation 2005;2:17.
- [105] Chang JR, Tai CC. A new wireless-type physiological signal measuring system using a PDA and the Bluetooth technology. Biomedical Engineering Applications, Basis & Communications 2005;17:229–35.
- [106] Jagos H, Oberzaucher J. Development of a wearable measurement system to identify characteristics in human gait – eSHOE. In: Proc ICCHP 2008. 2008. p. 1301–4.
- [107] <http://www.cs.uoregon.edu/research/wearables/> [accessed 05.07.12].
- [108] Riva G, Gorini A, Gaggioli A. The Intrepid project – biosensor-enhanced virtual therapy for the treatment of generalized anxiety disorders. Studies in Health Technology and Informatics 2009;142:155–60.
- [109] <http://www.ehealthnews.eu/aubade/> [accessed 05.07.12].
- [110] Vuorela T, Seppä VP, Vanhala J, Hyttinen J. Design and implementation of a portable long-term physiological signal recorder. IEEE Transactions on Information Technology in Biomedicine 2010;14(3):718–25.
- [111] MyHeart: fighting cardio-vascular diseases by preventive lifestyle & early diagnosis. Available from: <http://www.hitech-projects.com/euprojects/myheart/> [accessed 05.07.12].
- [112] Di Rienzo M, Rizzo F, Meriggi P, Castiglioni P, Mazzoleni P, Ferrarin M, et al. MagIC: a textile system for vital signs monitoring. Advancement in design and embedded intelligence for daily life applications. In: Proc 29th annual international conference of the IEEE EMBS. 2007.
- [113] Luprano J. European projects on smart fabrics, interactive textiles: sharing opportunities and challenges. In: Proc workshop on wearable technology and intelligent textiles. 2006.
- [114] Weber JL, Blanc D, Dittmar A, Comet B, Corroy C, Noury N, et al. Telemonitoring of vital parameters with newly designed biomedical clothing VTAM. In: Proc new generation wearable systems EHealth international workshop. 2003. p. 258–64.
- [115] <http://www.fas.org/man/dod-101/sys/land/land-warrior.htm/> [accessed 05.07.12].
- [116] Knight JF, Schwirtz A, Psomadellis F, Baber C, Bristow HW, Arvanitis TN. The design of the SensVest. Personal and Ubiquitous Computing 2005;9:6–19.
- [117] Borges LM, Rente A, Velez FJ, Salvado LR, Lebres AS, Oliveira JM, et al. Overview of progress in Smart-Clothing project for health monitoring and sport applications. In: Proc 1st international symposium on applied sciences in biomedical and communication technologies. 2008.
- [118] <http://www.media.mit.edu/wearables/mithril/> [accessed 05.07.12].
- [119] Pandian PS, Mohanavelu K, Saeef KP, Kotresh TM, Shakunthala DT, Gopal P, et al. Smart Vest: wearable multi-parameter remote physiological monitoring system. Medical Engineering & Physics 2008;30:466–77.
- [120] Shnyder V, Chen BR, Lorincz K, Fulford-Jones TRF, Welsh M. Sensor networks for medical care. Division Eng. Appl. Sci. Harvard University, Cambridge, MA, technical report TR-08-05; 2005.
- [121] Chung WY, Lee SC, Toh SH. WSN based mobile u-healthcare system with ECG, blood pressure measurement function. In: Proc 30th annual international conference of the IEEE EMBS. 2008. p. 1529–32.
- [122] Loew N, Winzer KJ, Becher G, Schönfuß D, Falck T, Ulrich G, et al. Medical sensors of the BASUMA body sensor network. In: Proc 4th international workshop on wearable and implantable body sensor networks. 2007. p. 171–6.
- [123] Xiao S, Dhamdhare A, Sivaraman V, Burdett A. Transmission power control in body area sensor networks for healthcare monitoring. IEEE Journal on Selected Areas in Communications 2009;27(1):37–48.
- [124] Guo DG, Tay FEH, Xu L, Yu LM, Nyan MN, Chong FW, et al. Characterization and fabrication of novel micromachined electrode for BSN-based vital signs monitoring system. In: Proc sixth international workshop on body sensor networks. 2009.
- [125] Oliver N, Mangas FF. HealthGear: a real-time wearable system for monitoring and analyzing physiological signals. In: Proc international workshop on body sensor networks. 2006.
- [126] Sullivan F, Wyatt JC. ABC of health informatics, why is this patient here today? BMJ 2005;331:678–80.
- [127] Schneider A, Stieglitz T. Implantable flexible electrodes for functional electrical stimulation. Medical Device Technology 2004;15(1):16–8.
- [128] Valdastrì P, Menciassi A, Arena A, Caccamo C, Dario P. An implantable telemetry platform system for *in-vivo* monitoring of physiological parameters. IEEE Transactions on Information Technology in Biomedicine 2002;8(3): 271–8.
- [129] Adler DG, Gostout CJ. Wireless capsule endoscopy. Hospital Physician 2003;May:14–22.
- [130] Sieg A, Guy RH, Delgado-Charro MB. Simultaneous extraction of urea and glucose by reverse iontophoresis *in vivo*. Pharmaceutical Research 2004;21(10):1805–10.
- [131] Jean B, Green E, McClung M. A microwave frequency sensor for non-invasive blood-glucose measurement. In: Sensors applications symposium, SAS 2008. 2008. p. 4–7.
- [132] Jiang LC, Zhang WD. A highly sensitive nonenzymatic glucose sensor based on CuO nanoparticles-modified carbon nanotube electrode. Biosensors and Bioelectronics 2010;25:1402–7.
- [133] Bhattacharya M, Hong S, Lee D, Cui T, Goyal SM. Carbon nanotube based sensors for the detection of viruses. Sensors and Actuators B: Chemical 2011;155:67–74.
- [134] Kawano T, Takao H, Sawada K, Ishida M. Neural recording chip with penetrating Si microprobe electrode array by selective vapour-liquid-solid growth method. In: Proc 26th of the IEEE EMBS. 2004.
- [135] Cherevko S, Chung CH. Gold nanowire array electrode for non-enzymatic voltammetric and amperometric glucose detection. Sensors and Actuators B: Chemical 2009;142:216–23.
- [136] Lu G, Yang F, Jing X, Wang J. Contact-free measurement of heartbeat signal via a Doppler radar using adaptive filtering. In: Proc international conference on image analysis and signal processing (IASP). 2010.
- [137] Morgan DR, Zierdt M. Novel signal processing techniques for Doppler radar cardiopulmonary sensing. Signal Processing 2009;89:45–66.
- [138] Yazicioglu RF, Torfs T, Merken P, Penders J, Leonov V, Puers R, et al. Ultra-low-power biopotential interfaces and their applications in wearable and implantable systems. Microelectronics Journal 2009;40:1313–21.
- [139] Sinex JE. Pulse oximetry: principles and limitations. American Journal of Emergency Medicine 1999;17(1):59–66.

- [140] Hayes MJ, Smith PR. A new method for pulse oximetry possessing inherent insensitivity to artefact. *IEEE Transactions on Biomedical Engineering* 2001;48(4):452–61.
- [141] Lee BK, Olgin JE. Role of wearable and automatic external defibrillators in improving survival in patients at risk for sudden cardiac death. *Current Treatment Options in Cardiovascular Medicine* 2009;11:360–5.
- [142] Chan M, Campo E, Estève D. Assessment of activity of elderly people using a home monitoring system. *International Journal of Rehabilitation Research* 2005;28(1):69–76.
- [143] Campo E, Bonhomme S, Chan M, Estève D. Remote tracking patients in retirement home using wireless multisensor system. In: *International conference on e-health networking, application & services (Healthcom'10)*. 2010. p. 226–30.
- [144] Chan M, Bonhomme S, Estève D, Campo E. Individual movement trajectories in smart homes. In: *Proc 13th international conference on biomedical engineering (ICBME 2008)*. 2008.
- [145] Mailhes C, Comet B, De Bernard H, Campo E, Prieto A, Bonhomme S. Telemedicine applications in OURSES project. In: *Proc workshop on satellite and space communications*. 2008.
- [146] Chan M, Campo E, Bourennane W, Estève D. Connectivity for the indoor and outdoor elderly people safety management: an example from our current project. In: *Proc European symposium on biomedical engineering (ESBME 2010)*. 2010.
- [147] Bourennane W, Charlon Y, Chan M, Estève D, Campo E. Integration of wearable device with actigraphy system for monitoring Alzheimer's patients. In: *Proc 8th international conference on wearable micro and nano technologies for personalised health (pHealth 2011)*. 2011.
- [148] Kang MG, Koh SB, Cha BS, Park JK, Baik SK, Chang SJ. Job stress and cardiovascular risk factors in male workers. *Preventive Medicine* 2005;40:583–8.
- [149] Berntson GG, Bigger Jr JT, Eckberg DL, Grossman P, Kaufmann PG, Malik M, et al. Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiology* 1997;34:623–48.
- [150] Dikecligil GN, Mujica-Parodi LR. Ambulatory and challenge-associated heart rate variability measures predict cardiac responses to real-world acute emotional stress. *Biological Psychiatry* 2010;67(12):1185–90.
- [151] <http://www.bodymedia.com/> [accessed 06.03.12].
- [152] <http://www.vivometrics.com/> [accessed 06.03.12].
- [153] <http://www.welchallyn.com/> [accessed 06.03.12].
- [154] <http://www.sensatex.com/> [accessed 06.03.12].
- [155] <http://www.cardionet.com/> [accessed 06.03.12].
- [156] Medtronic, Inc. <http://www.medtronic.com/> [accessed 05.07.12].
- [157] Poscia A, Mascini M, Moscone D, Luzzana M, Caramenti G, Cremonesi P, et al. A microdialysis technique for continuous subcutaneous glucose monitoring in diabetic patients (Part 1). *Biosensors and Bioelectronics* 2003;18:891–8.
- [158] Varalli M, Marelli G, Maran A, Bistoni S, Luzzana M, Cremonesi P, et al. A microdialysis technique for continuous subcutaneous glucose monitoring in diabetic patients (Part 2). *Biosensors and Bioelectronics* 2003;18:899–905.
- [159] Buckingham B, Beck RW, Tamborlane WV, Xing D, Kollman C, Fiallo-Scharrer R, et al. Continuous glucose monitoring in children with type 1 diabetes. *Journal of Pediatrics* 2007;151(4):388–93.
- [160] Davis FD. Perceived usefulness, perceived ease of use, and user acceptance of information technology. *Management Information Systems Quarterly* 1989;13(3):319–40.
- [161] Steele R, Lo A, Secombe C, Wong YK. Elderly persons' perception and acceptance of using wireless sensor networks to assist healthcare. *International Journal of Medical Informatics* 2009;78:788–801.
- [162] Mountain G, Wilson S, Eccleston C, Mawson S, Hammerton J, Ware T, et al. Developing and testing a telerehabilitation system for people following stroke: issues of usability. *Journal of Engineering Design* 2010;21(2):223–36.
- [163] Wilson S, Davies R, Stone T, Hammerton J, Ware S, Mawson S, et al. Developing a telemonitoring system for stroke rehabilitation. In: *Proc ergonomics society annual conference*. 2007.
- [164] Fensli R, Dale P, O'Reilly P, O'Donoghue J, Sammon D, Gundersen T. Towards improved healthcare performance: examining technological possibilities and patient satisfaction with wireless body area networks. *Journal of Medical Systems* 2009;34(4):767–75.
- [165] Duval S, Hashizume H. Questions to improve quality of life with wearables: humans, technology, and the world. In: *Proc international conference on hybrid information technology (ICHIT'06)*. 2006.
- [166] Hensel BK, Demiris G, Karen L, Courtney KL. Defining obtrusiveness in home telehealth technologies: a conceptual framework. *Journal of the American Medical Informatics Association* 2006;13:428–31.
- [167] Gifford R, Kehoe JJ, Barnes SL, Kornilayev BA, Alterman MA, Wilson GS. Protein interactions with subcutaneous implanted biosensors. *Biomaterials* 2006;27:2587–98.
- [168] Wisniewski N, Klitzman B, Miller B, Reichert WM. Decreased analyte transport through implanted membranes: differentiation of biofouling from tissue effects. *Journal of Biomedical Materials Research Part A* 2001;57(4):513–21.
- [169] Wisniewski N, Moussy F, Reichert WM. Characterization of implantable biosensor membrane biofouling. *Fresenius Journal of Analytical Chemistry* 2000;366:611–21.
- [170] Kerner W, Kiwit M, Linke B, Keck FS, Zier H, Pfeiffer EF. The function of a hydrogen peroxide-detecting electroenzymatic glucose electrode is markedly impaired in human sub-cutaneous tissue and plasma. *Biosensors and Bioelectronics* 1993;8(9–10):473–82.
- [171] Perry M, Li Q, Kennedy RT. Review of recent advances in analytical techniques for the determination of neurotransmitters. *Analytica Chimica Acta* 2009;653(1):1–22.
- [172] Clark RA, Inglis SC, McAlister FA, Cleland JGF, Stewart S. Telemonitoring or structured telephone support programmes for patients with chronic heart failure: systematic review and meta-analysis. *British Medical Journal* 2007;334:942.
- [173] Jaana M, Paré G, Sicotte C. Home telemonitoring for respiratory conditions: a systematic review. *American Journal of Managed Care* 2009;15(5):313–20.
- [174] Tran K, Polisen J, Coyle D. Home telehealth for chronic disease management. *Canadian Agency for Drugs and Technologies in Health* 2008;(113).
- [175] Feldman AM, Klein H, Tchou P, Murali S, Hall J, Mancini D, et al. Use of a wearable defibrillator in terminating tachyarrhythmias in patients at high risk for sudden death: results of the WEART/BROAD. *Pacing and Clinical Electrophysiology* 2004;27:4–9.
- [176] Yuksel M, Dogac A. Interoperability of medical device information and the clinical applications: an HL7 RMIM based on the ISO/IEEE 11073 DIM. *IEEE Transactions on Information Technology in Biomedicine* 2011;15(4):557–66.
- [177] Helmer A, Song B, Ludwig W, Schulze M, Eichelberg M, Hein A, et al. A sensor-enhanced health information system to support automatically controlled exercise training of COPD patients. In: *Proc pervasive health*. 2010.
- [178] Hung K, Zhang YT, Tai B. Wearable medical devices for tele-home healthcare. In: *Proc. 26th annual conference of the IEEE EMBS*. 2004.
- [179] Balka E, Doyle-Waters M, Lecznarowicz D, FitzGerald JM. Technology, governance and patient safety: systems issues in technology and patient safety. *International Journal of Medical Informatics* 2007;76(S1):S35–47.
- [180] Lymberis A. Smart wearable systems for personalized health management: current R&D and future challenges. In: *Proc 25th annual international conference of the IEEE EMBS*. 2003.
- [181] Hayashi Y, Livshits L, Caduff A, Feldman Y. Dielectric spectroscopy study of specific glucose influence on human erythrocyte membranes. *Journal of Physics D: Applied Physics* 2003;36:369–74.
- [182] Kudo H, Sawada T, Kazawa E, Yoshida H, Iwasaki Y, Mitsubayashi K. A flexible and wearable glucose sensor based on functional polymers with soft-MEMS techniques. *Biosensors and Bioelectronics* 2006;22:558–62.
- [183] Moran J. Technical advances in home dialysis. *Advances in Chronic Kidney Disease* 2009;16(3):215–20.
- [184] Chen B, Wei J, Tay FEH, Wong YT, Iliescu C. Silicon microneedle array with biodegradable tips for transdermal drug delivery. *Microsystem Technologies – Micro and Nanosystems – Information Storage and Processing System* 2008;14:1015–9.
- [185] Coughlin JF. Aging and family caregiving: why should financial services care? In: *AgeLab 06-02*. MIT; 2006.
- [186] Barlow J, Bayer S, Curry R. Implementing complex innovations in fluid multi-stakeholder environments: experiences of 'telecare'. *Technovation* 2006;26:396–406.
- [187] Mahoney DF, Tarlow B. Workplace response to virtual caregiver support and remote home monitoring of elders: the Win project. *Studies in Health Technology and Informatics* 2006;122:676–80.
- [188] Shroover F, Baert I, Truijten S, Pieters L, Denis T, Williams K, et al. Real time location systems over WiFi in a healthcare environment. *Journal on Information Technology in Healthcare* 2006;4(6):401–6.
- [189] Coiera E. Four rules for the reinvention of health care. *British Medical Journal* 2004;328:1197–9.
- [190] Leino-Kilpi H, Välimäki M, Dassen T, Gasull M, Lemonidou C, Scott A, et al. Privacy: a review of the literature. *International Journal of Nursing Studies* 2001;38:663–71.
- [191] Abascal J, Nicolle C. Moving towards inclusive design guidelines for socially and ethically aware HCI. *Interacting with Computers* 2005;17:484–505.
- [192] Langheinrich M. Privacy by design – principles of privacy-aware ubiquitous systems. In: *Proc 3rd international conference on ubiquitous computing*. Atlanta, Georgia, USA, London: Springer-Verlag; 2001. p. 273–91.
- [193] Dickens BM, Cook RJ. Legal and ethical issues in telemedicine and robotics. *International Journal of Gynecology & Obstetrics* 2006;94:73–8.
- [194] McCubbin CN. Legal and ethico-legal issues in e-healthcare research projects in the UK. *Social Science & Medicine* 2006;62:2768–73.
- [195] Hill JW, Powell P. The national healthcare crisis: is eHealth a key solution? *Business Horizons* 2009;52:265–77.
- [196] Middleton B, Hammond WE, Brennan PF, Cooper GF. Accelerating U.S. EHR adoption: how to get there from here. Recommendations based on the 2004 ACMI retreat. *Journal of the American Medical Informatics Association* 2005;12(1):13–9.
- [197] Middleton B. Achieving U.S. health information technology adoption: the need for a third hand. *Health Affairs* 2005;24(5):1269–72.
- [198] Friedman EA. Will nephrologists use a wearable artificial kidney? *Clinical Journal of the American Society of Nephrology* 2009;4:1401–2.
- [199] Poon CCY, Zhang YT. Perspectives on high technologies for low-cost healthcare, the Chinese scenario. *IEEE Engineering in Medicine and Biology Magazine* 2008;September/October:42–7.
- [200] Park S, Jayaraman S. Smart textile-based wearable biomedical systems: a transition plan for research to reality. *IEEE Transactions on Information Technology in Biomedicine* 2010;14(1):86–92.
- [201] Robinson S, Stroetmann KA, Stroetmann VN. Tele-homecare for chronically ill persons: pilot trials, medical outcomes and future perspectives. *Studies in Health Technology and Informatics* 2004;103:197–205.

- [202] Lamothe L, Fortin JP, Labbé F, Gagnon MP, Messikh D. Impacts of telehome-care on patients, providers, and organizations. *Telemedicine and e-Health* 2006;12(3):363–9.
- [203] Daniel KM, Cason CL, Ferrell S. Emerging technologies to enhance the safety of older people in their homes. *Geriatric Nursing* 2009;30(6):384–9.
- [204] Mynatt ED, Melenhorst AS, Fisk AD, Rogers WA. Aware technologies for aging in place: understanding user needs and attitudes. *Pervasive Computing* 2004;April–June:36–41.
- [205] <http://www.CPME.be> [accessed 06.03.12].
- [206] Blobel BGME. Educational challenge of health information systems interoperability. *Methods of Information in Medicine* 2007;46:52–6.
- [207] Essén A, Conrick M. New e-service development in the home sector: beyond implementing a radical technology. *International Journal of Medical Informatics* 2008;77:679–88.
- [208] Pelletier-Fleury N, Fargeon V, Lanoé JL, Fardeau M. Transaction cost economics as a conceptual framework for the analysis of barriers to the diffusion of telemedicine. *Health Policy* 1997;42:1–14.
- [209] Bergmo TS. Economic evaluation in telemedicine – still room for improvement. *Journal of Telemedicine and Telecare* 2010;6:229–31.
- [210] Paul DL. Assessing technological barriers to telemedicine: technology-management implications. *IEEE Transactions on Engineering Management* 1999;46(3):279–88.
- [211] Percival J, Hanson J. Big brother or brave new world? Telecare and its implication for older people's independence and social inclusion. *Critical Social Policy* 2006;26(4):888–909.
- [212] Anderson JG. Social, ethical and legal barriers to E-health. *International Journal of Medical Informatics* 2007;76:480–3.
- [213] Kleinke JD. Dot-Gov: market failure and the creation of a national health information technology system. *Health Affairs* 2005;24(5):1246–62.
- [214] Doukas C, Metsis V, Becker E, Le Z, Makedon F, Magliogiannis I. Digital cities of the future: extending @home assistive technologies for the elderly and the disabled. *Telematics and Informatics* 2011;28:176–90.