Smart Clothes for Rehabilitation Context: Technical and Technological Issues

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Abstract Smart clothes have the potential to improve rehabilitation processes by allowing clinicians to gather measures on patients' functional capacity, activity level, exercise compliance, the effectiveness of treatment, and the ability of patients to perform efficiently specific motor tasks at rehabilitation centers, at home or in community settings. The chapter provides an overview of smart clothing for health monitoring and healthcare, mainly for rehabilitation context. We present recent advances in the field of researches related smart clothes with capability of human body vital functions (i.e. heart beats, respiration) and activity monitoring, as well as several commercial smart clothes for rehabilitation context. Technical and technological issues related smart clothes design and development, and several directions for future research are also presented. Manufacturability, connectivity, integrations of things for smart clothing, durability, testing, wearability, maintainability and affordability of smart clothes are discussed.

1 Introduction

> "It can feel your heartbeat … look…" Sure enough there was a big red spot on the plastic shirt just over her heart, a spot that spread out into an expanding ring that moved on over her shoulders and down to her sleeves. Her heart beat again, and a new spot started - each beat of her heart started a new red splash in the blue heartshirt.
>
> Source: Wetware, by Rudy Rucker, 1988.

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In 2010 Vivian Jang and Nick Lee from Cornell University designed and built a LED T-shirt [1] capable of displaying the heart rate of the wearer via a pulsing LED heart (see Fig. 1). The imagined T-shirt by the writer Rudy Rucker in his science fiction novel *Wetware*, published in 1988, is turned real. The photoplethysmography (PPG) technique (that recorded light absorption by a finger or ear lobe) and a technique proposed by Charlie Allen in early 1995 (at Maxim Integrated) for driving a multiplexed display (in which a microcontroller, with few I/O, was wired into T-shirt). The microcontroller was used for heart rate processing and driving of an LEDs' array. Heart beat signal is displayed in this T-shirt by a LEDs array producing a propagating effect. At that time, T-shirts that integrate technology for recording electrocardiogram (ECG) or plethysmogram were developed in several research projects, and also were commercialized in some countries (see Figs. 2, 3, 4 and 5). This was possible as a result of progress in development of sensors technology, miniaturization and increase in processing and communication capability of

Fig. 1 T-shirt with pulsing LED related with wearer heart beat

Fig. 2 Smart T-shirt with capability of heart rate monitoring

Fig. 3 Smart T-shirt with capability of heart rate, respiratory rate and activity recording

Fig. 4 Smart T-shirt with capability of heart rate and activity recording

Fig. 5 Smart T-shirt with capability of recording heart rate (HR), electrocardiography (ECG), respiration, electromyography (EMG)

wearable devices as well as increased awareness on the necessity of monitoring cardiac function for prevention, or better management of cardiovascular diseases—the main leading cause of mortality worldwide. Ageing population in many countries was also an important factor for development and use of wearable technology for fitness and clinical purposes.

In the last decades, demographic, social and economic changes as well as progress in *information and communication technologies* (ICT) have produced dramatic changes in healthcare provision. ICT promise: fast access to reliable information about illness and treatment options; attention to physical and environmental needs; participation in health care decision and service developments [2]. Technologies that allow health monitoring at home are now emerging as a distinct segment within the larger ICT market, forecasting the increase of consumers using home health technologies from 14.3 million worldwide in 2014 to 78.5 million by 2020 [3]. The terms *wearable technology*, *wearables*, *wearable device* or *wearable electronics* are used to refer to electronic technologies (i.e. ICT) that are worn as accessories or as clothes. The term wearable technology is sometimes used for implanted devices such as micro-chip or even smart tattoos. In the last decades a wealth of research was carried out in order to design and develop wearable systems with capability to automatically recognize the activity and the behavioral status of the user as well as of the situation around her/him, and to use this information to adjust the systems' configuration and functionality. Wearable technology includes some form of data acquisition and processing as well as communication capability. Examples of wearable devices are smart watches, glasses with image recording or data display capability or for recording eye movements, wearable strap for recording heart rate or respiratory rate, smart T-shirt, smart shoes. According to the International Data Corporation (IDC) report published in 2015 on the wearable devices market, total shipment volume for the quarter came to 18.1 million units, up 223.2 % from the 5.6 million units shipped in previous year [4]. IDC also projects this market to reach 155.4 million annual shipments by 2019, up from about 26.4 million last year. Rapid advances in ICT, increased the access to Internet for milions of peoples (82.1 % of European and 60 % American population has now Internet access at home). During the last years the increased development of mobile technologies, and increased access to mobile technologies (approximately 80 % of Europeans and Americans have active mobile broadband subscriptions) [5] have contributed to the fast growing wearable-tech market after 2014, faster than any other segment in the consumer-electronics market. Most of wearable devices are sold for fitness, entertainment and gaming purposes. However, wearable devices are nowadays viewed as important technology to promote preventive healthcare, patient engagement in healthcare and to achieve tailored treatment, better healthcare outcome and cost effective use of health services. Wearable devices can be divided into two categories:

1. garments (i.e. clothes) with embedded sensors and/or computation capability
2. body worn electronic accessories.

Because the humans prefer to wear textiles rather than "hard" or "heavy" "boxes", most research on wearable products is related with e-textile and smart clothing. Generally, *smart clothes* are defined as clothes made or that include *e-textile* (electronic textile). E-textiles are textiles that include electronic components making these able to sense, communicate, compute and actuate. *Smart textiles* are defined as textile products such as fibers and filaments, yarns together with woven, knitted or non-woven structures, which can interact with the environment/user [6]. Also, the term is used when is referring to neat textile (free from dirt), clothes that fit well or is stylish. Many smart textiles with different functionality and behavior were created in the last decades by combining flexible materials—having different properties (i.e. conductivity, sensing volume change)—with computing structures. Its may be categorized into three subgroups be categorized into three subgroups [6]:

1. Passive smart textiles: only able to sense the environment/user, based on sensors;
2. Active smart textiles: reactive sensing to stimuli from the environment, integrating an actuator function and a sensing device;
3. Very smart textiles: able to sense, react and adapt their behavior to the given circumstances.

Big investment in research projects related to e-textile fabric and smart clothing for different healthcare needs have made possible the development of several commercial products based on e-textile. Great influence of these products on health monitoring and healthcare services is envisioned. Progress in smart clothes research made possible integration from a few isolated sensing and computing elements on the fabric (i.e. plethysmography based recording of heart rate) to a network of many sensing, actuating and computing elements distributed over the entire textile (i.e. Antelope, Vibe-ing smart clothes, Fig. 8) [7, 8]. Being close to the body, smart clothes might enable: monitoring of our activities or health; human-computer interaction; computer based context awareness. Smart clothes can provide biometric data inconspicuously and without intrusion to the user or healthcare service provider. Also, it is envisioned that they would possibly be the best support for people in rehabilitation process, by enabling improved sensing, in addition to actuation, both embedded in garments that might be worn at rehabilitations centers (for gathering information suitable to adjust the intensity and modality of the prescribed therapeutic exercises), as well as in—or outside home, during daily activities or therapeutic intervention.

This chapter provides an overview of smart clothing for health monitoring and healthcare, mainly for rehabilitation context. We present recent advances in the field of smart clothes with capability of vital signs and activity monitoring, as well as several commercial smart clothes for rehabilitation context (Sect. 2). Technical and technology issues related smart clothes design and development are discussed in Sect. 3. In this section, several directions for future research are also presented.

2 Smart Clothes for Rehabilitation

Various smart clothes were developed in the last years, worldwide, with potential on improving rehabilitation processes by allowing clinicians to gather measures on patients' functional capacity, activity level and exercise compliance, the effectiveness of treatment, and the ability of patients to perform efficiently specific motor tasks at rehabilitation centers, at home and in community settings. Available unobtrusive sensors based on e-textile allow clinical personnel to monitor patients' movements and physiological data such as heart rate, respiratory rate, etc. Sensors based on e-textile, mobile technology (i.e. smartphone, tablets) and the widespread access to Internet provide nowadays means to implement systems designed to remotely monitor patients' status and optimize interventions based on individual responses to different rehabilitation approaches.

The motor rehabilitation process is guided by clinical assessments of motor abilities, which are expected to improve over time in response to rehabilitation interventions. Assessing the impact of rehabilitation interventions on the individuals is a key element of the decision-making process for choosing rehabilitation strategy and for improving outcomes of rehabilitation process. In the past, therapists and physicians inferred the effectiveness of a given rehabilitation approach from observations performed in a clinical setting and self-reports by patients. Recent developments in wearable technology, particularly in smart clothing provide tools to complement the information gathered by health professionals. Smart clothes may contribute to functional ability assessment in the real life of patients receiving rehabilitation. Data gathered in the home and community settings are very useful to quantify impact of therapeutic on the performance of activities of daily living and quality of life, and to compare different rehabilitation intervention. It is envisioned that such data would allow health professionals to help patients achieve higher level of independence and better quality of life. Following some examples of smart clothes and their current or potential role in rehabilitation are presented.

2.1 Vital Signs Monitoring

Smart textiles were introduced in early 1990s. The first T-shirt with capacity of recording heart rate was presented in 1998, by Clothing+ (Clothing plus) company from Finland [9], and in 2002 the company started mass producing their heart rate sensor strap in their factory in China. Soon after, SmartLife Technology from U.K. [10], Sensatex from U.S.A [11] and GEO View and FALKE KG [12] (Fig. 2) began marketing their heart rate sensing T-shirt. A research team at Georgia Institute of Technology had an important role in pioneer work related to development of smart clothing. Funded initially in 1996 by the U.S Department of the Navy, the Georgia Tech Wearable Motherboard uses optical fibers to detect bullet wounds and special sensors and interconnects to monitor the body's vital signs during combat conditions [13]. The Sensatex Smart Shirt is based on patented technology of Wearable Motherboard. This patent describes a T-shirt which incorporates optical fibers, a data *bus*, a microphone, various sensors (i.e. for heart rate, respiration rate, electrocardiogram, temperature, pulse oximetry), and a multifunction processor, all embedded in textile grid. The garment aimed to rescue soldiers by monitoring their health status in real time. The motherboard or “plug and play” concept means other sensors might be easily integrated into the structure. The sensors might be easily plugged and positioned on any location into Wearable Motherboard. The flexible *bus* integrated into the structure routes the information from the sensors to a smart shirt controller that is plugged into the shirt.

The controller can wirelessly transmit the monitored data to the desired display device (i.e. personal computer) via communication protocol (i.e. Bluetooth). The *bus* has also the role of transmitting information to the sensors. In Sensatex Smart Shirt that monitors heart rate, body temperature and motion of the trunk, data are transmitted to a pager-size device attached to the waist part of the shirt, from where it is sent via a wireless gateway to the Internet and routed to a data server where the data is processed. As the research progressed chips and processors were designed and developed to be plugged into Wearable Motherboard turning this into versatile framework for incorporation of sensing, monitoring, and information processing, to obtain the desired information. Several generations of the woven and knitted versions of the Wearable Motherboard have been produced. Following this pioneer work realized by the research team at Georgia Institute of Technology [14] several companies and research groups from U.S.A. pursued the development of garments with embedded sensors—i.e. the smart T-shirts developed by VivoMetrics (nowadays Vivonoetics) [15], Sensoria [16], Ralph Lauren [17], TruPosture [18], Athos [19], Hexoskin [20] (Figs. 3, 4, 5 and 6).

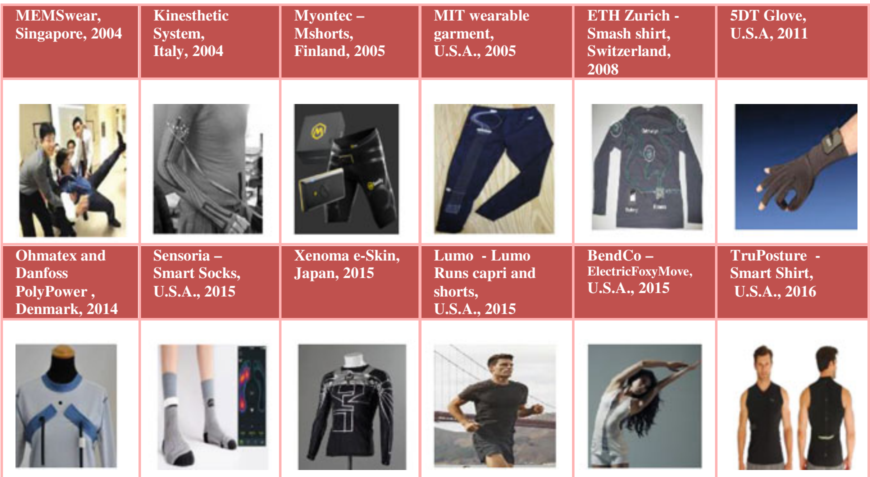

Fig. 6 Smart T-shirt with capability of recording body motion

In Europe, EU funded research projects WEALTHY (Wearable Health Care System, 2002–2005), MYHEART (Fighting Cardio-Vascular Diseases by Preventive Lifestyle and Early Diagnosis, 2004–2007), MERMOTH (Medical Remote Monitoring of Clothes, 2003–2006), BIOTEX (Bio-Sensing Textiles to Support Health Management, 2006–2008), PROeTEX (PROtection e-TEXtile: Micro-Nanostructured fibre systems for Emergency-Disaster Wear, 2006–2010), CONTEX (Contact Less Sensors for Body Monitoring Incorporated in Textiles, 2006–2008), OFSETH (Optical Fibre Sensors Embedded into technical Textile for Healthcare, 2006–2009), STELLA (Stretchable Electronics for Large Area Applications, 2006–2010) contribute for development of smart T-shirts able to record body temperature, ECG signals, blood pressure, breath frequencies, acceleration for fall detection. The focus was on patients receiving cardiac rehabilitation and elderly people and the aim was development of a system that allow continuous monitoring of subject health, real-time alert on emergency event, telemedicine, telehealth, or telerehabilitation. Telerehabilitation (delivery of the rehabilitation services over telecommunications network or internet, also named e-rehabilitation)—has the potential to facilitate extending therapy and assessment capabilities beyond what can be achieved in a clinical setting. The information on EU funded project is in public domain (http://cordis.europa.eu/home_en.html).

The present commercial smart T-shirt developed in Europe is miCoach from Adidas [21] (Fig. 4). The T-shirt includes technology developed by Textronics company that is incorporated in the Adidas group as Adidas Wearable Sports. The company is specialized in wearable electronics and textile sensors with a certain focus on sports performance. Textronics T-shirt is based on four groups of components. The first is the textile sensors used to monitor heart or breathing rate. The second is a family of conductive elastic yarns, which are building blocks in sensors and interconnects. These sensors consist of conductive nano-composite elastomeric polymers that exhibit changes in electrical conductivity as the material is stretched. The last group of components is conductive ribbon that is attached to standard electronic connectors. MiCoach T-shirt that record heart beat, steps and position of body (through GPS) is mainly used for fitness purpose. However, it might be used in cardiac rehabilitation, for objective measurement of walking and impact of exercises on heart rate. Several other T-shirts commercially available nowadays may be used for activity monitoring in cardiac rehabilitation context (Figs. 2, 3, 4 and 5).

Work realized by a team from Harvard University [22] since 2003, proved that measurement of cumulative free-living physical activity with wearable technology in the patient's home environment, combined with physiological data collection (heart rate, respiratory rate, and oxygen saturation), can improve monitoring of patients with chronic obstructive pulmonary disease (COPD) and therapy outcomes. A smart wearable platform based on multi-parametric sensors data processing, for monitoring people suffering from Chronic Obstructive Pulmonary Disease (COPD) was developed in a European funded project—CHRONIOUS (2008–2012) (Fig. 3). The system is able to constantly monitor patients' health condition, through sensors integrated in a T-shirt, or scattered in the living environment, and through ad hoc questionnaires on symptoms and lifestyle displayed on a smart device (touch screen PC or smart phone). The system generates alerts when health and behavior data lay outside the established patterns. A multi-parametric expert system was developed for the analysis of the collected data using intelligent algorithms and complex techniques. Collected data and alarms are used to notify the healthcare providers through a dedicated and secure web platform. The integrated platform provides real-time patient monitoring and supervision, both indoors and outdoors and represents a generic platform for the management of various chronic diseases. In addition, an ontological information retrieval system is being delivered satisfying the necessities for up-to-date clinical information. These works have great relevance for healthcare systems as COPD is a major public health problem in many countries and is currently the fourth leading cause of death in the world [23]. The CHRONIOUS platform was validated through clinical trials in several medical centers and patient's home environments around Europe with 100 patients in two stages.

2.2 Activity Monitoring

Several smart clothes were developed for tracking the activities of the user by using heart rate sensing textile (Fig. 4), electromyography sensing textile (Fig. 5) as well as textile-based sensors for monitoring deformation along textile, positions, **angles**, velocities and accelerations of body segments or **joints** during motion. Such smart clothes might be used for rehabilitation monitoring and training of movements. Following several techniques and technologies based on e-textile for activity monitoring are presented.

Many of smart T-shirt estimate activities of the user by analyzing **heart rate** signal (Figs. 4 and 5). For instance, Hexoskin app estimate resting condition (the lowest number of heart beats per minute when user wake up), maximum effort that the person can do—maximum heart rate (the highest heart rate that the person achieves during exercise), heart rate recovery (the difference between heart rate values at peak intensity exercise and after 60 s without exercising). The app also is able to estimate heart rate variability (time domain heart rate variability statistics). The app uses this data to inform user on training fatigue to avoid overtraining. Most of these measurements are not conforming to measurements established through evidence from physiology and clinical studies. Moreover, most of commercial fitness T-shirts that include electronics acquire heart beats signal at lower sampling frequency than the medical devices (thus reducing their capacity to accurately estimate clinical conditions). Therefore, for adoption of these smart T-shirts in rehabilitation context the characteristics of hardware and software should be comprehensively analyzed as well as validation studies of these smart clothes in clinical settings should be carried out.

Myontec [24] have developed and commercialized, since 2005, the MBody (Fig. 6) a e-textile based pants with capability of monitoring **electromyography** (EMG). Myontec is a company producing system for the monitoring physical performance and capacity of the muscles. The company portfolio consists of a system based on trousers and shirts integrated with sensors and different modules for the measurement and handling of measured data. The trousers are recording the big muscles such as quadriceps, hamstrings, gastrocnemius and gluteus. The Harry Asada team [25] at Massachusetts Institute of Technology (MIT) developed pants (Fig. 6) with conductive fibers incorporated into the fabric to measure lower body movements. The Athos [19] (Fig. 5) claim monitoring of muscle activity through stretch and electromyography sensors integrated in pants and T-shirt. In 2008 the Karlsson team [26] present a smart T-shirt with capability of recording heart rate, respiratory rate as well as muscle activity through electromyography (i.e. trapezius muscle), as result of many years of research developed in Swedish School in collaboration with Umea University Hospital, MedTech West and Chalmers University. Athos and Jabil Circuit company [27] (Figs. 5 and 6) commercialize nowadays sports suits with capability of recording muscle activity through electomiography. Reliability of EMG measurements with these two smart clothes should be analyzed. Also, clinical trials may give valuable information on the effectiveness of these garments in rehabilitation context.

Electrocardiography (ECG) and electromyography systems based on e-textiles were developed by our team [28, 29]. In Fig. 7 some example of the signals obtained with the developed system based on ECG and EMG integrating e-textile is presented. The shirt integrating ECG and EMG electrodes was developed as part of information system for physiotherapy [29]. ECG signal is used to infer on health and activities of patients during physiotherapy sessions in clinics or remotely monitoring of patients in rehabilitation. EMG electrodes integrated in shirtsleeve are used for monitoring muscle activity during flexion, pronation-supination of the upper limbs in motor rehabilitation.

Shape-sensitive fabrics can sense movement, and can be combined with EMG sensing to derive muscle fitness [30]. By measuring the **deformation along**

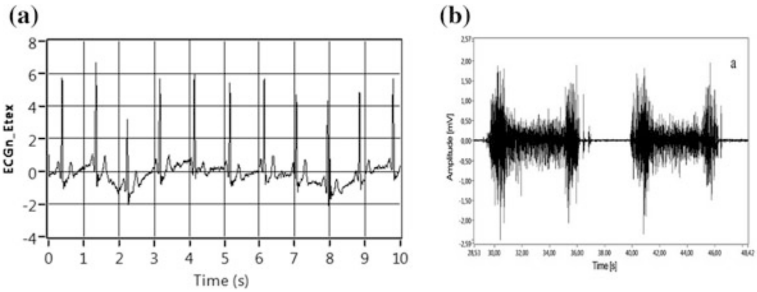

Fig. 7 ECG and EMG signals acquired with textile electrode. **a** Electrocardiogram **b** electromyogram from bicipital muscle

e-textile sensors the physical configuration of the user's body can be detected and information on body posture, balance and movements might be extracted (i.e. Xenoma e-Skin [31], TruPosture [18], Kinesthetic System [32], Fig. 6). In their pioneer work, the de Rossi group at University of Pisa [32] developed a Kinesthetic System that includes: skin like tactile sensors for fine-form discrimination and for incipient object slippage detection; and electroactive polymer based actuators, for producing flexion and extension in an active glove. Many, approaches of sensorized gloves are described in various websites. This type of gloves might be very useful in upper limb motor rehabilitation. The feasibility of using a sensorized glove to implement physiotherapy for motor retraining based on the use of video games was investigated [22]. In the study from Harvard University [22], the glove was used to implement grasp and release of objects in the video games. Processing data gathered from the data glove was used for a measure of "hand aperture" and estimating it. Calibration of the data glove was achieved by asking individuals to hold a wooden cone-shaped object with diameter ranging from 1 cm to 11.8 cm at different points of the cone corresponding to a known diameter. The output of the sensors on the glove was used to estimate the diameter of the section of the cone-shaped object corresponding to the position of the middle finger. Gloves developed by 5DT (Fifth Dimension Technologies Virtual Reality for Real World!) [33] (Fig. 6) might be used in upper limb rehabilitation by using driver for hand animation as well as for interaction with serious games. The Wearable Computing Lab. of ETH Zurich developed a matrix with several **capacitive pressure sensors** for integration into a piece of clothing. Applying this matrix on different body areas, more details on movements or for the detection of physical state of the muscles might be obtained [30]. In 2008 the Harms team [34] from Wearable Computing Lab., ETH Zurich has also presented a T-shirt with distributed sensing and processing architecture for posture classification. The group has been active in different EU-project, but has also carried out research on national levels. A SMASH (SMArt Shirt) integrates **acceleration sensors**. The classification performance was analyzed on data from overall 8 users, conducting 12 posture types, relevant for shoulder and elbow joint rehabilitation [34]. Body movements analysis based on integrated accelerometer into T-shirt (i.e. Nuubo Wearable Medical Technologies UC3 M [35], Fig. 4) or capri and shorts (i.e. Lumo Run Data [36], Fig. 6) was also presented.

2.3 Smart Clothes for Physiotherapy

Many wearable devices have been turned in valuable tools in physiotherapy interventions. In our knowledge clothes based on e-textile currently are not yet being used in physiotherapy practice. However, several smart clothes that are nowadays commercialized may be used in physiotherapy.

One example—the clothes based on e-textiles that record electromyography, might be used in neuromuscular reeducation (i.e. to assist patients in improving the strength and voluntary control of muscle that are week, unreliable and poorly controlled as a result of a stroke). Evidence from a small number of studies suggest that EMG *biofeedback* plus standard physiotherapy produces improvements in motor power, functional recovery and gait quality when compared to standard physiotherapy alone [37]. Smart clothes with EMG recording capability may contribute for clarifying the level of evidence on EMG biofeedback, allowing large data collection using the same and objective outcome measurements.

Smart clothes with capability on monitoring gait (i.e. including accelerometers, textile-based stretch or pressure sensors) as well as those providing biofeedback on gait or auditive, vibrotactile or visual cues may also benefit patients with Parkinson's disease [38, 39].

EMS (Electrical muscle stimulation) devices are frequently used in physiotherapy practice. *Electrical muscle stimulation*, also known as *neuromuscular electrical stimulation* (NMES) or *electromyostimulation* use electric impulses to induce contraction of muscles. EMS has received increasing attention in the last few years because of its potential to serve as a strength training tool for healthy subjects or as a rehabilitation [40] and preventive tool for partially or totally immobilized patients.

Generally, the impulses are generated by a device and delivered through electrodes on the skin in direct proximity to the muscles to be stimulated. Antelope [7] suit (Fig. 8) commercialized by Wearable Life Science from Germany is based on the embedded EMS technology into a sport suit. The suit might be a valuable tool if would be adapted for patients receiving motor rehabilitation.

Smart clothes produced by WARMx [41] from Germany and COOLSHIRT SYSTEMS [42] from U.S.A. are other examples of clothes that might influence the way in which physiotherapy is provided. In physiotherapy practice *thermotherapy* (that consists of application of heat or cold for the purpose of changing the cutaneous, intra-articular and core temperature of soft tissue) is also frequently used with the intention of improving the symptoms of certain conditions. Cold therapy are useful adjuncts for the treatment of musculoskeletal injuries and soft tissue injuries. Using ice or heat as a therapeutic intervention decreases pain in joint and muscle as well as soft tissues. Also, heat or cold is used to change tissue metabolism, blood flow, inflammation, edema and connective tissue extensibility. Thermotherapy can be used in rehabilitation facilities or at home. Heated knitted

Fig. 8 Smart clothes for therapy

system is produced by WARMx GmbH (Fig. 8). The company has an own worldwide-patented technology for heating textiles called WARMx-technology as well as "know how" and partners in both textiles and electronics. The WARMx-undershirt is the classic in WARMx collection. The textiles knitted with silver coated fibers were adapted also for trunk and neck areas, for shoulder/neck area, knees, feet, or around the kidneys. The heating textile is supplied with power from a controller located in the side pocket, which closes the power circuit via pushbuttons. Li-ION batteries supply the power. Smart clothes for rehabilitation context may be developed also by including the technology by Thermotron of UNITIKA [43] (Japan). Thermotron is a particular fabric able to convert sun light into thermal energy while storing heat without wasting it. The inner layer of the fabric withholds the heat generated and prevents it from becoming lost. Inside the Thermotron there are microparticles of zirconium carbide which allow the fabric to absorb and filter sunlight. [43]. Clothes that function as cooling system were developed by COOLSHIRT SYSTEMS (Fig. 8). The company provides personal cooling systems for surgeons, race car drivers, football players, fire and emergency services, military and industrial workers. The invention that launched COOLSHIRT was a cooling vest for surgeons to use in the operating room. COOLSHIRT 6 Person Rehab Station—that incorporates a water port panel that allows for up to 6 connections, 6 Active Aqua Vests (sizes S-XXXL) and twelve 12′ safety pull hoses —may allow cold therapy for 6 persons at the same time.

E-Textile are also developed and used for v*ibration training*, also known as *vibration therapy*, *biomechanical stimulation* (BMS), and *biomechanical oscillation* (*BMO*), a training method that employ low amplitude, low frequency mechanical stimulation to exercise musculoskeletal structures for the improvement of muscle strength, power, and flexibility. Vibration training has been advocated as a therapeutic method in the treatment of osteoporosis, metabolic syndrome, stroke, neurodegenerative diseases (i.e. Parkinson) and is used in the fitness industry, professional sports, beauty and wellness applications [44]. Vibe-ing garment (Fig. 8) developed by partners from Eindhoven University of Technology, Mechatronics Engineering, the TextielMuseum, TextielLab Tilburg, was designed to stimulate the body by the vibration elements [8]. The garment includes several types of knitted areas, each of them according to the need of the specific function, and a certain amount of in-knit pockets situated in a specific way. In the pockets are 3D printed castings with one flat side and one structured side, to invite moving direction and stimulate the touched area more intensively. Small motor chips are included in castings. CRISP motor and vibration actuators have different programmes on them depending on the specific person's need for rehabilitation and vibration stimulation. They can react to the touch of the person (or therapist) or according to a specific programme tuned to the specific user. Also, the garment is designed to be worn in four different manners, which allow more body areas to be stimulated by the vibration elements with the use of minimal electronic components possible.

Therefore, the progress in e-textile and smart clothes might have great influence on the way the rehabilitation will be provided in the future. Nowadays, not many smart clothes products are adopted by people for health monitoring or healthcare. Moreover, not many smart clothes can be seen in the streets today and only a few are integrated in the ready to wear clothing segment or are affordable. Quality of the products, problem with connectivity and durability of the smart clothes, power consumption and problems related power supply for continuous functioning, have been identified as barriers for adoption of these products [45]. Low level of population knowledge (particularly of engineers or health professionals) on smart textile or smart clothes also might contribute for less use of these products. Low production rates and costs are other barriers as well as safety and health constraints. There are also critical issues concerning the real need for smart textiles and the ethical issues of being monitored [45].

3 Technical and Technological Issues

Following we present several technical and technological issues related smart clothing for rehabilitation context. Information on conductive textile, type of textile/fabric manufacturing, sensors based on textile, textile as antenna, textile as actuator, textile as computer interface, circuit board into textile are presented and discussed. As an important challenge described by engineers on smart clothing is related with management of power supply, we present solutions described in the last years for power supply in smart clothing, particularly related energy harvesting. Connectivity, integration of things (i.e. integration of sensors, computing circuits, power supply) in smart clothing, wearability, maintainability, as well as issues related to design for durability and affordability of smart clothes are also discussed.

3.1 Manufacturability

The design of smart clothing involves the explorations of materials, structures, and manufacturing technologies. Electronic components for smart clothing should be designed in a functional, robust, small, unobtrusive and inexpensive way. As clothes should be designed for production in large quantities over different sizes of bodies, the manufacturability of smart clothing requires extensive research and comprehensive understanding of processes. By their nature, wearable e-textiles have a more complex form, structure and stress factors that should be considered in comparison with their non wearable e-textile and common textiles.

3.1.1 Conductive Textile

The conductive textile should be made from materials that should be robust to weaving, washing, and wearing stresses, should allow transmitting signals at high

Table 1 Electrical properties of metal monofilaments fibers

Conductivity [Sm/mm^2]								
Ag 99.99 %	Cu/Ag	AgCu1	Cu	Ms/Ag	Ms[a]70	Bronze	Steel 304	Steel 316 L
62.5	58.5	57.5	58.5	16.0	16.0	7.5	1.4	1.3

[a]German Milbe denomination, where Ms is accompanied by a number stating the composition in %Cu with respect to a Zn complement to 100 %

frequency with sufficient signal integrity and should be insulated to prevent shorts. The company Sprint Metal (Germany) [46] defined metal fibers and wires according to their diameter. A fine wire has a diameter between 30 µm and 1.4 mm, while a metal fiber possesses a diameter of 2–40 µm [47]. The advantages of metal fibers are their strength, composition, biological inertness and ready availability in textile form at low costs [6]. Due to its inertness some fibers are less sensitive to washing or sweating. The metal fibers are heavier than most textile fibers making homogeneous blends difficult to produce [48]. Moreover, they cannot provide uniform heating and their brittleness can damage spinning machinery over time. As the wired are not only characterized by their resistance, but also by wave effects depending on the line geometries and the surrounding material, the geometric structures that are created in the textile fabrication processes should also be carefully considered [49]. Moreover, the textiles that are used for smart clothing have to be made of fine and elastic fibers so that they are comfortable and lightweight.

According to the material used, conductive textiles with different electrical properties were developed. The products range from copper (Cu) and silver-plated copper (Cu/Ag) filaments, brass (Ms) and silver-plated brass (Ms/Ag) filaments, aluminum (Al) filaments to copper-clad aluminum (CCA) filaments [50]. In Table 1 electrical properties for various metal monofilaments [50] fibers are presented. The desired properties of the textile/fabric should be considered in choosing conductive filaments. Depending on the raw material used and the e-textile structure, different impedance behaviors could be obtained. Using the 'conductive thread' approach, no additional step after manufacturing of the fabric is required to establish conductivity. The conductivity of these conductive threads lies in the range of 10–500 Ω/m [51].

3.1.2 Types of Textile/Fabric Manufacturing

The integration of conductive yarns in a structure is a complex process. Different ways exist to produce electrically conductive fabrics. E-textiles might be produced by embroidering, sewing, non-woven textile, knitting, weaving, making a spinning, braiding, coating/laminating, printing and chemical treatments (Fig. 9) [6].

It should always be ensured that the electrically conductive fabric is comfortable to wear or soft in touch rather than hard and rigid. Embroidery offers advantages over knitting or weaving [6]. The image from Fig. 9 related embroidery technique represents a textile antenna realized at Ohio State University by embroidery process with a geometrical accuracy of 0.1 mm [52]. Embroidery technique allows

Fig. 9 Types of textile/fabric manufacturing

precisely specifying the circuit layout and stitching pattern in a computer-aided design (CAD) environment, from which any number of articles can be sewn under machine control. This process also allows control and integration of yarns with different electrical properties, for instance, different resistances. Conductive thread and yarn embroidery can be accomplished on single or multiple layers of fabric or can be applied on various types of textile and apparel products in one step [6]. The image from Fig. 9 related with spinning represents the production of thread by Spheral Power company [53] by alignment and connection of micro spherical solar cell. This thread is then used for textile-based energy harvesting. A group of researchers of Instituto Italiano di Tecnologia—Center for Space Human Robotics, Politecnico di Torino—Applied Science and Technology Department, in collaboration with a spin-off company, Politronica Inkjet Printing (Italy), developed EMG sensor matrices by inkjet printing a silver nanoparticle-based ink on a polyimide flexible patch. Their results indicate good behavior and a base conductivity of 35 % with respect to traditional electrodes [6].

In Fig. 9 the image related with coating/laminating represents the stretchable material produced by DuPont Microcircuit Materials, Research Triangle Park, N.C., that was launched in 2014 [54]. The stretchable conductive inks and related materials produced by DuPont Microcircuit can be printed on a textile to produce smart active wear, health monitoring clothing and other smart textiles [54]. The silver-based conductive ink is applied to thin thermoplastic polyurethane (TPU) film that is then laminated onto the fabric. The company reports that the new materials provide a durable (the inks resist to repeated elongation and continue to show strong performance after 100 wash cycles), comfortable, flexible, cost-competitive, manufacturing-ready alternative to electronically conductive yarns, polymers and other materials. Nanotechnology contributes to development of various textiles with great potential in development of smart clothes. Nano-treated textiles were developed with capability of self-cleaning, water repellent, anti-microbial function, fire retardation, etc. In Fig. 9 the image related with nano-treated textile represents one product developed by Swiss company—Schoeller [55]. By using 3XDRY technology the Schoeller produced a textile that on the outside is finished with water-repellent function whereas on the fabrics inside it absorbs perspiration.

Knitted electrodes for electrocardiography and electromyography [28, 29] were developed by our team. A study was conducted using several conductive raw materials, in the form of continuous filaments or staple yarns with the purpose of constructing single face weft-knitted structure and to investigate their electrical behavior. One of the key characteristics of weft knitted fabrics is their elasticity, very appreciated by the end user, which results in body fit and very comfortable pieces of garment. This kind of fabrics might be adequate to embed electrodes due to their capability to closely follow the human body and thus to provide an optimal contact between skin and electrode. Three distinct yarns were compared in our studies: Bekitex, which is a one-ply 80 % polyester/20 % stainless steel staple fiber yarn (Bekaert, Belgium [46]), Elitex silver coated polyamide multifilaments, with and without a core of bare elastane (Elitex, TITV-Greiz, Germany [56]) and Shieldex silver plated polyamide yarn (Statex, Germany [57]). Conductivity of the silver plated yarns is in the order of tens of Ω/m, whilst the much cheaper Bekitex yarn has a reference value for the resistance of 100 Ω/cm. A MERZ model MBS seamless jacquard knitting machine with a single needles system, located in the cylinder, was used. The disk is equipped with transferring jacks, knives and springs which allow a very flexible control of the yarn entry in the knitting zone. Being a jacquard machine, it is possible to obtain complex structures with localized variations, and to produce embedded electrodes. Different knitted structure were studied that may be categorized in two groups: (1) structures designed with knit and float loops and (2) structures designed with knit and tuck loops. A total of 40 structures were designed and divided into two groups of twenty, as stated above, according to the loops used [29]: (1) knit and float loops (LF's) and (2) knit and tuck loops (LC's) (Fig. 10). The design was done trying to produce smooth fabrics with the highest density technically possible. Using fabrics with smaller distances between conductive and non-conductive threads (that means between signal and ground line) would enable lower line impedance [49]. Materials with higher density have a better electrical conductivity and contact than the same material with a lower density [29]. Hence, the higher the structure's density, the better the performance is. Five structures of each of the groups were then produced in a Merz MBS circular knitting machine, with normal, non-conductive textile yarns. After fabricating the first samples, those that showed little mechanical strength or other technical problems from the textile point of view were replaced by new structures. The procedure was repeated until ten adequate structures were obtained. The repetition module of the selected structures is given in Fig. 10, where the rows represent knitted courses and the columns the number of needles used in this module. After the ten knitted structures were finally selected, the electrodes started to be fabricated

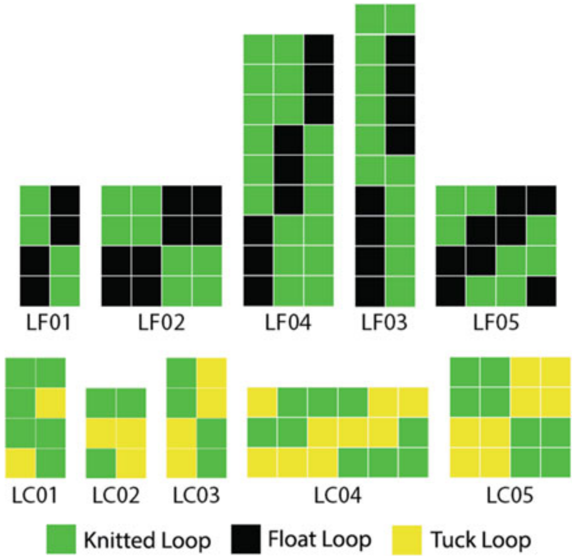

Fig. 10 Selected knitted structures LF: Float loop based, LC: Tuck loop based structure

with Bekitex yarn. All electrodes have 34 courses by 56 columns, resulting in a 2 cm side square. A line of 16 courses for 85 columns was also designed along with the electrode to provide the electrical connection to the conditioning circuit. The silver coated yarn, with or without bare elastane and with minor differences between the different structures have proved to be better yarn for knitted textile electrodes than Bekitex yarn [29]. Electrodes produced with one of the loop types produced better results than the others, namely the tuck loop used in the LC structures. Electrical insulation, if necessary, is achieved by coating with specific silicone compounds (Elastosil® from Wacker [58]). Elastosil silicone has been found to have a high adhesion capability, high electric isolation and stretch when compared with similar materials. The electrode area protrudes from the rest of the fabric, improving contact between the skin and the electrode. Electrodes based on silver coated yarn have proved more adequate for integration in T-shirt presenting better wearability and conductive properties than other tested electrodes. Electrodes based on Bekitex yarn presented good electrical characteristics, however, the resulting fabric cannot be used being too abrasive and unpleasant when in contact with skin and it was not able to recover its rest dimensions after stretching.

3.1.3 Textile as Sensors

Conductive textiles that change their electrical properties as a result of the environmental impact can be used as sensors. Most important for motor rehabilitation are the **strain gauge sensors**. Textiles acting as strain gauge sensors were developed with the purpose of monitoring respiration rate as well as for detection and monitoring posture, position of body segments and body motion. Textiles able **to**

acquire bio-potential (i.e. electrocardiography signal, electromyography signals) and smart T-shirts able to monitor **temperature** were also developed. Textiles that **react to deformations** have being used as pressure sensors, stretch sensors or as breathing sensors. Textile for **accelerometry** was also developed and included in smart clothing.

The most important progress in textile sensors for health monitoring is in the area of **heart beats sensing**. In European funded project WEALTHY coordinated by team from Italy, two types of sensors were developed for the integration in garments. The first sensor was a lycra based fabric coated with carbon black and rubber, for breathing rate recording. The other sensor was metal yarns based for heart rate monitoring. All sensors were integrated in a garment knitting process. Together with the textile development a miniaturized short-range wireless system was developed in order to transfer biophysiological signals from the garment to a computer or a mobile phone. In MYHEART project, a continuation of the WEALTHY project, two type of e-textile were created. One was a woven fabric with insulated copper wires, using the linear dependency of wires temperature and their resistance as a temperature sensing e-textile. Other types of textile sensors developed in this European project were a pressure sensing matrix and sensors for heart rate and muscle activity recording. The aim of the project was to gain knowledge on health status of a large group of people by continuous monitoring vital signs using flexible and wearable systems. In the last decade different textile based on various fabric processes were developed aiming heart beats signal acquisition [59–62]. Different yarns as well as different knitting structures were used in order to acquire changes in volume in measured body part (plethysmography) or electrical potential produced by heart (electrocardiography). A textile based system was developed by Lanata team, from Pisa University, for the area of cardiac monitoring and cardiac rehabilitation [63]. The heart and respiratory function is acquired through a textile based piezoelectric sensor (plethysmography) as well as with ultrasound (US) transceiver. The multimodal broadband piezoelectric transducer is based on polyvinylidene fluoride polymer integrated into a textile belt that might be wrapped around the chest. The system include advanced electronic control unit, floating power supply, and wireless communication support. The multimodal transducer works either as an ultrasound transceiver or piezoelectric sensor. The US transceiver is enabled to work at high frequency, i.e., it is excited by suitable pulses to emit an ultrasonic wave, which penetrates the body and receives the echo signals bouncing off the biological interfaces having different acoustic impedances. The piezoelectric sensor works at low frequency and acquires both signals generated by heart apex movements and the mechanical movement of the chest induced by respiration. The smart clothes based on the Lanata system, beside heart rate and respiratory rate detection may give rich information on the cardiac and respiratory functions in clinical context.

Fabrics incorporating thermocouples can be used for **sensing temperature** [64]. Textiles able to monitor body temperature were developed [61] and nowadays T-shirts monitoring temperature in addition to other vital or body motion signals are commercialized (i.e. Cityzen Sciences [65] Fig. 4). The information on temperature has great relevance in clinical context and smart clothes integrating temperature sensor are important for health monitoring and healthcare services.

The Meyer team [30] developed a **capacitive pressure sensor** for integration into clothing that might be used in rehabilitation, pressure-sore prevention or muscle activities monitoring. The developed sensor has spatial resolution of 2 times 2 cm and an average error below 4 percent within the measurement range 0–10 N/cm^2. Applied on the upper arm the textile pressure sensor determines the deflection of the forearm between 0 and 135° due to the muscle bending.

In EU funded project MICROFLEX (2008–2012) micro fabrication production technologies for MEMS on textile fabrics was investigated. The processes used are based on thick film printing, inkjet printing and sacrificial etching for the MEMS. These printing processes have many benefits including low-cost, repeatability, flexibility, suitability for high throughput production, relatively inexpensive equipment, short development time and the capability of depositing a wide range of materials. This technology is promising as it contributes for textile **accelerometer** development with application on smart clothes that might monitor both body motion as well as vital signs (i.e. heart rate, respiratory rate) at a lower price, therefore increasing affordability of smart clothes for rehabilitation context.

3.1.4 Textile as Antenna

An antenna is essential, if the purpose is to develop a wearable and autonomous system. It allows one to transfer information from the sensors hosted inside the garment to a control unit, or to monitor other electronic parameters. A wearable antenna is thus the bond that integrates clothes into the communication system, making electronic devices less obtrusive [6]. Fabric-based antennas are a relatively simple application of smart fabrics. Simple textile antennas are merely conductive yarns of specific lengths that can be stitched or woven into non-conducting fabrics [66]. Rapid progress on the fabrication of conductive textiles has produced significant development of wearable antennas, exploiting new flexible and conformable smart structures [67]. To achieve good results, wearable antennas have to be thin, lightweight, low maintenance, robust, inexpensive and easily integrated in radio frequency (RF) circuits. Stoppa and Chiolerio [6] indicated as main requirements for a correct antenna in a smart clothes project:

1. choosing the correct positioning of the textile antenna;
2. the textile antenna must be made with an accurate thickness stacking the different fabrics;
3. the geometrical dimensions of the patch must remain stable;
4. the connections between the layers must not affect the electrical properties and the connections with other parts of e-garments have to be stable and robust.

Planar structures, flexible conductive and dielectric materials are specific requirements for wearable antennas [68, 69]. Lowering the dielectric constant increases spatial waves and hence increases the impedance bandwidth of the antenna [70]. The moisture can affect the dielectric behavior of textiles. In particular, when water is absorbed by the fibers, an increase of the dielectric constant and loss tangent occurs. A textile cover or superficial treatment may then provide a sufficient protection from the humidity and varying climatic conditions [71]. Another issue related to textile antenna integrated in smart clothes regards the movement of the body that can deform the spatial geometry of the antenna and affect its performance. When the textile fabric adapts to the surface topology it bends and deforms, causing changes to its electromagnetic properties and thus influencing the antenna performance [72]. Thus, a wearable FM antenna should be designed so as to be wider than the FM broadcast band (about 81–130 MHz) not to suffer from the detuning caused by the human body [73]. Patria (Finland) is a company with expertise in textile antenna design. It develops textile antennas composed by conventional or industrial fabrics, and typically conductive antenna parts are made out of modern conductive fibers [74]. Textile RFID (Radio-Frequency Identification) is a particular solution of antenna. In this sector TexTrace AG (Switzerland) provides the manufacturing line as well as the components for industrial in-house production of woven RFID labels. Integrating RFID and the label will provide added value for garment manufacturing, logistics, sales and after-sales management [75]. Textiles based RFID integrated in smart clothes might greatly contribute to management of the data for patients receiving rehabilitation in healthcare information system.

3.1.5 Textile as Actuator

Actuators respond to a signal and cause effects such as a color change in a textile, release of substances, change of shape, vibrate and others. One example of textile acting as actuator with potential use in rehabilitation is the electroluminescence materials that are light emitting materials where an applied voltage is the source of excitation. Light emitting diodes convert electrical potential to light and are often used as actuators in smart textile applications [76]. These materials may be used for providing biofeedback [77] in motor rehabilitation.

3.1.6 Textile as Human-Computer Interface

Human-computer interfaces based on e-textile can be grouped into two categories: input devices and annunciation or display devices. Input devices can include capacitive patches that function as push buttons [78], or shape-sensitive fabrics [79] based on motion or flexing, pressure, stretching or compression sensors. Annunciation and display devices may include e-textile based speakers [80], electroluminescent yarns [81], or yarns that are processed to contain arrays of organic light emitting diodes (OLEDs) [82]. Shirt developed by Xenoma e-Skin [31] (Fig. 6) from Japan allows subject interaction with virtual reality. Gloves developed by 5DT—DataGlove™ VRLOGIC with hand flexion sensors based on fiber optic allows to take input from user's hand gestures. Four wires were used for each finger or tube to build up a circuit. The voltages coming out are varying depending on the finger position [33]. Gloves versions with 5 or 14 sensors detect the wearer's hand movements and allow better working with 3D modeling and animation software. The drivers allow for the animation of hands as well as using the glove as a puppeteering tool.

3.1.7 Power Supply in Smart Clothes

The most common power sources in smart clothes are AA batteries or lithium batteries. Great importance in smart clothing is nowadays given on energy harvesting (scavenging) and conservation. Energy harvesting and distributed power management are essential in design and development of smart clothes. The generation of electrical power from body movements and wearing mechanical stresses [83–88] body heat [89, 90], or solar cells [53, 91–95] have been demonstrated.

For example, Infineon claim a technology that might recover energy by body movements to feed MP3 players integrated in a jacket using piezoelectric materials [83]. In the U.K. the University of Bolton has developed a novel technology that integrates piezoelectric polymer substrate and photovoltaic coating system to create a film or fiber structure that is capable of harvesting energy from nature, including sun, rain, wind, wave and tide [85, 86]. Georgia Tech researchers have made a flexible fiber coated with zinc oxide nanowires that can convert mechanical energy into electricity [87]. A technology based on gold-plated zinc oxide nanowires with potential to harvest energy from many kind of vibration or motion for generation of electric current was developed. Gold-plated zinc oxide nanowires, each about 3.5 μm tall, are grown on a flexible polymer fiber and these nanowires brush against untreated nanowires, which flex and generate current [88].

Distributed batteries, possibly fuel cells or filament-type batteries woven into the fabric have already been demonstrated [49]. Photovoltaic is the most advanced way of providing electricity far from any mains supply. Integration of flexible solar cells into clothing can provide power for portable electronic devices. However, it might suffer from the limits of ambient light intensity. Nevertheless the energy demand of portable devices is now low enough that clothing-integrated solar cells are able to power most mobile electronics [92]. The European funded project Dephotex (2008–2011) explored and developed photovoltaic cells, in order to get flexible photovoltaic textiles based on fibers that turn solar radiation into energy. The research was based on fibers with conductive properties as substrate for flexible photovoltaic textiles. Sphelar Power Corporation developed an energy-harvesting textile where spherical solar cells are interweaved [53]. The ILLUM jacket is based on technologies including printed electroluminescent ink and printed photovoltaic technology. The functional parts are placed outside the jacket and into several ergonomic places at the front, and the photovoltaic e-textile at the shoulders and top of the back [95].

Unlike low-power systems that have a centralized power source like batteries, energy harvesting elements are distributed across the fabric, giving each processor access to local power. Because the local power supplies will be depleted and recharged at different rates, the task assignment service should predict and balance remaining power across the textile. The power requirements of the system can be reduced by optimal management of active sensors and processing units [49] as well as selecting communication protocols and architecture [96]. A stochastic approach to communication-based design, integrating wireless networks-on-chip (WNoC), voltage frequency island (VFI), and dynamic voltage/frequency (V/F) tuning in a synergistic manner, was proposed to achieve significant energy savings without paying a noticeable performance penalty [96].

3.1.8 Circuit Board into Textile

In addition to behaviour like sensing, reacting on and conducting electricity, the textile will be able to perform computational operations [97]. Most integrated circuits are made of silicon because of the semiconductor properties of this substance. Researches on materials for organic electronics allow development of circuits suitable for wearable application. These materials are flexible, lightweight, strong and have a low production cost, however the electronic properties of the conducting polymers do not match those of silicon [98]. The P-FCB [6] is one of the new technologies allowing implementation of a circuit board on a plain fabric patch for wearable electronics applications. It features a soft and flexible impression just as normal clothes.

3.2 Connectivity

Smart clothes typically contain just enough onboard computing to gather data and transmit it over a network. Communications may be a low-powered wireless local area network (WLAN) connection to a gateway, or a high-powered connection to the Internet via mobile technologies, like smartphone or tablet. The implementation of a high-level application programming interface for communication requires that the routing service know the embedding of the e-textile in three-space, and low-power, fault-tolerant communication [49]. In the event of a tear in the fabric, single leads running to one collection point could lead to significant rather than graceful degradation in performance. The smart clothes require multiple points at which analog data is converted to digital data; these conversion units, likely in the microcontroller or digital signal processor class, would need to communicate within a fault-tolerant network [49, 96]. The networks with multiple sensors should be designed so that the whole network continues to function even if individual nodes fail, or lose connectivity, though data may be lost. Attaching the leads of every sensor/actuator to a single processing unit and power supply increase risk for data lost and fail in data communication.

Sensors from clothes together with embedded data communication and computation in smart clothes ensure mobility, ubiquitous connectivity or cloud based clinical decision support. While robust analytics and algorithms run at information system based on smart clothes, alert condition along with annotated data may be real time reported to the health professional on his/her mobile device allowing decision on optimal strategy for rehabilitation in a timely manner. In conjunction with the availability of textile embedded computing, the necessity of textile-based interconnectivity has also emerged. Internet of Clothes (term related with Internet of Things) may increase the quality of user experience. Unique identifier for smart clothes combined with communication capability and online presence pave the way for Internet of Clothes.

3.3 Integration of Things for Smart Clothing

Intelligent/smart clothes are characterized by optimal design, development and integration into textile of different things (i.e. yarns, textile, sensor(s), microchip(s), keypad(s), display(s), power supply, communication and control structure(s)).

In many smart clothing the computation is made *offline* (that is, on a separate system, connected to the fabric itself) or *onto* the fabric (on controllers attached onto the fabric) [49]. Generally, the computation is done in silicon, but with the advances in nanotechnology, molecular or polymer based technology, the possibility exists of having computation embedded into fibers (computation *into* the fabric) [97]. Better power efficiency might be achieved when communication among processing elements is wired with conductive textile in comparison with wireless communication. However, as textiles have generally low manufacturing costs the defect rate of the processing nodes and physical links might be higher than in the case of wireless network [49]. When many processing elements are connected in a textile area network, acquisition, processing, storage and communication capabilities shall be considered together with power consumption. For example, in smart clothing that includes electromyography elements together with other body motion or vital signals components, many technological aspects are challenging in terms of textile fabric as well as signal acquisition and processing. Sampling frequency of at least 250 Hz is necessary for the clothes that record surface EMG. The majority of the body sensor networks manage gathered data at a sampling rate of a 1–100 Hz per channel. Moreover, when requirements of being lightweight, comfortable, and at low cost is added, developing smart clothes that monitor muscle activity through EMG with accuracy necessary for assessment of impairment in clinical condition, remain a complex work and yet with many technological issues to be solved in the future. In our approach, Bluetooth communication sensor modules (Shimmer3ExG) were used as part of a wearable solution for surface EMG and ECG monitoring using smart clothes for physiotherapy context [29]. The

Shimmer3ExG module provides a configurable digital front-end, optimized for the measurement of physiological signals, for example 5-lead ECG or 2-channel EMG. The measurement channels of each sensor module were connected to the electrodes with metallic snaps. Using a desktop or mobile application the sensor modules were configured in order to perform the signal acquisition with a maximum of 1024 samples. To improve the SNR a second-order Butterworth high-pass filter at 10 Hz was used, thus the constant presence of signal fluctuation and some motion artefacts were removed.

In terms of intelligence, the smart system will requires a central processing unit [99] that will receive, store and evaluate data from the different sensors and decide action on the basis of the results. The processing unit is a complex structure of electronic circuitry that executes stored program instructions. Included in this structure are; integrated circuits, secondary storages, power supply and communications technologies [98]. For better protection of the electronics and to increase durability some electronic components might be encapsulated in a robust package. Detachable structures should provide easily recharging and data transfer. Redundancy for both computation and interconnects, as well as energy sources was proposed [49] to ensure reliable operation in the presence of harsh or regular wear-and-tear environments.

3.4 Durability

Making smart clothes durable dictates that the system should: tolerate faults both permanent and transient, that are inherent in the manufacture and clothes use; have protection against various type of stress; be repairable; and that the system functionality should gracefully decline as components fail. For example, as textile material has viscoelastic behavior, inner tensions decrease over time and the geometry may change (especially in washing treatments) [49]. Damage of the components by washing processes and daily use shall be considered. Most solutions known so far require removal of complex electronics before starting the cleaning process. Several solutions for reducing impact of washing processes on e-textile were presented in the last years: (i) easy separation of electronic most influenced by washes; (ii) developing e-textile resistant to many washing cycles (i.e. NTT DoCoMo [100] shirt from Japan); (iii) developing textile resistant to dirt and with self-cleaning properties [101–103]. For example, WARMx underwear allow easily separation of the accumulator battery from the item of clothing without a problem thanks to the pushbuttons. Exhaustive testing has also proved that the conductivity remains even after a very high number of WARMx underwear washes. Treating a textile with a thin coating of titanium dioxide particle which measure just 20 nm in diameters, turn the textile able of self-cleaning [102] when is exposed to light. The surface of the textile material when exposed to light breaks down the impurities such as dirt, pollutants, and micro-organisms that come in contact with the fabric into carbon dioxide and oxygen, making possible cleaning of clothes only with light

[101, 102]. Other method presented for development of textile with potential of self-cleaning is based on synthesis of photo-active fabrics of silver and copper nanoparticles [103]. The hierarchical superstructure of these functional fabrics facilitates the access of reactants and visible light to the catalytically active sites of a localized surface plasmon resonance (LSPR)-active nano-metals. This improves the efficiency of redox processes under visible light photoexcitation. Mechanistic investigations reveal that light can dramatically influence the electron transfer processes in Ag@Cotton and Cu@Cotton that are critical for efficient redox reactions. The results of this work will be helpful in designing new multifunctional fabrics with the ability to absorb visible light and thereby enhance light-activated catalytic processes.

Other important concern related with durability is the connection between the conductive fibers and electronic components. In smart clothes with a large number of sensors and actuators simply attaching the leads of every sensor/actuator to a single processing unit and power supply would not meet the design goal of a durable e-textile. Redundancy for computation, interconnects, energy source [49] and design of the whole network so it would continues to function even if individual nodes fail, or lose connectivity, was proposed to ensure reliable operation in the presence of harsh or regular wear-and-tear environments.

To ensure durability and sustainability of smart clothing the design should also consider the potential environmental impact of manufacturing and services through the whole life cycle from raw-material acquisition, the production processes leading to products, transport processes, the product's use phase and its end-of-life stage [104].

3.5 Testing

Testing is necessary during smart clothes manufacturing process as well as for certification as medical device, or validation of their effectiveness on rehabilitation context. Among requirements for certification of smart clothes for medical use, data shall be included related to specifications, methods of manufacture, method of sterilization, results of risk analysis, results of calculations and test reports, reference to applicable harmonized standards, evidence that the essential requirements have been met [105]. Suitable quality system should be implemented in all relevant stages to ensure product performance and safety.

Various techniques for testing electrical properties of different textile and to optimize the fabrics and the signal line configurations are currently used. Time domain reflectometry, that measure the signal reflections along the transmission line, might be used for impedance measurement of e-textile. The textile with metal only in X direction have lower capacitance and inductance and, therefore, provide faster signal propagation that the textile with metal in XY direction [49]. Frequency characterization of the textile might be realized by using a network analyzer, to investigate textile transmission lines and transmission properties. Testing of digital transmission should consider the line length, number of line and crosstalk effects from neighboring lines. Based on frequency characterizations, conclusions on possible line lengths, resulting losses, and usable bandwidth might be extracted [49].

In our work [28, 29] samples of knitted textiles developed by our team with different sizes were submitted to electrical characterization. The parameters under study were the sensor's dimension and the structure.

As thermal comfort when wearing smart clothes in rehabilitation sessions has great relevance for patient as well as for health professionals (taking into account that many patients might have impaired thermoregulation function) we proposed the use of thermography to investigate the effect of developed e-textile on body temperature during relatively long physical effort [29].

Confirmation of conformity with the requirements concerning characteristics and performances under normal conditions of use of the smart clothes and the evaluation of the undesirable side-effects must be based on 'clinical data' [105]. Several guidelines were deployed for assessment of the effectiveness of the medical devices in therapeutic processes. For example, the methodology guidelines for testing effectiveness of physiotherapy interventions are defined in PEDro (the Physiotherapy Evidence Database) [106]. We also proposed a methodology of rating quality of evidence related devices for health monitoring and healthcare based on RE-AIM (Reach, Effectiveness, Adoption, Implementation and Maintenance) and GRADE (Grading of Recommendations Assessment, Development and Evaluation) guidelines [107].

3.6 Wearability

Smart clothing should be lightweight, breathable, comfortable, easy to clean, easy to wear and take off. The wearer needs a comfortable touch in case the e-textile gets into direct contact with the skin. The textiles that are used for clothing have to be made of fine and elastic fibers to be comfortable and lightweight (a low weight per unit area, not more than 300 g/m^2) [6]. Especially for clothing, tactile properties such as smoothness stretch, recovery, drape, shear and handle are quite important. These demands are inconsistent with the materials and geometries that are needed for a reasonable electrical conductivity, because the incorporation of elements such as metal fibers within textiles increases stiffness and reduces elasticity. However, in the last years various fibers, yarns, textile with conductive properties with high level of wearability were produced. Smooth surfaces are, in principle, more comfortable. They increase heat flow and the area of contact, which not only improves electrical conductivity, but also creates a cooler feeling [29]. However, they slide more easily over the skin, being thus more difficult to stabilize. These aspects are quite relevant in garments that are to be worn in sports, or in smart clothes that required fixed position of the sensors or electronic components necessary for communication and position detection. Moreover, it should be better that the design of smart clothes follows the principle of universal design. Universal design is a term coined by

R.L. Mace in [108], to describe the concept of designing all products and the built environment to be aesthetic and usable to the greatest extent possible by everyone, regardless of their age, ability, or status in life. Similar to 'design for all', rather than designing for certain disabilities, the approach aims to create a design solution that works for everybody, whether disabled or not. Universal design aims to make products usable in the broadest range of situations, whether the user is permanently disabled or not. The seven principles of universal design [108] can help with that.

Principle 1: Equitable use—The design is useful and marketable to people with diverse abilities.
Principle 2: Flexibility in Use—The design accommodates a wide range of individual preferences and abilities.
Principle 3: Simple and Intuitive Use—Use of the design is easy to understand, regardless of the users experience, knowledge, language skills, or current concentration level.
Principle 4: Perceptible Information—The design communication necessary information effectively to the users, regardless of ambient conditions or the user's sensory abilities.
Principles 5: Tolerance for Error—The design minimizes hazards and the adverse consequences of accidental or unintended actions.
Principle 6: Low Physical Effort—the design can be used efficiently and comfortably and with a minimum of fatigue.
Principle 7: Size and Space for Approach and Use—appropriate size and space is provided for approach, reach, manipulation, and use regardless of user's body size, posture, or mobility.

3.7 Maintainability

Maintainability is an important issue when wearable devices are deployed for health or healthcare purposes. Smart clothing should be designed and developed for easily cleaning, drying and repairing.

3.8 Affordability

Higher accessibility to rehabilitation services, convenience of home healthcare, enhanced and optimized care, reducing the needs for in clinic visits may increase affordability of smart clothes for patients in rehabilitation process. Wearable devices, particularly smart clothes may improve diagnostic and ensure time-sensitive intervention, increase patient participation and empowerment. Smart clothes can also create better conditions for patient rehabilitation interventions in the comfort of their homes. The patient receives the exercise and mobility instructions from the health professionals (i.e. physician, physiotherapist, occupational therapist) and follows these instructions. The smart clothes record patient activity and transmit the data to the care provider in real time. After the analysis of the transmitted data, if it appears that the patient is deviating from the instructions, the therapist can initiate the corrections remotely and ensure that the prescribed treatment is followed accurately. These not only saves time and energy of the individuals in rehabilitation contexts, increase quality of care, reduce the need for in clinic visits, but also reduces the burden of the healthcare resources to a large extent. However, clinical staff as well as patients should be sufficiently trained on these technologies to make the best use of wearable system.

Low cost smart clothes with capacity for hardware and software upgrade as well as modular clothes are important to increase affordability. For example, smart clothes, as pants and shoes with capacity to monitor gait might be adopted by patient with Parkinson's disease or health professionals to improve diagnostic or outcome measurements. The patients or health professionals that achieve these smart clothes should have possibility to add other hardware (clothes or accessories) or software components, to monitor others parameters (i.e. balance, heart rate or heart rate variability) when are necessary and to combine and analyze all the acquired data. Therefore, interconnectivity and interoperability should be considered in the design of smart clothes for patients receiving rehabilitation. Also, upgrade with hardware and software for subject environment monitoring may provide a holistic non-invasive patient-centric health monitoring. Fair payment for healthcare services realized by using smart clothes and incentive for adoption of these technologies may also contribute to increase affordability.

4 Conclusions

Smart clothes can serve us in an unobtrusive and natural way. Current advances in textile technologies, new materials, nanotechnology and miniaturized electronics increase the smart clothes properties and features. Different smart clothes were developed and are nowadays commercialized, some with potential benefits for patients in cardiac, respiratory or motor rehabilitation.

Although, several smart clothes with capability of health monitoring or for healthcare have been brought to market with potential benefit for patients receiving rehabilitation services, in our knowledge their adoption in healthcare practice is non-existent or very low. The research projects in the area of e-textile are dominantly related with health monitoring and healthcare services while company activities are more represented in the sport and fashion areas. Low level of population awareness (particularly of health professionals) on available e-textile and smart clothes, and their potential benefits for health and healthcare might contribute to the gap between research, progress in smart clothes development and their adoption in healthcare services.

We discussed the technical and technological issues related with smart clothes designed for rehabilitation context. Information on conductive textile, type of textile/fabric manufacturing, sensors based on textile, textile as antenna, textile as actuator, textile as computer interface, circuit board into textile was presented and discussed. As an important challenge described by engineers on smart clothing is related with management of power supply, our study identified relevant progress in this domain, particularly on energy harvesting. Connectivity, integration of things in smart clothing, wearability, maintainability, as well as issues related to design for durability and affordability of smart clothes were also discussed. The data that we present on smart clothing for rehabilitation context underscore the requirement of multidisciplinary team, in which knowledge on human physiology and consumer behavior, rehabilitation techniques and technologies, textile fabric, sensors, electronic device deployment, telecommunications, computing, informatics, chemistry, physics should be integrated for design and development of tailored smart clothes, for subjects receiving rehabilitation.

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