

Review

Intelligent Biomedical Clothing for Personal Health and Disease Management: State of the Art and Future Vision

ANDREAS LYMBERIS, Ph.D., and SILAS OLSSON, M.Sc.

ABSTRACT

Telemedicine has been introduced to overcome distance in order to get prompt access to medical knowledge and appropriate health care. More recently, work in telemedicine has aimed at developing solutions to support the management of chronic diseases such as diabetes, and lung and heart diseases, as well as to provide support for home care services. Telemedicine is also entering the fields of health promotion/prevention disease, life style management, and well-being. The evolution and broadening of telemedicine gives birth to a nomenclature that includes "e-health," "telehealth," and "telecare." The latest developments in microsystems and nanotechnologies as well as in information processing and communication technologies allow miniaturization and non-invasive smart monitoring of physiological and physical data. Ongoing cutting-edge multidisciplinary research in textile fibers, biomedical sensors, and wireless and mobile telecommunications integrated with telemedicine, aims at developing intelligent biomedical clothing (IBC) that could pave the way to support personalized management of health and diseases at the point of need and at any time. In this study, we aim to describe the current status of multidisciplinary research and development of IBC, based on bibliographic research and reports from seminars, workshops, conferences, and working groups. A further aim is to inform the developers, the decision makers, and users in the health and healthcare sector regarding future solutions to support personalized health care and disease management. Both the textile sector and healthcare sector are looking with great interest at the innovative products and applications that could result from the integration of microsystems, nanotechnologies, biomedical sensors, textiles, and mobile telecommunications. For health monitoring, disease prevention and management, rehabilitation, and sport medicine, IBC may offer, in the mid-term future, a unique, wearable non-obtrusive telemedicine platform for individualized services that is readily accessible and of good quality.

INTRODUCTION

TELEMEDICINE WAS PIONEERED at the beginning of the 20th century, for example, in the field of maritime medicine by using telecom-

munication and Morse code. Along with developments in telecommunications and computer technology during the last half of the 20th century, and spurred by greater emphasis on the need for improving healthcare delivery, in-

European Commission, Information Society Directorate-General, Brussels, Belgium.

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terest in telemedicine applications increased. Although not yet broadly integrated in the healthcare and health delivery systems, telemedicine has evolved from research and development (R&D) into actual clinical practice.

Development in healthcare telematics—including telemedicine—has been strongly supported for 10–15 years through R&D programs and initiatives in European Union countries, in the United States, and in other regions of the world.^{1–4} Ongoing restructuring of healthcare delivery includes the concept of “continuity of care,” which supports the paradigm shift from “hospital-centered healthcare” to “patient/citizen-centered health” as well as from “cure” to “prevention,”⁵ broadening significantly the scope and the use of telemedicine. Information technologies became one of the major driving forces for healthcare evolution and have received acceptance by an increasing number of health professionals.⁶ A substantial and growing market for healthcare information society technologies products was identified and estimated worldwide to be worth \$65 billion for 2002, with a distribution of 45% United States, 24% Western Europe, 15% Japan, and 16% other countries.⁷

The evolution underway in healthcare and health delivery is driven by three main factors: Major societal changes, progress in science and technology and increased medical knowledge. Many societies are undergoing demographic changes such as the aging of the population, further integration of disabled persons and an increase in chronic diseases.^{8,9} Citizens, patients and health providers face new challenges as they strive to optimize quality, cost and access to care. People are becoming more “health conscious” and eager to assume a more active role in managing their own health, and patients are becoming “health consumers” asking for better health and life style management, including nutrition, fitness and sport.¹⁰

Progress in science and technology, such as microsystems and nano-technologies, offer, for the first time, a number of new possibilities and solutions such as artificial intelligence, miniaturization, reduced power consumption and new materials at low cost.¹¹ In addition, significant progress has occurred in mobile and

wireless telecommunications as well as in signal processing, human–computer interface and navigation tools for information retrieval and management.

There is a growing interest in finding new solutions to deliver healthcare, manage and support patients with chronic diseases including diabetes, coronary artery diseases, hypertension, chronic obstructive pulmonary disease, depression and multiple sclerosis. Beyond the quality of life and societal impact, the direct annual medical cost is considerable. For example, the direct medical costs in the United States for asthma, depression and diabetes are estimated to account, annually, for \$5.1, \$12.4, and \$44 billion, respectively.¹² During the last few years, telemedicine developments also aim at finding solutions to support management of chronic diseases as well as providing support for home care services.^{13,14}

Currently, innovative portable and wearable health monitoring applications are being developed by international research, industrial and healthcare organizations involving public and private funding.^{15,16} The integration of textile with biomedical sensors and mobile telecommunications represent a great opportunity for research, healthcare and health provision as well as market potential.^{17,18}

The evolution and broadening of telemedicine has given birth to a new nomenclature that includes “e-health,” “telehealth,” “telecare,” “telemonitoring,” “telediagnosis,” “telerehabilitation,” “teletreatment,” and “home telecare.”¹⁹ Lacking a broad international consensus of the precise definition of these terms, we use the term “telemedicine” in this paper as an inclusive umbrella for all these terms.

PROGRESS IN TECHNOLOGY INTEGRATION TOWARDS PERSONAL HEALTH AND DISEASE MANAGEMENT

Development of smart wearables for health monitoring

The new generation of biomedical sensors and actuators demonstrates unlimited virtual capabilities in measuring, processing, communicating and acting in an intelligent way.²⁰ New measurements and new approaches are

possible including diagnosis, ambulatory healthcare, care at home and at the point of need. From non-invasive microsensors, to implants, and to disposable biochips for blood analysis and clinical diagnosis, the large variety of biomedical sensors and devices results from a strong market demand for microsystems and nanotechnologies in medical applications.²¹ The portability and particularly the wearability of integrated sensing, processing, actuating and communicating are moving from “wishful thinking” to reality.

Non-invasive sensors are the most promising innovations to monitor physiological functions and also daily activities and individual behavior. They offer painless applications, comfort and enhanced prevention from infections and contamination. These sensors can be applied either in contact with the body or near to it (wearable), or can be embedded in surroundings, e.g. “intelligent home” and automobile.²² They can measure vital signs such as ECG, cardiac frequency, respiration, blood oxygen saturation, temperature, CO₂ and O₂, but also body kinematics, sensorial, emotional and cognitive reactivity such as EMG, microcirculation, posture, fall, movement, speed, acceleration and pressure.^{23,24}

The market of remote portable personal health monitoring, offers at present, mainly single physiological parameter systems, based either on telephonic transmission or on optical transmission through a handheld recording system. The storage and viewing of the data, as well as the analysis, are performed mainly on the service provider side. Currently, a great effort is placed, through public and private financial support, on the research and development of personal smart wearable systems for health management.^{25,26} The objective is to increase autonomy with embedded decision support, enhanced user-friendliness and multi-parameter monitoring capabilities. One of the possible shortcomings of such smart wearables is the limited physiological parameters collected, due to the reduced contact area between the body, for example, wrist, chest, abdomen, and the device. A possible solution to overcome this limitation could be the integration of the different sensors into a unified, user-friendly wearable

platform that has large contact surface with the body, i.e. the textile.

During the last few years, textile research laboratories have tested the symbiosis of textiles with wearable computing, augmented reality, human machine interfaces, media and interface design and finally high tech-fashion.^{27,28} Leveraging the disparate materials, technologies and techniques available within the established electronics and textile industries are leading to a totally new class of large-area, flexible, conformable informative and interactive wearable systems.²⁹ New applications are opening-up for the apparel textile industry, in healthcare, environment, automobile, worker protection, sport, etc.

These new means have the potential to reshape significantly the provision of healthcare services and health support, and also assigning new responsibilities to device manufacturers, health practitioners as well as to patients and citizens.³⁰ Given the ambulatory instrumentation, for example, in home telecare, the responsibilities of each actor become less clear especially in cross-border telemedicine. Personal telemedicine applications have to comply with user authentication restrictions as well as with personal data protection laws and regulations.³¹ In addition, security problems have to be tackled for each specific application and selection of countermeasures has to be made through risk analysis. On the other hand, wearable health applications may address source problems in healthcare services, including medical errors, which account for between 44,000 to 98,000 deaths in United States each year.³²

Marriage of information and communication technologies and textiles: towards intelligent biomedical clothing for personal health and disease management

The textile industry is, along with steam engine, the oldest and most traditional industrial sector, the driving force of the economy in the 19th century. Although, currently remaining one of the major industrial sectors, with an annual turnover of 198 million € and a total workforce of 2.2 million in Europe, textile and clothing face increasingly fierce global compe-

tition and continued relocation of manufacturing to low-wage countries. The small and medium sized companies, which represent the absolute majority of the sector (95% in Europe), need to focus on competitive advantage other than cost. The industry recognizes the demand for more functionality and non-conventional textile products and the importance of the involvement of information technologies for textile innovation.³³ Hence, the textile industry is experiencing various innovations with the creation of new textile fibers and sophisticated chemical processes for coating and waterproofing. Miniaturization of electronics and informatics (e.g., computer, microsensors, signal processing, transmission), make possible the integration of multiple smart functions into textiles without being a burden, which are likely to be readily accepted by the user.³⁴ Ongoing cutting edge research aims at the development of a new generation of textile materials with new mechanical, physical, thermal, electric, optical and other ergonomic functions.

A smart textile is the integration into the textile, of sensors, actuators, computing, and power sources, the whole being part of an interactive communication network. These essential instrumental functions could be implemented onto fabric substrates³⁵ using, currently inorganic materials such as metal fiber. The ongoing R&D to produce new fibers, yarns and fabrics from organic and smart materials (e.g., polymers) will enable textiles to behave both as passive and active systems.

Truly instrumented garments capable of recording physiological, neurological and body kinematic parameters³⁶ are crucial for health-care and health provision. They can provide physicians with data to detect and manage health risks, diagnose at an early stage, recommend treatment and, finally, make confident professional decisions based on objective information—all in a reasonably short time.

Intelligent biomedical clothing (IBC) has the potential to change substantially the provision of health and health care services for large population groups. Some examples of this are, those suffering from chronic diseases, high-risk patients and the elderly with specific needs, offering a unique opportunity to integrate seamlessly health care into the daily lives of citizens.

Smart sensor systems and new approaches to analyse and interpret data, combined with cost-effective telematics approaches can fundamentally change the interface between citizen/patient and the health care provider. IBC has the potential to be a key enabler technology for cost-effective disease management, disease prevention, rehabilitation and overall life style management (e.g., sport, fitness, weight control, stress management, therapy).

IBC is based on multidisciplinary research and development and requires strong co-operation between engineers and scientists from various fields including, mobile and wireless telecommunications, microsystems and nanotechnologies, textile & clothing, biomedical engineering, telemedicine, as well as public health and medicine (Fig. 1).

There is a conceptual transition from “medical clothes” for patients to “health clothes” for citizens. The first category includes medical clothes that could be relatively cumbersome resulting from a merge of existing tools and sensors on regular clothes. This is at present realized in pre-commercial prototypes such as Mamagoose, pajamas for the detection of Sudden Infant Death Syndrome,³⁷ or in products such as LifeShirtTM, a system providing continuous ambulatory monitoring of respiratory and cardiac parameters.³⁸ In addition to their health related functionality, these clothes should be elegant, easy to wear, and include invisible sensors and information technologies. This would require medium to long term R&D for integration of sensors/actuators, energy sources, processing, and communication functions within the clothes. Current prototypes such as SmartShirtTM³⁹ and “medical assistance suit” (VTAMN Project)⁴⁰ still require further medical validation. Longer research involving new fiber materials aims at “e-textiles,” where sensing, processing, and communications are integrated in a woven structure to monitor physiological signals and biomechanical variables.

Crucial to the success of IBC is the user acceptance and user benefits, as well as the active involvement from healthcare providers, authorities and third party payers. The economic aspects of the services to be offered have to be addressed at an early stage of develop-

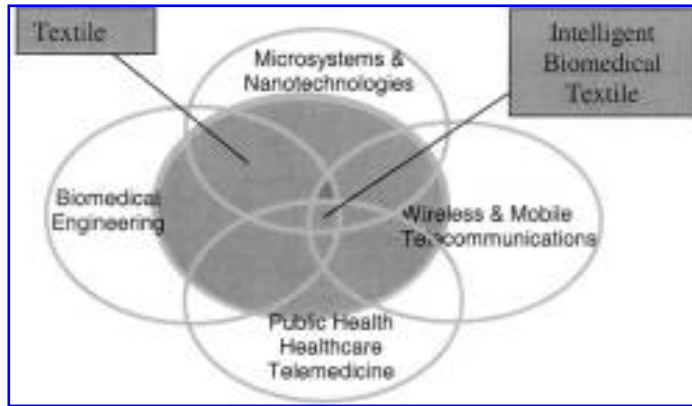


FIG. 1. Disciplines involved in developing intelligent biomedical clothing.

ment. This includes the formation of the complete value chain as well as a co-development of business models with, for example, health authorities and health and life insurance establishments.

EXAMPLES OF POTENTIAL APPLICATIONS AND BENEFITS OF IBC

IBC has the potential for continuous measurement, processing and communication of physiological and physical parameters from patients to service providers, family and other support people. The appropriate design and integration of different kinds of sensors, as well as the appropriate medical algorithms to process the data could offer new possibilities for monitoring and preventing health risks (e.g., cardiovascular diseases). IBC can also monitor body kinematics and analyze posture and gesture with major applications for ergonomic, virtual reality, rehabilitation and treatment follow-up. It could also provide support to chronically ill persons as well as those at risk situations e.g. sport.

The wide spectrum of cardiovascular disease remains the leading cause of death and early disability worldwide. It creates a substantial financial burden on the health care systems.⁴¹ Although hospital mortality has been reduced and the overall life expectancy has increased in recent years, out-of-hospital mortality rate from coronary disease remains high.⁴² Cardiac diseases are, at least partially, caused by un-

healthy lifestyle.⁴³ Risk factors can be reduced by changes in lifestyle. The use of IBC could reduce incidence rates by (a) predicting acute events by long term trend analysis, (b) providing instant diagnosis of acute event and links to health care provider/emergency system, and (c) reducing the time to intervention by tele-diagnosis and tele-therapy. Rehabilitation at home could be also supported.

Diabetes is the fourth to fifth leading cause of death in most developed countries, and there are more than 150 million people with diabetes worldwide.⁴⁴ Diabetes could be better managed by timely advice based on informed decisions and with, if available, non-invasive monitoring and insulin delivery systems. The continuous monitoring of blood glucose remain a challenge. State-of-the-art glucose sensors as well as miniaturized implantable insulin delivery devices have been recently developed in prototype level.^{45,46} Further miniaturization and on-line decision making systems are under development. Research in smart clothing to bring together the required physiological measurement, telecommunication and drug delivery functions could lead to a unique platform for enhanced personal diabetes management.

Several chronic diseases require medication over a certain time period. The ability of the user to take the medication on time, according to the prescription, is a major problem leading to medication errors. This represents the eighth leading cause of death, at a rate greater than motor vehicle accidents, breast cancer, or

AIDS⁴⁷ and financial loss evaluated to about \$80 billion per year in the United States.⁴⁸ IBC has the potential to support timely delivery of medication (through intelligent microsystem patches or using micro-pumps), monitor the delivery and its effects as well as feedback vital parameters to the medical service providers.

Besides the potential enhancement in terms of access to health services and quality, IBC could result in more effective use of available resources through reductions in number and length of hospital stays and optimisation of medication therapy.

However, the integration of biomedical sensors into a textile remains a technical and medical challenge. New approaches have to be developed to analyze and interpret the medical data in order to achieve a reliable diagnosis and appropriate treatment, as well as, smart wearables with health monitoring facilities, designed for daily use, obviously, involve, a number of ethical issues, for example, misuse of data collected.

CONCLUSION

The textile and clothing industry recognizes the importance of continuous product and material innovation for maintaining and improving competitiveness. Smart textiles bring more innovation and functionality than one could ask from an ordinary textile, and also have the potential to make people's daily life more comfortable and safe. Smart clothing is an effort to make electronic devices a genuine part of our daily lives by embedding entire systems into clothing and accessories. The achievements so far on material processing, microsensor design and system communication make it realistic, however challenging, to concentrate efforts on the realization of smart textiles and clothing.

From the public health and healthcare perspectives, developments within IBC have the potential to offer unique advantages to combine, in a seamless way, the oldest and most frequently worn material with the most technologically advanced, sensing, processing, actuating and communicating capabilities.

IBC research and development is based on multidisciplinary fields, and require strong co-

operation between engineers, scientists, designers, clinicians, and public health practitioners.

The approach of ongoing R&D is to integrate monitoring, diagnosis, treatment and communication functions into fabrics. The combination of biomedical functionality, added health value and fashion constitutes key success factor to make the long-term monitoring a lifestyle product. There are a number of possible IBC applications spanning from a citizens' health watch, to patients' disease and life management, including rehabilitation. With respect to disease management, IBC has the potential to increase the quality of life for chronically ill patients by providing quality care, shortening or avoiding hospital stays and optimizing medication therapy, as well as providing peace of mind. IBC also has the potential to reduce risk factors by supporting healthy lifestyle and predicting acute events and reducing time to intervention.

Several issues, technical as well as medical, remain to be solved before clinical trials can be performed. Among the most important challenges are the production of higher conductivity textile material according to current industrial processes, as well as the interfacing and protection of electronic components. Along with these challenges, cleaning and washing issues have to be solved. Further research is required also in signal processing, data interpretation, user acceptance, cost effectiveness, product adaptation, market segmentation and business models.

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Address reprint requests to:

Andreas Lymberis, Ph.D.

European Commission

Information Society Directorate-General

Office BU-31, e-Health Unit

B-1049 Brussels, Belgium

E-mail: Andreas.lymberis@cec.eu.int

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