TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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Textile-Based Sensors and Smart Clothing System for Respiratory Monitoring

Julkaisu 1210 • Publication 1210

Tampere 2014

Tampereen teknillinen yliopisto. Julkaisu 1210
Tampere University of Technology. Publication 1210

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Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Konetalo Building, Auditorium K1702, at Tampere University of Technology, on the 23rd of May 2014, at 12 noon.

Tampereen teknillinen yliopisto - Tampere University of Technology
Tampere 2014

ISBN 978-952-15-3280-1 (printed)
ISBN 978-952-15-3295-5 (PDF)
ISSN 1459-2045

谨以此文献给天堂中的爷爷

This thesis is dedicated to the loving memory of my grandfather

ABSTRACT

Long-term respiratory monitoring provides valuable information for diagnostic and clinical treatment. Traditional measures of respiration require a mouthpiece or a mask, neither of which can be used as ubiquitous healthcare equipment. Using a smart clothing system seems to be a better alternative. Researchers in the field of smart textiles have focused on the development of health-related products since the 1990s, and textile-based sensors used for respiratory measurements have been discussed in several projects. Although the soft and flexible characteristics of textile-based sensors make them attractive, the flexibility of the materials also affects the signal quality. In a laboratory situation, where each sensor is tested as a single element, this is not as critical as in a user situation, where the sensor is integrated into the clothing and worn by different users engaging in different activities.

The principal objective of this thesis was to explore the possibility of performing reliable respiratory monitoring using a clothing platform. The research began by investigating the possible methods and materials that can be used to produce textile-based sensors for respiratory monitoring applications. The aim was to determine the most suitable method for integrating the sensing function into the clothing system. Study results have shown that sensors made with a conductive coating demonstrated superior performance in terms of sensitivity, stability, and reliability. Therefore, five prototype systems based on conductive coating technique were developed. Sensor placement, signal collection techniques, and the clothing system configuration were the main concerns, while issues related to the sensor wearability, maintenance, and aesthetic appearance, as well as the environment and health, were also discussed. Knitting was found to be the most economical method for producing the textile-based sensors; however, sensors made of knit fabric do not perform as well as the coated ones. Therefore, elastic-conductive hybrid yarns have been created to improve the electro-mechanical properties of knitted-based sensors, and eventually, a prototype with two sensors and a built-in data-bus was made by fully-fashion knitting technique.

Two smart clothing system prototypes, based on conductive coating technique, were tested systematically by ten subjects. The first prototype consisted of one sensing element, and the results show that the smart clothing system could successfully monitor the subjects' breathing patterns during sitting, standing, and different forms of running. The system has also proven to be useful in the observation of sleep apnea disorder symptoms. The second prototype consisted of two sensing elements. Apart from all the characteristics of the first prototype system, a system with two sensing elements can be used to determine the relationship between the rib cage and abdomen compartments, which provides information for certain diseases, e.g., cardiac arrhythmias. The second smart clothing system prototype was compared with a conventional respiratory belt for validation. Signals from the clothing system and the respiratory belt were collected simultaneously with a self-designed LabVIEW program, and further processed with MATLAB. Quantitative analyses were conducted based upon different comparison techniques, such as Pearson's correlation, ANOVA and Fast Fourier Transform analysis. The results demonstrate that the smart clothing system can provide reliable respiratory measurements, with signals of comparable quality to the conventional respiratory belt. In addition, the wearability and user acceptance were studied by means of a survey. The survey results indicate that users were more comfortable with the smart clothing system and that most believe that using a smart clothing system will improve both health condition and quality of life.

Keyword: Smart textiles, textile sensors, wearable computing, e-health, conductive coating, knitting, respiratory monitoring

ACKNOWLEDGEMENT

This thesis work was carried out at the Swedish School of Textiles (THS), University of Borås (HB) and Department of Materials Science, Tampere University of Technology (TUT). THS and TEKO, Sveriges Textil och Modeföretag has provided me with financial support, without which the thesis may not have been completed. City of Tampere (Tiederahaston Toimikunta) has supported this thesis with a grant for covering the printing costs. I wish to acknowledge the many people who have helped to make this work possible, through technical contributions and by making my time in Sweden some of the greatest years of my life.

First, I would like to give special thanks to Professor Kenneth Tingsvik, who encouraged me to come to Sweden for my master's degree project and supported me during my continued Ph.D. study.

I wish to thank Professor Heikki Mattila, my principal supervisor, who guided and supported me from beginning to end. I wish to thank Dr. Lena Berglin, my practical advisor at THS. Thanks for being ever enthusiastic about my research and for encouraging my interests both within and outside my research. I would also like to thank my co-supervisors, Professor Mikael Skrifvars and Associate Professor Urban Wiklund, for their assistance throughout my Ph.D. study.

The internal examiner Professor Jouko Halttunen and the official examiners of the thesis, Professor Lieva Van Langenhove and Professor George Stylios, are gratefully acknowledged for their useful comments and suggestions.

I am obliged to acknowledge many of my co-authors and colleagues for their fruitful co-operation: Associate Professor Urban Wiklund, for signal processing and MATLAB coding; Dr. Joel Peterson, for the knowledge of knitting; Siw Eriksson, for her experience in 3D weaving; Emanuel Gunnarsson, for useful discussions of physics and electronics; Associate Professor Leif Sandsjö, for encouraging my future ambitions; and Erik Bresky and Professor Håkan Torstensson, for their wise leadership.

I would like to express my gratitude to the Polymer group in School of Engineering (IH) and Professor Mikael Skrifvars for providing many cooperative opportunities and a well-equipped laboratory, Dr. Azadeh Soroudi and Dr. Tariq Bashir for their experience in the area of conductive polymers, Adib Kalantar Mehrjerdi for his contribution to make the *cyclic tester* a reality, and Haike Hilke for introducing the lab equipment and assistance with the testing.

I also want to thank the students with whom I worked: Waqas Qureshi, for preparing knitted sensors; Cristina Li, for producing prototypes; and Suchawadee Ratnarathorn, for developing wireless connections.

Thanks are also due to all my Chinese friends. Special thanks are given to my cousin Dr. Wang Liang (王亮), for his knowledge of chemistry, and Zhao FeiHu (赵飞虎) for his knowledge of

modeling and mechanics. I would like to mention people from Tianjin Polytechnic University (TJPU), China as well. Special thanks to Professor Ma Chongqi (马崇启) for guiding me in my future career.

Finally, my warmest thanks must be given to my family. Thanks to my parents, for their endless love and support from a distance. And to two special guys, my husband Kun (韩崑) and our son, Kai Xu (韩铠旭). Kun has been incredibly supportive during my studies, Thank you, Kun, I love you! Kai Xu, you are the light of my life. I can only hope to bring you as much joy as you have given me.

Borås, April 2014
Guo Li

TABLE OF CONTENTS

LIST OF PUBLICATIONS

This dissertation is based on the following peer-reviewed publications. The articles are reprinted with the permission of the copyright holders.

1. Guo, L., & Berglin, L. Test and Evaluation of Textile-based Stretch Sensors. In proceeding of *AUTEX 2009 World Textile Conference,* Izmir, Turkey. 26-28 May, 2009.
2. Guo, L., Berglin, L., Li, Y.J., Mattila, H., Mehrjerdi, A.K. & Skrifvars, M. Disappearing Sensor: Textile-Based Sensors for Monitoring Breathing. In proceeding of *2011 International Conference on Control, Automation and Systems Engineering (CASE),* Singapore, 30-31 July, 2011, pp. 1-4.
3. Qureshi W., Guo L., Peterson J., Berglin L., Mehrjerdi A. K., & Skrifvars, M. Knitted wearable stretch sensor for breathing monitoring application. In proceeding of *Ambience* 2011*,* Borås, Sweden, 28-30 November, 2011, pp.72–6.
4. Guo L., Berglin L., & Mattila H. (2012). Improvement of electro-mechanical properties of strain sensors made of elastic-conductive hybrid yarns. *Textile Research Journal* 82(19), 1937-47.
5. Guo L., Berglin L., Wiklund U., & Mattila H. (2013). Design of a garment-based sensing system for breathing monitoring. *Textile Research Journal* 83(5), 499-509.

AUTHOR'S CONTRIBUTION

Article 1: Li Guo planned and conducted the experiments and wrote the main part of the article. The co-authors provided input from their fields of expertise and commented on the text. Li Guo is the corresponding author.

Article 2: Li Guo planned and conducted the experiments and wrote the main part of the article. The co-author Adib Mehrjerdi provided input for building the *cyclic tester*, and the co-author Yinjun Li provided input for constructing prototypes. Li Guo is the corresponding author.

Article 3: Li Guo planned and conducted the experiments, together with Waqas Quireshi. Li Guo analyzed the experimental results, wrote the results and discussion sections, and is the corresponding author.

Article 4: Li Guo planned and conducted the experiments and wrote the main part of the article. The co-authors provided input from their fields of expertise and commented on the text. Li Guo is the corresponding author.

Article 5: Li Guo planned and conducted the experiments and wrote the main part of the article. The co-author Urban Wiklund provided input based on his expertise in MATLAB coding and signal processing. Li Guo is the corresponding author.

LIST OF FIGURES AND TABLES

ABBREVIATION LIST

CLR	Carbon black-Loaded Rubber
COPD	Chronic Obstructive Pulmonary Disorder
CPCs	Conductive Polymer Composites
ECG	Electrocardiogram
EU	European Union
FBG	Fiber Bragg Grating
FFT	Fast Fourier Transform
GF	Gauge Factor
GTWM	Georgia Tech Wearable Motherboard™
ICPs	Intrinsically Conductive Polymers
IP	Impedance Pneumography
KPF	Knitted Piezoresistive Fabric
MRI	Magnetic Resonance Imaging
NIRS	Near-infrared Spectrometry
PA	Polyamide
PD-RCR	Plastic Deformation-related Resistance Change Ratio
PEDOT-PSS	Poly(3,4-ethylendioxythiophene) - poly(styrenesulfonate)
PET	Polyester
PPy	Polypyrrole
RCR	Resistance Change Ratio
RIP	Respiratory Inductance Plethysmography
SD	Standard Deviation
TPE	Thermo-Plastic Elastomer

1 INTRODUCTION

This thesis is a study in the cross-areas of smart textiles, wearable computers, and ubiquitous healthcare. This work aims to investigate the feasibility of performing reliable respiratory monitoring from textile-based sensors using clothing as platform. The first chapter presents the background of the study, the objective and research questions addressed in the study, the research methodology and the structure of the study.

1.1 Background of the study

Respiration is defined as *the process of gaseous exchange between an organism and its environment* [1]. It is a single complete act of breathing in and breathing out. In humans and most air-breathing animals, respiration takes place in the lungs. The air fills the lungs during inhalation and lungs expel air during exhalation.

The interpretation of respiration signals is a relatively inexpensive, rapid method, which provides rich information for clinical practice and diagnostic treatment. Knowledge from the respiration cycle is valuable for the synchronization and compensation of heart and thorax magnetic resonance imaging (MRI) scan sequences [2]. Moody *et al*. [3] identified that certain cardiac arrhythmias may be implicit only by reference to respiration. Sleeping apnea, defined as *a cessation in airflow of 10 seconds or longer in a continuous breathing*, indicates a sleeping disorder problem [4, 5], which can be discovered by measuring the respiration rate, depth, and pattern over time [6]. The phase relationship between the rib cage and abdominal compartment breathing, known as thoracoabdominal coordination [7], delivers information on the study of muscle fatigue [8]. Furthermore, researchers recently found that the respiration pattern provides important knowledge in stress studies [9].

1.1.1 Conventional respiratory monitoring devices

Respiration can be monitored by directly measuring the movement of air transformed, or other properties, into and out of the lungs. For example, spirometry measures the flow rate of air, and is considered the ‘gold standard’ for the assessment of lung function [10]; nasal thermocouples are used to measure the temperature change in the air; and mass-spectrometry or acoustic sensors are used to measure the change in carbon dioxide in the inhaled and exhaled air [11]. In the measurement of direct respiration, a mouthpiece or a mask is required. Such items are uncomfortable to the users and rarely applied for home and ambulatory monitoring.

Respiration can also be measured indirectly by measuring changes in body volume. Indirect measurement usually involves the assignment of displacement and movement of the two main body compartments, the upper rib cage and the abdomen [12]. In practice, there are three different kinds of methods used as indirect measurement: impedance pneumography (IP), respiratory inductance plethysmography (RIP), and strain-gauge respirometry [13-15].

IP simultaneously measures the electrical impedance of the respiration signal with the electrocardiogram (ECG) signal [16]. Ernet *et al.* [17] noted that the respiration cycle represents a source of 'noise' in ECG signals. In IP measurement, a weak alternating electrical current is passed through a pair of electrodes (or sometimes four or more) to the human body, allowing the impedance to be measured. This method yields a non-linear signal that is useful only as a qualitative measurement of respiration compartmental movement [18]. In addition, this method cannot be used for thoracoabdominal coordination assessment; as a result, IP cannot be used to detect central or mixed apnea from obstructive apnea in sleep disorder studies [7]. RIP provides an accurate and linear signal by measuring the cross-sectional area change during respiration. In practice, RIP measures the self-inductance of an elastic belt containing insulated zig-zagging wires, which are wrapped around the chest and abdomen [16]. The correct tension is critical. Pulling the belt too tightly will produce a ceiling effect to the actual signal, while a looser belt may not be sensitive enough to detect small respirations [19]. Strain-gauge respirometry measures the circumference change of body compartments. It is a simple and economical way of determining the respiration, however, the sensor is sensitive to any mechanical pressure, and a change in body position can lead to a false signal.

1.1.2 Smart clothing for respiratory measurement

Some disorders, such as chronic obstructive pulmonary disorder (COPD), are difficult to diagnose in clinic, and reliable wearable devices for home and ambulatory monitoring would increase the chance of detecting, diagnosing, treating, and preventing such diseases [20]. Using smart clothing technology seems to be a better alternative to conventional methods of respiratory measurement. The integration of a sensing function into clothing has been presented in several projects since 1990s'. The Georgia Tech Wearable Motherboard™ (GTWM) [21] is considered the first generation of smart clothing for medical applications. The GTWM uses an electrical wiring system with conventional sensors to measure different physiological parameters, which are more precisely designated 'wearable electronics'. One of the first successful smart clothing systems in which the textile-based sensors were used was created by the European Union (EU) project WEALTHY in 2005 [22-24]. In this system, carbon black-loaded rubber (CLR) coated on Lycra® fabrics were used as piezoresistive sensors to monitor respiration frequency. The MyHeart [25] and OFSETH [26] projects also attempted to obtain respiration signals with piezoresistive sensors or optical fibers. In the MyHeart project, piezoresistive sensors and electrodes made of knitted piezoresistive fabric (KPF) were produced to collect physiological data, such as heart rate, respiration, and body temperature. In the OFSETH project, optical fibers were selected as the sensor, Fiber Bragg grating (FBG) and near-infrared spectrometry (NIRS) technologies were used in this project. Using this optical fiber as the sensing element effectively eliminated the electrical noise, but the manufacture and the maintenance of the system become more complex.

1.1.3 The research gap

The long-term monitoring of respiration signals requires new types of sensing systems that are wearable and allow user mobility. Textile-based sensors are seen as attractive; nevertheless, the flexibility of the material is also problematic. In laboratory situations, each sensor is tested as a single element, and sensitivity is not as critical as in user scenarios, where the sensor is integrated into clothing or clothing accessories and worn by different users engaging in different activities. Knowledge of the sensor functionality in a user scenario is critical for a better understanding and development of the smart clothing, and a gap in this research was identified by a literature review. Some studies relating to the development of textile-based sensors for respiratory monitoring have been published [22, 23, 27-31], but literature evaluating the performance of these systems, compared to currently available techniques, is difficult to find. Such an evaluation is necessary to resolve any problems of textile-based sensing systems and to advance their development. Furthermore, in a user scenario, the functionality is not the only measurement that evaluates the importance of the application. Parameters such as wearability, user acceptance, and aesthetic requirements should all be considered.

1.2 Objectives and research questions

The main objective of this thesis is to investigate the feasibility of performing reliable respiratory monitoring from a smart clothing system. This raises the following questions:

Research question 1 (RQ 1): Which materials and technologies are suitable for integrating stretch-sensing functions into clothing? This question is theoretically discussed in Chapter 3 and verified with measurements in Article 1, Article 3, and Article 4.

Research question 2 (RQ 2): How can sensors be embedded into the clothing system? This question is studied and answered in Section 4.2.4, Section 5.2, Article 2, and Article 5.

Research question 3 (RQ 3): How does the clothing system perform in terms of sensor functionality and wearability? This sensor functionality is studied in Article 2 and Article 5, the preliminary system performance results are presented in Article 2, and the comparison results are presented in Article 5. System wearability is studied in Section 5.6.

1.3 Methodology and structure of the study

Research methods utilized during this thesis work involved iterative development and prototyping combined with quantitative evaluations of sensor and system performance. This methodology was found to be suitable for this work due to its multi-disciplinary nature. Implementation of respiration measurement into a clothing system involves knowledge of many fields, including textile technology, materials science, electronics, and biomedicine technology. Therefore, this work has also required collaboration with expertise from diverse research fields. In addition, since this thesis works in a new field, which lacks existing performance testing devices and methods, the development of new testing devices was required.

The overall structure of this thesis is illustrated in Figure 1. Four study packages and five articles support this thesis, as described below.

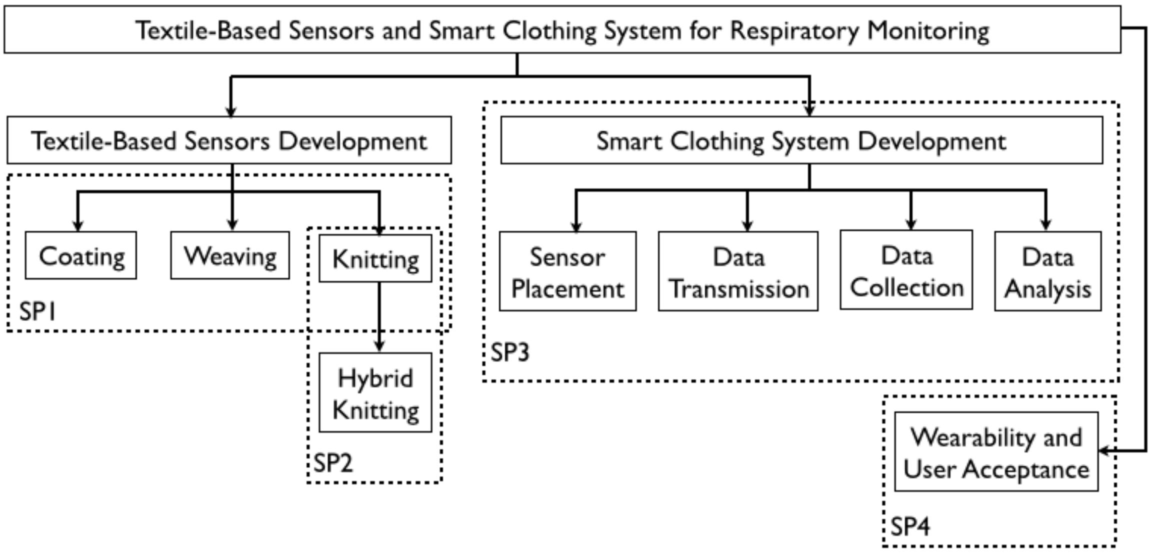

Figure 1. Structure of the thesis work.

Study package 1 (SP1), discussed in Article 1: Textile-based sensors made by different textile manufacture and finishing methods are studied. In Article 1, conductive fabric-based sensors made by weaving and knitting, and conductive coated sensors are evaluated in terms of sensitivity, linear working range and hysteresis. In addition, two measurement methods were used and compared in Article 1. The entire Ph.D. study was based upon the principal findings from Article 1.

Study package 2 (SP2), discussed in Article 3 and Article 4: In Article 3, knitted sensors made of different conductive yarns and different fabric constructions are studied. The aim of the study is to determine the optimal combination of the materials and structures. In Article 4, elastic-conductive hybrid yarns invented to improve the performance of sensing functions are described and evaluated.

Study package 3 (SP3), discussed in Article 2 and Article 5: A new testing device, called a '*cyclic tester*', was designed by the author and manufactured to exam the cyclic electrical-mechanical properties of the sensors. The testing results are presented in Article 2. In this study package, five prototypes have been developed in order to determine the optimal sensing system for respiratory monitoring purposes. Prototype 2 is qualitatively evaluated in Article 2. Article 5 studied the system performance of Prototype 4 in comparison with a conventional respiratory belt.

Study package 4 (SP4): In this SP, surveys were used to determine the user acceptance and the wearability of the prototypes developed in SP2. The result of a preliminary study is given in this thesis but not included in appended articles.

1.4 Scope of the study

Both SP1 and SP2 focus on the selection of materials and technologies for making textile-based sensors suitable for integration into clothing platform. Weaving, knitting, and conductive coating technologies are examined, as these are the main technologies used in fabric production and finishing processes. Due to the limitations of weaving machines, the development of smart clothing system is limited to knitting and conductive coatings.

The author aimed to investigate the entire development process, including sensor manufacture, clothing system design, signal collection, and signal analysis; however, this study is limited to the development of sensor and prototype, as well as signal analysis. The development of an electronic unit is currently in the laboratory testing phase; further development of the electronic unit is beyond the scope of this thesis. Furthermore, verification of temperature-dependent electrical-mechanical properties and long-term reliability was not possible during this thesis, due to the limitations of time and testing resources. It is planned as future work, and is described in Chapter 8.

2 RESEARCH AREA

This thesis work is in the cross-area of ubiquitous healthcare, smart textiles and wearable computers (see Figure 2). This chapter provides a description of the research area, followed by the definition of relevant terms.

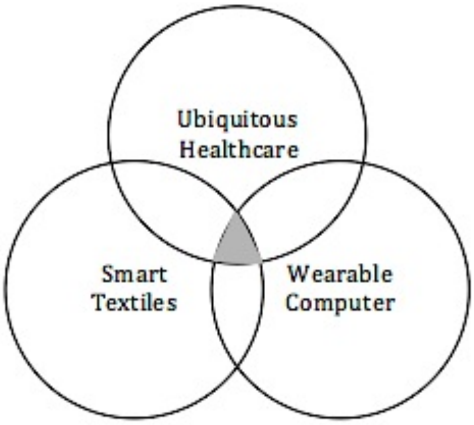

Figure 2. The cross-disciplinary feature of the thesis work.

2.1 Ubiquitous healthcare

According to the statistical forecast from European Commission, the proportion of persons aged 65 years or over in the total population will increase from 17.1% in 2008 to 30.0% in 2060 [32]. Inhabitants demand more healthcare services, which cannot be easily provided without increases in operational costs. However, the current economic slowdown does not allow any significant increases in health budgets [33, 34]; hence, a more accessible and less expensive healthcare solution is required.

Ubiquitous healthcare is a novel field, which uses a large number of environmental and wearable sensors and actuators to monitor and record health conditions of humans. With the help of wearable sensors and actuators, physiological parameters such as respiration, heart rate, blood pressure, and body temperature could be measured to diagnose health problems. Ubiquitous healthcare technology is primarily used by family doctors to remotely monitor patients, and special application areas include chronic disease patients, or those recovering from surgery, heart attack, stroke, or traumatic brain injury. Technology development supports greater self-monitoring by all individuals, which signifies a shift towards ‘well-being management’, and long-term health conditions, such as exercise and diet, can be monitored using ubiquitous healthcare technologies [35].

2.2 Smart textiles

Textiles have been part of human life for thousands of years; the primary function of textiles has been to protect against nature and environmental stimuli. Textiles have lost their unique protective function with the development of civilization; modern textiles bring new functions such as aesthetic pleasure, comfort, and cleaning properties for different applications. In recent years, the textile and clothing market has segmented into two distinct areas: 1) low-cost, high-volume goods, and 2) high-end specification goods, such as sport performance and protective clothing for extreme conditions [36, 37]. The continual shrinkage of traditional textile industries in developed countries indicates the necessity of the paradigm shift, which requires that products enhance quality of life and create added value in terms of functionality and performance. Smart textiles fulfill all criteria of high-added value functionalities, allowing the textile industry to shift from a resource-oriented to a knowledge-oriented industry, and from mass-production to customization [38].

The vision of smart textiles is to create textile products by combining smart materials with computing technology. This combination is introducing a shift from products having static functionalities to those exhibiting dynamic behaviors [39], including, for example, sensing body temperature and actuating thermochromic patterns. This shift changes the method of textile design and use. When textiles become dynamic, the designer approaches interactive design [40], which will affect user needs and preferences. Besides new behavior, smart textiles also introduce shifts in research paradigms. Traditionally, textile researchers are mainly involved with materials, machines, and the processes of development. The methodologies used by the textile researchers are also very straight forward: most of the studies have been quantitative and researchers usually belong to positivist/postpostivist paradigms. However, the multi-disciplinary nature of smart textiles directed a shift in methodology from quantitative to mixed methods belonging to the pragmatic paradigm [41].

2.3 Wearable computer

The convergence of textiles and computing technology also changes the way we design and interact with computers. A so-called wearable computer is the product of such convergence. Bass *et al.* describes a wearable computer, which differs from other computers in that it is utilized during motion, hands-free or with only one hand [42], and without impeding the user's mobility.

Besides mobility, 'disappearance' is another desirable feature of a wearable computer. For this reason, designers of wearable computers are beginning to focus on the issue of making the electronics and the system more like clothing and less like computers. As a result, the hardware of the computer is beginning to disappear into the clothing structure, and clothing, as the new interface, brings the human-computer interaction from operational to simultaneous activity [43]. The complete 'disappearance' occurs not only with the hardware, but also with the awareness of operation. Weiser predicts that in the future, computers will become invisible along with the conscious notion of 'computer' [44], meaning that computer systems will become a part of the human body, such that one can work with them without actively thinking of them.

2.4 Definitions

Both smart textiles and wearable computers are relatively new fields of research and, as a result, much of the terminology has been mixed and misused—for example, ‘smart textiles’ and ‘smart structures’; ‘intelligent textiles’ and ‘functional textiles’; and ‘wearable computing’, ‘wearable electronics’ and ‘e-textiles’. An overview of the different definitions is presented below.

2.4.1 Smart textiles versus smart structures

The definition of ‘smart textiles’ was given by Tao [45], as *textiles that can sense stimuli from the environments, to react to them and adapt to them by integration of functionalities in the textile structure. The stimulus and response can be in the form of electrical, thermal, chemical, magnetic or other origin*.

The ‘smartness’ of the textiles/materials is measured by their responsiveness to environmental stimuli and their agility [46]. **Passive smart textiles** can only sense environments; they act as sensors, it has the capability to convert a signal to another kind of signal. **Active smart textiles** can both sense and react to environments; they have the characteristics of sensors and actuators. **Smart textile system** is a system exhibits an intended and exploitable response as a reaction either to changes in its environment or to an external signal/input. It has the ability to adopt itself to the environment continually [47].

The word ‘intelligent’ once often replaced ‘smart’, and the engineering and computer science world seemed to not distinguish between the two terms. However, regarding to Addington and Schodek [48], the term ‘intelligent’ implies a higher order of organization and performance than ‘smart’.

A smart system/structure, on the other hand, is a system containing multifunctional parts that are capable of controlling, sensing, and reacting to the surrounding environments [46]. The materials utilized in the structure/system are not limited to textiles.

2.4.2 Smart materials versus functional materials

Smart materials are used to construct the smart structures. Similar terms are ‘smart fabrics’ and ‘smart clothing’, where fabrics and clothing are defined as materials. One example is thermochromic materials, which change color in response to changes in temperature.

Functional materials cover a broader range of materials than smart materials. Any material that has functionality is attributed to functional materials, in most of cases functional materials utilize the native properties of their own to achieve an intelligent action [49]. For example, fluorescent and phosphorescent materials, semiconducting devices and superconductors, optical fibers, and liquid crystals all belong to the functional materials category.

2.4.3 Wearable electronics versus electrotextiles (e-textiles)

‘Wearable electronics’, in general, refers to systems that contain electronics and that can be carried or worn during usage. The materials utilized in wearable electronics are not restricted to textiles. The electronics can be integrated into non-textile wearable substrates, for example, a watch or wristband.

Electrotextiles, also called e-textiles, have actually evolved from wearable electronics, which can be classified according to the design paradigm chosen to integrate electronic functions into the textile architecture [50]. The first classification of e-textiles is similar to wearable computers, in which textiles or clothing act as a structure or substrate for the attachment of sensors, output devices, and printed circuit boards. The electronic components used in wearable computers are usually conventional electronics, which have completely different functions than the clothing. This is a hybrid system consisting of functionality from electronics and textiles separately. In the second category of e-textiles, textile materials—such as fiber, yarn, or fabrics—become one essential part of the device or circuit. The functionalities are built into the textile structures, rather than simply added into the structures as extra resources.

Often, the concept of ‘smart textile’ is mixed with ‘e-textile’, as they are both used to create a structure or system that has sensing and actuating functions. However, this is technically incorrect. Smart textiles can be used without electrical and the electronic components involved in, the stimulus and response can be of thermal, mechanical, or other forms. To use the above example, thermochromic materials change color under thermal induction, and the entire process has no relation to electronics.

3 SENSING MECHANISM

SP1 and SP2 focus on RQ1: what materials and technologies are suitable for integrating the sensing function into clothing? Different textile manufacturing techniques and finishing methods were applied to different fabrics to determine the optimal combination of materials and methods. Before sensor production, sensing mechanisms were studied.

3.1 Piezoresistive sensors

The essence of the study is conductive materials used in two ways: piezoresistivity from extension of piezoresistive materials and piezoresistivity from contact resistance between conductive yarns. Theoretical background of piezoresistive materials is given as below.

3.1.1 Piezoresistive effects

The piezoresistive effect describes the change in a material's electrical resistivity when it experiences a strain and deformation. *Piezo* is derived from the Greek word *piezein*, which means to squeeze or press [51]. Semiconductors such as silicon and germanium exhibit large piezoresistive effect. Piezoresistive effect can be seen in metals as well.

The resistivity of piezoresistive sensors made from silicon can be modified by introducing trace impurities into their crystal lattice. The resistivity (μ) of a semiconductor material can be calculated as [52]:

$$\mu = \frac{q\bar{t}}{m^*} \qquad (1)$$

Where q is the charge per unit charge carrier, $\bar{t}$ is the mean free time between carrier collision events, and m^* is the effective mass of a carrier in the crystal lattice.

In such materials, the electron charge and the number of charge carriers can be controlled during the manufacturing process by changing the amount and type of trace impurities added to the material. The effect of applied mechanical strain is to change the number and the mobility of the charge carriers within a material, thus causing large changes in resistivity.

The piezoresistance effect is small in metal compared with it is in semiconductors. It can be calculated using the resistance equation derived from Ohm's law.

$$R = \rho\frac{l}{A} \qquad (2)$$

Where,

l is the conductor length, A is the cross-sectional area of the current flow, and ρ is the resistivity of the material.

The resistance value is determined by both the dimensions and the bulk resistivity of materials. Resistance change in metals is mostly due to the change of dimensions, including the length and cross section, resulting from applied mechanical strain. Bulk resistivity of certain materials may change as a function of strain as well. The magnitude of resistance change stemming from resistivity change is much greater than what is achievable from the dimension change.

3.1.2 Textile-based piezoresistive sensors

Numerous different techniques for creating textile-based piezoresistive sensors have been studied by many research groups (see Table 1). One of the approaches is to integrate piezoresistive yarns directly into the textile structures. This approach has advantages such as being more comfortable in wearing and easier to be fabricated by conventional textile process. Yarn-based sensors have been made using warping methods by Huang *et al.* [53, 54]. In Huang's studies, both metallic-based and polymer-based conductive yarns were warped around an elastic core yarn in order to combine the conductive and elastic properties, so that the resistance of the yarn is proportional to the total length of the yarn. Piezoresistive yarn can be made by coating conductive polymers on to textile yarns, Xue [55] and Jones [56] used chemical vapor deposition method to deposit polypyrrole (PPy) onto Lycra yarns. The mechanical strain is limited in both warped and coated yarns, thus the resistance signal becomes unstable when applying strain beyond the limitation. Melnykowycz *et al.* [57] developed a monofilament piezoresistive sensor. The sensor was obtained from melt spinning of carbon black/Thermo-plastic Elastomer (TPE) composite. The sensor provided a near-linear response when the mechanical strain is between 15% to 30%. Gibbis *at el.* [58] used an array of conductive yarns sewing onto a spandex pant in one end and attached an elastic cord in the other end of the yarns. They used the resistance change of the array of conductive yarns to indicate the joint movements. The drawback of piezoresistive yarn-based sensors comes when considering the textile electronics interface. It is difficult to make a strong connection between the conductive yarns and electronics, which is resistant to abrasion, wearing and washing.

Thick-film strain sensors are based on adding a conductive layer onto the high elastic fabrics. The most widely used conductive layers are polymer-based and can be identified into two subclasses: intrinsically conductive polymers (ICPs) and conductive polymer composites (CPCs). PPy is the most often used ICPs, which can be coated by an in situ chemical polymerization process onto the high elastic fabrics [27, 55, 59]. Poly(3,4-ethylendioxythiophene) - poly(styrenesulfonate) (PEDOT-PSS) is another ICPs often used in creating conductive fabrics. Calvert *et al.* [60] developed PEDOT sensors using inkjet-printing technique. They observed an initial increase in the resistance of PEDOT sensors with strain, and concluded that the rise of resistance corresponded to the cracking. Piezoresistive fabric made from ICPs exhibited a strong variation of strain-resistance with time and a long response time. Paradiso *et al*. [22, 23, 61] made stain sensing fabrics by using CPCs. Composite made from carbon black filled silicone were coated onto high elastic fabrics and such fabrics show good strain sensing properties between 5% and 35% strain. The same composites have been used by Mitchell *et al.* [62] using screen-printing technique.

Peizoresistive function can be embedded in textile by using weaving [30, 63], knitting [64-68] and nonwoven [69] techniques. As a distinction from the thick-film strain sensors, they offer an integration of the sensing function directly into the clothing environment. Kannaian and Neelaveni [63] weaved an elastomeric tape sensor with silver coated polyamide (PA) yarn and polyester (PET) in warp and PET in weft. Results showed that the change in resistance was linear and significant up to 10% extension, however, there was no resistance change beyond 20% extension. Zięba *et al.* [30] also investigated woven-based piezoresistive sensors in comparison with knitted ones. Since woven fabrics are generally characterized by their dimensional stability, poor skin contact and limited elastic recovery, knitted structures are more suitable for piezoresistive sensor applications as it is easier to create flexible structures, which fit closely against the human body. The contact resistance between overlapped knitted loops was approved to be the primary attribution to the overall resistance by Zhang *et al.* [70]. Van Langenhove's group [64, 65] developed a knitted fabric sensor, called the 'rispibelt' for measuring of the respiration rate. The respibelt was made of stainless steel yarn, kintted in a Lycra-containing belt. Paradiso's group [22, 23, 61, 67] produced a garment using piezoresistive yarns as sensors, electrodes and connectors to record vital signs from human body.

Table 1. Literature reviews of researches on textile-based piezoresistive sensors.

Category	Fabrication method	Conductive materials	Textile substrate	Research group	Applications	References
Conductive Yarn based	Chemical vapor deposition	PPy	Lycra	HongKong Polytechnic University	-	[55]
				MIT	Respiration rate	[56]
	Melt spinning	Carbon black	TPE	EMPA (Switzerland)	-	[57]
	Warping	Carbon-loaded fibre	PET & PET+Lycra	National Taiwan University	Infant breathing monitoring	[53, 54]
Thick film based	Coating	PPy	Lycra	HongKong Polytechnic University	-	[55]
				University of Pisa	Respiratory measurement	[59]
				Dublin City University	Body motion	[27]
		CLR	Lycra	University of Pisa	Respiratory measurement	[61]
	Screen printing	CLR	Lycra	Dublin City University	Respiratory measurement	[62]
	Inkjet printing	PEDOT	Cotton	UMass Dartmouth	Body motion	[60]
Conductive fabric based	Weaving	Conductive yarns (Euro-static)	-	Lodz University of Technology	Respiratory measurement	[30]
		Conductive yarns (Shieldex®)	PET yarn + rubber	IPSG College of Technology (Inida)	Elbow angle measurement	[63]
	Knitting	Conductive yarns e.g. stainless steel.	Cotton, elastomeric yarns, etc.	HongKong Polytechnic University	-	[66]
				Lodz University of Technology	Respiratory measurement	[30]
				University of Pisa	Respiratory measurement	[22, 23] [61, 67]
				Ghent University	Respiratory measurement	[64, 65]
				University of Manchester	-	[68]
	Non-woven	CLR	Non-woven	Seoul National University	Musical control	[69]

3.2 Sensing mechanism of conductive coated sensors

In this thesis, The CLR with brand name ELATOSIL LR3162 from Wacker Chemie AG; Munich, Germany was chosen as coating paste to produce the coated based sensors. The electrical behavior and the sensor mechanism are described below.

3.2.1 Electrical behavior of conductive rubber

Conductive rubbers can be used as substitutes for traditional conductive materials, where lightweight and flexibility are required. The use of conductive fillers is necessary to achieve a low resistance in rubber, and the most commonly used filler is carbon black. The new composite material exhibits various values of resistance, according to the percentage of conductive fillers (see Figure 3) [71, 72]. However, the dependency between resistance and concentration of carbon black is not linear, which could be interpreted by different mechanisms—namely, mechanical tunneling and percolation.

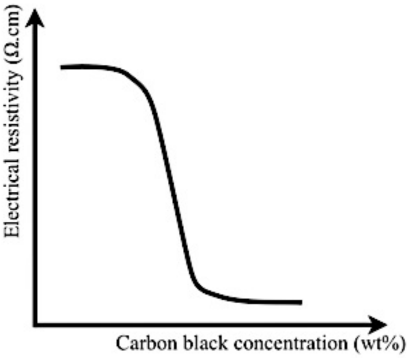

Figure 3. Electrical resistivity versus carbon black content, modified from [72, 73].

Electron transport is being conducted by means of tunneling, in case the carbon black loading has a very small volume fraction in the composite. The distance between the carbon black particles plays an important role to the composite resistance. When this distance is larger, compared to the atomic dimension, the resistance of the composite is controlled by the bulk resistivity of the rubber itself; however, when the distance is small, electrons may tunnel quantum-mechanically between the particles, forming a local conductive path. If the local conductive path penetrates the bulk material, an effective conductive path is produced, contributing to the conductivity of the composite (see Figure 4) [71].

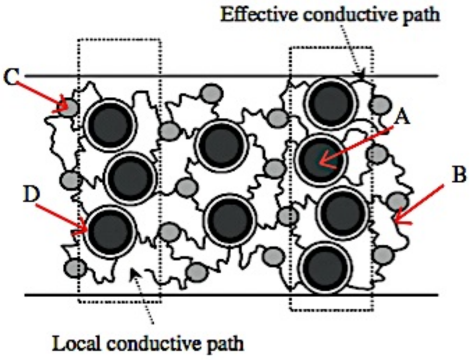

Figure 4. Schematic views of local and effective conductive paths. A: carbon black; B: rubber molecule chain; C: cross-linked rubber molecule chain; D: macro-rubber molecule chain absorbed to the surface of carbon black [71].

According to O'Farrell *et al*. [74], the tunneling effect can be used to explain the electro-mechanical effect of CLR under conditions in which the carbon black dispersed uniformly into the rubber with an average separation distance less than 5–10 Å.

In cases of large volume fractions of the conductive fillers, the particles come into contact with one another to form the conductive paths through the composite. The resistance drops many orders of magnitude at a critical threshold, which is called the *percolation threshold*. The value of the percolation threshold is not constant but depends on many factors, such as size, aspect ratio, structures, roughness of carbon particles, and type of silicone rubber [73], which gives the materials great potential to be used as flexible sensors.

3.2.2 Conductive rubber sensing mechanism

Stress-strain sensitivity becomes significant for rubber loaded with carbon black particles at concentrations around the percolation threshold [75]. The carbon black filler content is 18 wt% in the conductive rubber used for this study, which proved to be just above the percolation threshold. Hence, both percolation and tunneling mechanisms are applied to the study.

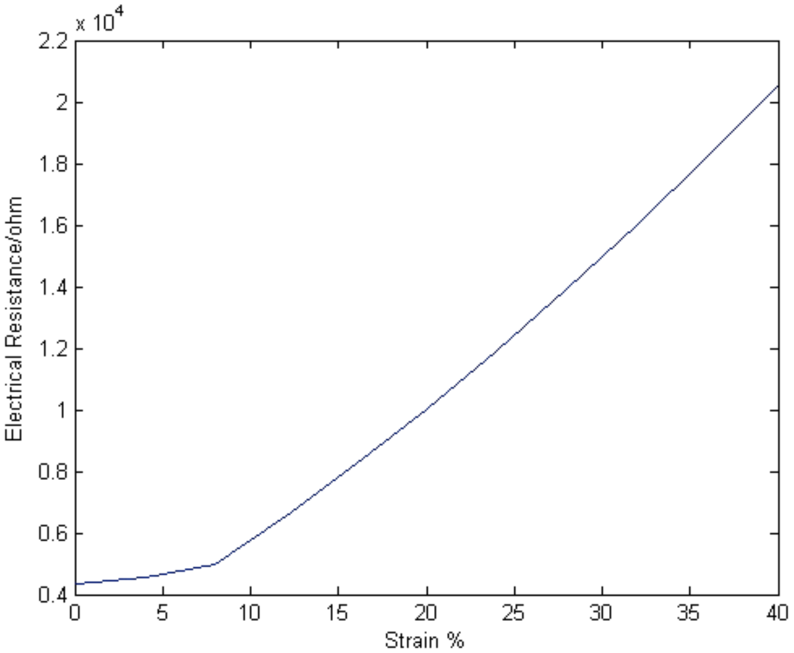

Figure 5. The electrical resistance change at different elongation strains.

According to our experiment, when a small strain was applied to the composite (between 2%–8%, depending on the viscosity of the mixture, the thickness of the coating, etc.), the resistance increases insignificantly; one example is given in Figure 5, which was made from the experimental results. This is because, beyond a critical limit, these conductive networks become continuous throughout the whole composite, due to the actual physical contacts between conductive particles. However, when the elongation is larger than the critical elongation, the resistance increases rapidly with the degree of elongation strain. This can be explained by: 1) the extension destroys some of the local conductive paths, so that the total effective conductive path decreases, or 2) the elongation strain makes the gaps between two adjacent carbon black particles larger, leading to fewer electrons that are able to tunnel to the others.

3.3 Sensing mechanism of knitted-based sensors

With great advantages such as reduction of the production processes and elimination of the coating wastes, knitting has been chosen as another method in the thesis study. The conductive knitted-based sensors have a different principle to achieve conductivity. The sensors were designed as the conductive yarns knitted into the central part of the fabric, forming the conductive path. The contact resistance between conductive yarns has proven to be the key attribution to the overall resistance in the knitted-based sensors [70]. According to Holm's contact theory [76]:

$$R_C = \frac{\rho}{2}\sqrt{\frac{\pi.H}{nP}}, \qquad (3)$$

Where R_c is the contact resistance, ρ is the electrical resistivity, H is the material hardness, n is the number of contact points, and P is the contact pressure.

It can be seen that the material hardness (H) and the electrical resistivity (ρ) of the materials keep constant to the applied elongation strain; therefore, the contact resistance (R_c) is associated only with the contact points (n) and the contact pressure (P). Figure 6 illustrates the contact points of the knit unit cell and the overall knit structure. Before applying any strain elongation to the loops, there were two essential contact points (A and B) in the knit unit cell [77]. When horizontal elongation (in the X-axis) is applied, it is obvious that the middle parts of two loops in the cell come in contact, creating a new contact point (C). When the strain elongation increases, the knit structure continues to compress vertically, and eventually the legs of the upper loops will come in contact with the heads of the lower loops. (The two sections in black in Figure 6)

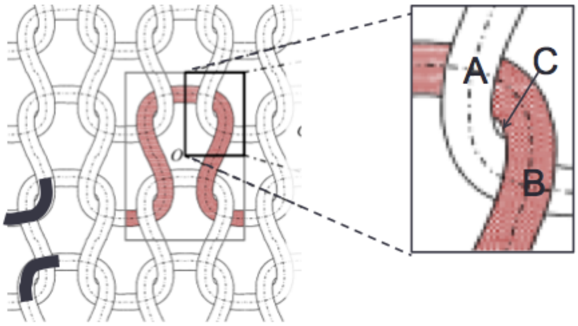

Figure 6. Knit unit cell and the contacting points between loops (The knit unit cell is one quarter of a knit loop) [77].

Considering the contact pressure (see Figure 7), and ignoring the gravity of the yarn, the pressure (P) on point C is the sum of the component forces of the upper and lower half of the loop as in equation (4):

$$P = (F_1 \cdot \cos\theta + F_2 \cdot \cos\theta)/A\,, \tag{4}$$

The Young's modulus is given in equation (5),

$$E = \frac{F/A}{\Delta l/l}\,, \tag{5}$$

Where *F* is the force, *A* is the cross-section area, *l* is the original length, and Δ*l* is the length change.

Thus,

$$P = E \cdot \cos\theta\left(\frac{\Delta l_1}{l_1} + \frac{\Delta l_2}{l_2}\right), \tag{6}$$

From equation (6), we can see that the pressure is only related to the contact angle and the elongation. Obviously, P is equal to zero when there is no contact between the two loops. When the two loops come in contact, both Δl_1 and Δl_2 increase with the horizontal elongation, while the contact angle decreases, due to the vertical comprise. As a result, the pressure increases with the elongation.

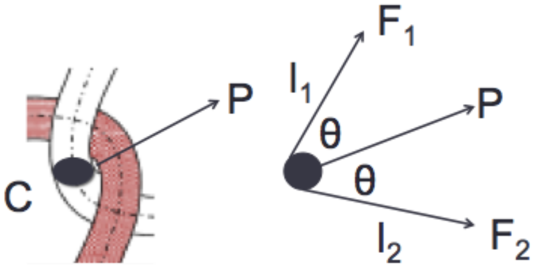

Figure 7. The force distribution on point C. F_1 and F_2 are the forces from the loops, θ is one half of the contact angle, l_1 and l_2 are the effective length of the loops, and A is the cross-sectional area.

As a conclusion, both the number of contact points and the contact pressure increase with the increase in elongation and, as a result, contact resistance decreases. Since the contact resistance dominates the overall resistance of the knitted-based sensor, the sensor resistance decreases accordingly. However, all above-mentioned sensing mechanisms are based on the assumption that the yarn is monofilament. For multifilament yarns and staple yarns, beside the change of contact pressure and the contact angle, there is a significant effect of the compression of the yarn as well, which also reduces the overall resistance.

4 TEXTILE-BASED SENSORS DEVELOPMENT

Textile-based sensors have been developed using numerous different technologies, of which conductive coating and embedding of conductive yarns into knitted and woven structures are the most attractive to researchers. In this thesis, textile-based sensors made of conductive coating and by weaving technique were studied in SP1, which mainly addressed the influence of fabric substrates' parameters on sensor properties. Sensors produced by knitting were studied in SP2, which was mainly concerned with the influence of the choice of conductive yarns and the knitted structure on sensor properties. The methods of introducing the sensing function into the fabrics, and the choice of textile substrates, are illustrated in Table 2.

Table 2. The materials and methods selection, modified from [A1].

Conductive materials	**Applied methods**	**Textile substrate**	**Textile structure**
CLR	Coating	PA/Lycra®	Plain weave
CLR	Coating	Inelastic cargo strap made of PET	Plain weave
Bekinox® BK 50/2	Weaving	PA/Lycra®	Plain weave
Bekinox® BK 50/2	Weaving	Cotton	Plain weave
Bekinox® BK 50/2	Knitting	PA/PET	1 ×1 rib
Beag EA 1088	Knitting	PA/PET	1 ×1 rib

4.1 Conductive coated sensors (SP1)

Two kinds of textile substrates were selected: one elastic woven fabric made of PA/Lycra®, and one inelastic woven strap made of PET. The latter one was a commercial cargo security strap (see figure 8). CLR (ELATOSIL LR3162) has been applied as a coated layer on textile substrate to establish conductivity. Experiments were conducted according to the manufacturer's instructions [78].

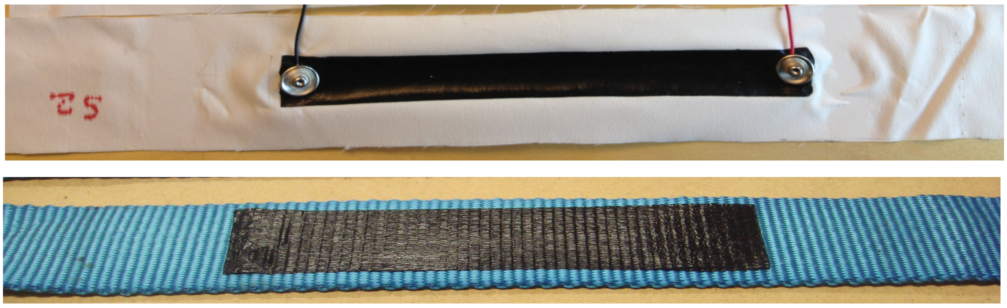

Figure 8. Examples of conductive rubber coated samples on elastic woven fabrics (top) and inelastic cargo strap (bottom).

4.2 Woven-based sensors (SP1)

The conductive yarn chosen for weaving was Bekinox® BK 50/2 metal spun yarn from (Bekaert; Kortrijk, Belgium), which consists of 80% PET stable fibre and 20% Bekinox® stainless steel fibres. Cotton was selected to create the inelastic textile substrate and PA/Lycra® was selected as the elastic textile substrate.

4.3 Knitted-based sensors (SP1 & SP2)

Since woven fabrics are generally characterized by their dimensional stability and limited elastic recovery, knitted structures are more suitable for textile-based sensor applications. However, knitted fabrics have more complicated structures, compared with woven ones, such that the interaction of the yarns in knitted fabrics is more complicated. In SP2, the influence of conductive yarns and knitting structures on the performance of knitted-based sensors and the improvement of sensor electro-mechanical properties by using a novel elastic-conductive hybrid yarn were investigated. The development process is given in Figure 9.

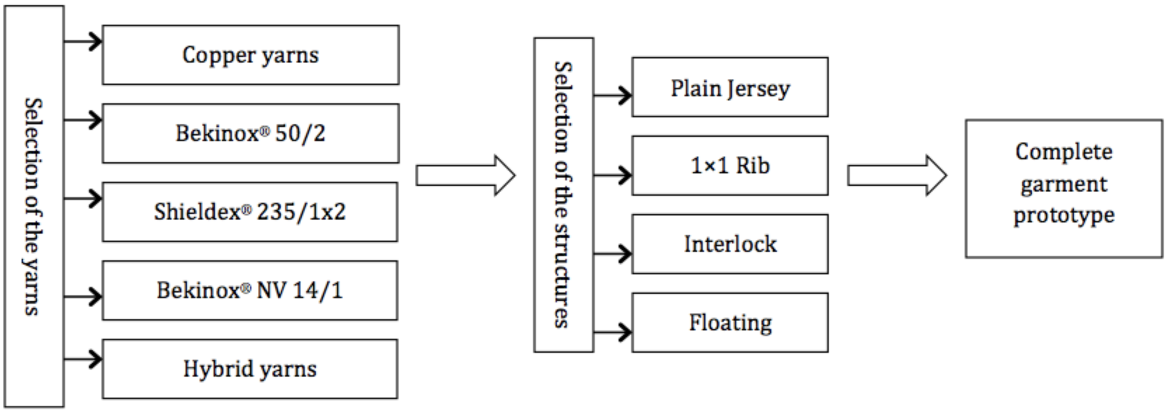

Figure 9. The development of a wearable sensing system based on flat knitting[1].

4.3.1 Yarn parameters

In order to produce resistance change when applying tension stress, conductive yarn with a moderate amount of electrical resistance is required. Hence, copper and aluminum monofilaments were not preferable, although copper yarn was still chosen, as referenced in Article 3. Bekinox® BK 50/2 metal spun yarn, Bekinox® VN 14/1 continuous stainless steel filament yarn, and Shieldex® silver coated PA multifilament yarns (Statex; Bremen, Germany) were investigated. Figure 10 illustrates a magnified section of the selected yarns, which was photographed during the experiments.

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[1] Resistance of Sensor made of Beag EA 1088 was not measureable. Therefore, it was excluded in SP2.

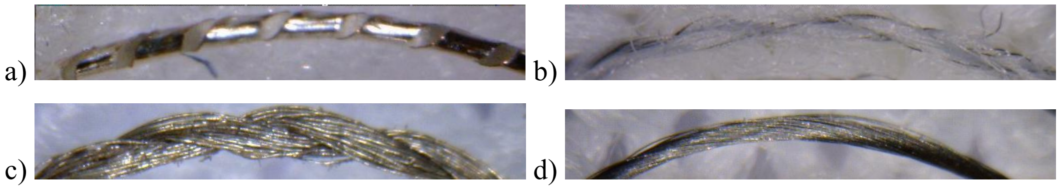


Figure 10. Microscope pictures of selected yarns: a). Cooper yarn; b). Bekinox $^{\circledR}$ BK 50/2; c). Shieldex $^{\circledR}$yarn; d). Bekinox $^{\circledR}$ VN 14/1 yarn [A3].

4.3.2 Elastic-conductive hybrid yarns

It was found that each of the selected yarns exhibits brittle characteristics and poor elasticity that were not typical of yarns used for strain sensor applications. Conductive yarn with good elasticity is required. When adding elasticity into the conductive yarns, variable methods may be used [79-81]. In this study, an elastic-conductive hybrid yarn was manufactured by a so-called direct twisting process. Elastic yarns, PA and PA/Lycra$^{\circledR}$ were chosen as core yarns, while the BK 50/1 and BK 50/2 were selected as the winding yarns. The core and winding yarns were fed separately into a chamber in the direct-twisting device, where a certain number of twists can be applied on the combined yarn at a pre-defined speed. The hybrid yarn exhibits a better elasticity and tenacity, which benefits the processing and the sensor performance. Examples of hybrid yarns are illustrated in Figure 11.

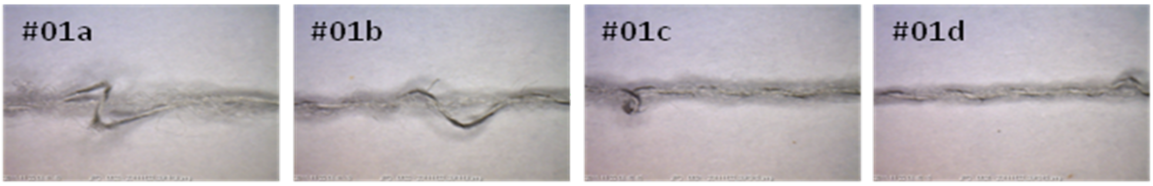


Figure 11. Microscope picture (unit: mm, magnification: × 40) of hybrid yarn made of PA/Lycra$^{\circledR}$ and BK 50/1 [A4].

4.3.3 Weft knitted structures

Four weft knitted structures have been investigated, namely: plain jersey, 1×1 rib, interlock, and floating (see Figure 12). Each of these structures is composed of a different combination of face and reverse mesh stitch—hence, different interconnections among yarns.

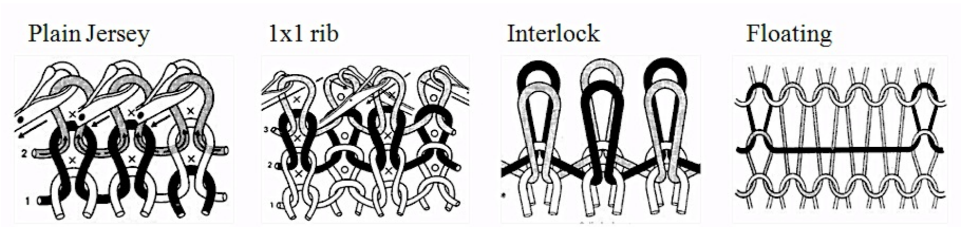


Figure 12. The technical face of plain jersey, 1×1 rib, interlock, and floating structures [82].

4.3.4 Prototype development

The goal of this SP is to make respiration-sensing clothing with complete garment knitting technique. A short view of different knitting methods for producing knitted clothing is presented below:

Cut and Sew

Cut and sew is the most common method for producing flat knitted garments. This garment manufacturing process is similar to when woven fabrics are used. The yarns are initially knitted into a piece of fabric, followed by the clothing components being cut out and finally assembled by sewing. With cut and sew, up to 30% of the original fabric may go to waste as cut-loss [83].

Fully-fashion technique

Each clothing component, e.g., front, back, and sleeves, is knitted into its final shape; then, the components are sewn together. The cutting process is eliminated using the fully-fashion technique, so that cut-loss is reduced compared with the cut and sew method.

Complete garment

The entire garment is knitted and ready-to-wear from the flat knitting machine; it is also known as ‘whole garment’ and ‘seamless garment’. No cutting waste is produced in this process; furthermore, the post-knitting process is eliminated.

One prototype has been created by the fully-fashion technique. The front panel, with two sensing units made of conductive yarns, together with four data-bus, was made in one process. The back panel was made in another process, and clothing was then sewn together on both sides (Figure 13). The basic structure of the prototype was full rib combined with interlocking structure over two conductive parts. Intarsia technique was used to lead in the conductive yarn to form the rectangular sensors, as shown in Figure 13.

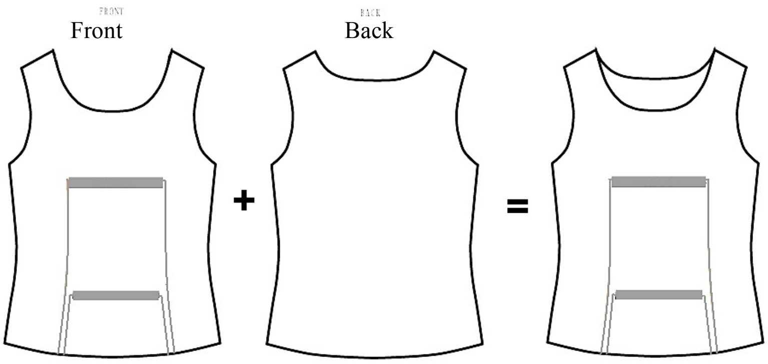


Figure 13. Front panel, back panel, and the prototype created by the fully-fashion technique.

5 SMART CLOTHING SYSTEM DEVELOPMENT

The clothing system used for respiratory monitoring based on conductive coating technique was developed in SP3. The system development consists of the sensor selection, clothing system design, the electronics architecture, and the software implementation. The clothing system design flow is presented in Figure 14.

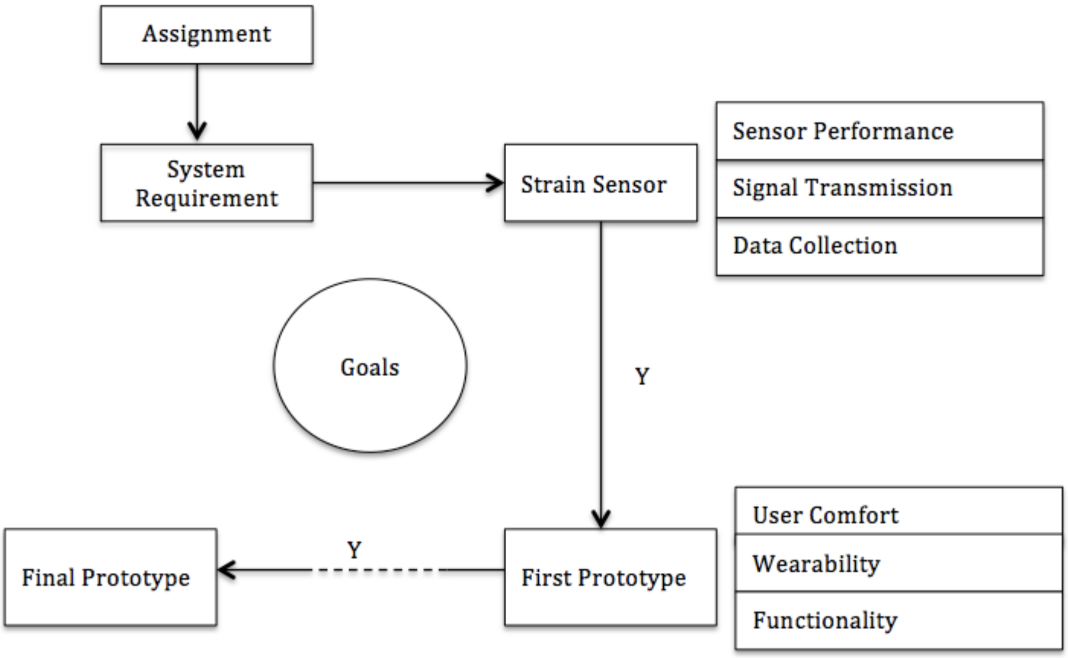


Figure 14. Smart clothing system design flow.

The starting point of the prototype is the decision, or the assignment, that a respiratory monitoring system using clothing as a platform must be produced. Based on the assignment, literature studies are necessary to determine the existing problems. The most important finding is that despite technology significant improved, commercially available smart clothing products are lacking, and the reason could be:

1. Textile-based sensors in general have low sensitivity and reproducibility.
2. The integration of sensors into the clothing was not considered. Smart clothing, as a system, forms an integrated complex; it is not possible to divide attributes for the clothing and electronics into discrete parts. In reality, sensor performance depends on not only its material properties and the process method, but also the placement into the clothing system and the interaction with the other elements in the system.
3. Conductive yarns such as silver have been reported as being environmentally hazardous in wastewater; the development of smart textiles based on conductive yarns must find a way to avoid the environmental hazard.

Furthermore, users may consider the smart textile products as ‘devices’ rather than ‘clothing’ due to poor aesthetic appearance [66].

5.1 Smart clothing system design requirements

The most salient aspect of a smart textile system is its sensing and actuating function, e.g., a respiratory monitoring shirt should primarily be able to monitor the user’s respiration pattern. Functionality provides a key solution to the problems for which the application is intended; however, functionality is not the only measurement by which to evaluate the importance of the application. Parameters affecting the design of clothing systems are presented in Table 3.

Table 3. Clothing system requirements, modified from [84].

Clothing system requirements	Explanation
Functionality	- Sensor performance
Configuration	- Sensor placement - Data-bus arrangement - Connection issue
Component requirements	- Clothing-like, detachable
Wearability requirements	- Comfort, ease of dress and undress, fitness
Maintenance requirements	- Washable, detachable
Aesthetic requirements	- Appearance and social acceptance
Health and environmental concerns	- Side effects - Environmental effects

5.1.1 Functionality requirements

Functionality is the main characteristic of all products, which dominates the user’s decision to buy and adopt the products. Most potential users are primarily interested in what the products can do for them. The functionality of smart clothing systems can be divided into two parts: the clothing function and the electronics function. As a piece of clothing, the system needs to be comfortable and fitted to the user. The electronic function is the sensor’s performance in detecting and monitoring the user’s respiration pattern. It requires high sensitivity and low hysteresis, as well as stable and linear in long-term performance.

5.1.2 Clothing system configuration

Configuration is the placement of sensors and electronics, the arrangement of the data-bus, and the interconnection of the components. Sensor placement greatly influences the clothing appearance and system performance. Designing a smart system requires unobtrusive placement of the sensor on the human body; however, the regular movement of the user should not affect the functionality. The criteria used for determining the sensor placement include [85]:

- areas that are relatively the same size in adults or can be sorted according to anthropometric data,
- areas that experience low movement, except when movement is the parameter to be sensed,
- areas of larger surface area.

The data-bus serves to transmit information from sensor units to the control unit, thus making the clothing a valuable information infrastructure. The data-bus must be protected from regular use and maintenance, as well as from electrical interference.

Another challenge in the design and development of a smart system involves establishing reliable contacts between different elements of the smart system, and between the clothing and the electronics. Electrical conductive adhesives were utilized to interconnect the conductive yarn and electronics. However, the contact points were broken easily when the system experienced humidity changes, mechanical stress, or washing [86, 87]. Therefore, ways of forming reliable contacts must be developed.

5.1.3 Components requirements

Some attempts have been made to embed conventional electronic components into clothing [88, 89]. These garments contain conventional cables, electronic components, and special connectors. However, because comfortable textiles are preferred over hard, rigid boxes, smart clothing must maintain the properties of clothing. Thus, clothing-like components and invisible connectors are intended to be utilized as often as possible in smart clothing applications [90]. In addition, the development of washable electronics is also required.

Smart systems are intended to be fully integrated systems, in which clothing and electronics are indistinguishable. At the moment, however, none of the smart systems are fully comprised of textiles; for example, no textile materials are available that can perform the data processing task [38]. A crucial issue is how these electronics are situated and attached to the soft clothing material, to maintain reliability and comfort. A stable attachment ensures the data transmission from the clothing to the control unit, even when the user is in motion. Comfortable attachment is dependent upon the size, weight, and position of the electronics. For instance, attachment by body-wrapping is considered more comfortable than a single-point fastening system [85].

5.1.4 Wearability requirements

'Wearability' implies *the physical shape of the wearable article and its active relationship with the human form* [91]. Wearability involves such issues as ease of dressing/undressing and fit, though comfort is the major concern. Comfortable is defined as *freedom from discomfort and pain* [85]. The discussion of comfort refers to both physical and cognitive comforts. Freedom of movement, thermal comfort, and the interaction between skin and clothing are major factors of physical comfort. Cognitive comfort considers how the wearers actually feel when wearing the clothing. The wearer may feel cognitively uncomfortable while feeling physically different; for example, the device safety and reliability could negatively affect the cognitive comfort of the user [92]. The design of smart systems requires bringing both physical and cognitive comfort to the users. The choice of materials, the placement of the sensors and electronic components, and the appearance should be considered.

5.1.5 Maintenance requirements

Washability, is an essential indication of the maintenance of clothing, regardless of whether it is a smart textile. In the smart system, electronic parts need to be either washable or removable for washing, and should avoid shrinking and other dimensional changes after washing [84].

5.1.6 Aesthetic requirements

Aesthetics, which describes the appearance of the clothing [85], is another important aspect of form and function of any wearable system, and a medium for communication. As mentioned before, clothing considered to be "ugly" and "weird" causes uncomfortable user emotions; therefore, aesthetics has a major impact on the personal and social acceptance of the system [93, 94]. Aesthetics is important in technical products by making the technology disappear from the user's perception.

5.1.7 Environmental and health issues

Possible health risks are generated from the fact that the electronics and the data-bus integrated into clothing are worn or kept close to the user's body. Current flows through the electronics, producing electrical radiation, which may present a hazard to the user [95]. The side effects from long-term exposure to electrical radiation are not currently clear.

Environmental issues are other concerns. As more and more clothing-like electronics are desired for use in smart systems, electronics are preferred to be wash-resistant. However, the wastewater may contain environmentally hazardous ingredients, for example, silver powder from silver-coated conductive yarn. The design of smart systems must minimize health risks and environmental hazards.

5.2 Prototype Design (SP3)

The prototype design follows the problem-solving approach. Gathering the general data to solve the problem, and determining and weighing alternatives are the next steps, which will eventually lead to the solution. The development and evaluation of prototypes is accomplished mainly in SP3, following RQ2 (how sensors can be embedded into the clothing system) and RQ3 (how the clothing system performs, in terms of sensor functionality and wearability).

Five prototypes were produced to optimize results. Sensor performance, sensor position, data-bus arrangement, and the clothing comfort are the major developmental concerns. Prototype functionality was tested and quantitatively evaluated, while wearability was another index of the system performance. The design steps were introduced as follows.

5.2.1 Selection of sensing elements

Coating was selected as the method for the application of sensing function into the clothing system. Coating is used to improve or modify the surface properties of a subject—usually textiles and plastics. Coating is a rather flexible surface modification technique; depending on the requirements, the coating area can be large or small, verbose or concise, profound or trivial. However, coating does not dominate the humans' thinking, in the way sensors and electronics do today. Conductive coated sensors exhibit good sensitivity and low hysteresis in comparison with conductive fabric-based sensors [A1]. Furthermore, a clothing-surface coating has no contact with the human body and will cause no skin irritation or other skin hazard. The manufacturer of the conductive rubber used in this study, Wacker Chemie AG claims that the production of coatings will not rise any environmental problems [96].

5.2.2 Placement of sensing units

Prototypes 1 consists of a single sensing unit placed on the standard chest position. Prototypes 2-5 consist of double sensing units placed on the standard chest and abdominal positions. The double sensing unit solution gives better accuracy of measurement (see Figure 15). Both machine simulation and on-body tests have been performed on prototype 2, and the testing results were reported in Article 2. On-body tests have been performed on prototype 4 in comparison with a commercial respiratory belt; these results were reported in Article 5.

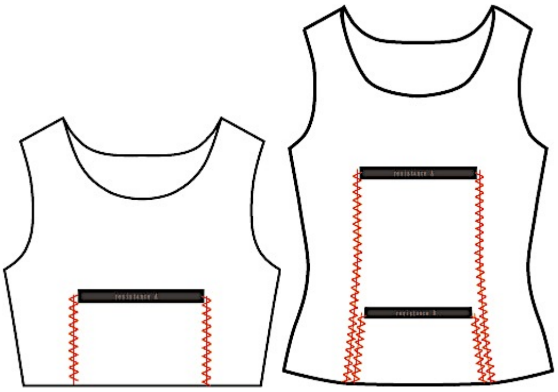


Figure 15. Prototype 1, with one sensing unit, and prototype 3, with two sensing units.

5.2.3 Wearability concerns

Comfort and the ease of dressing/undressing are major concerns in the wearability study. The pattern development of prototypes 3, 4, and 5 is presented in Figure 16.

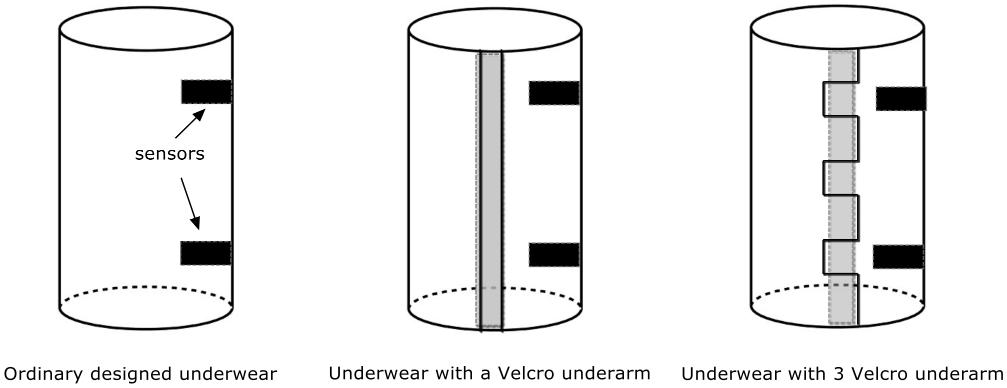


Figure 16. Design of easy wear in prototypes 3, 4, and 5.

The torso circumference change ratio of an adult during respiration is around 2% [97]. In order to get reliable respiration patterns, the clothing should be tightly fitted to the body.

In prototype 3, an inelastic woven fabric was selected as the basic textile of the clothing to ensure the good performance of the sensor. A zipper at the back of the clothing was designed for easy dressing and undressing. The inelastic woven fabrics restrict the freedom of torso movement to fasten and unfasten the back zipper, which is inconvenient for the wearer. Prototype 4 was developed with a focus on accuracy of measurement, while improving the comfort and convenience of use. Hook-and-loop fasteners with the brand name Velcro® were used in the shoulder and side seam positions. This special design makes the clothing easy to put on and take off. The side Velcro® also guaranteed a customized tight fit on different users, to ensure the high sensitivity of the sensor [A5]. The drawback of prototype 4 became apparent when the garment was tried on the testers: the side Velcro® is difficult to align under the 2% pre-stretch tension of the sensing units.

Prototype 5 kept the main concepts from prototype 4; however, the size of Velcro® was modified. Instead of one long Velcro® strip, three smaller pieces of Velcro® were used. The upper and lower ones aligned with the two sensing units, guarantees the effective pre-stretch. The third Velcro® strip lay in the middle of the other two, providing more freedom for torso movement.

5.2.4 Configuration of the data-bus

In prototypes 1 and 2, zig-zag sewing (see Figure 15) was used to apply conductive yarn onto the clothing, functioning as the data-bus. However, sewing directly into the clothing creates the tendency for the yarn to fray easily, eventually influencing the durability.

In prototypes 3 and 4, the piping was used to attach the data-bus to the clothing. Piping protects and isolates the core yarn from abrasion and washing damage.

In prototype 5, Velcro® fasteners were used to attach the piped data-bus (see Figure 17), and the detachability of the Velcro® fasteners allowed removal prior to washing, which prolongs the lifetime of the conductive yarn and protects the environment.

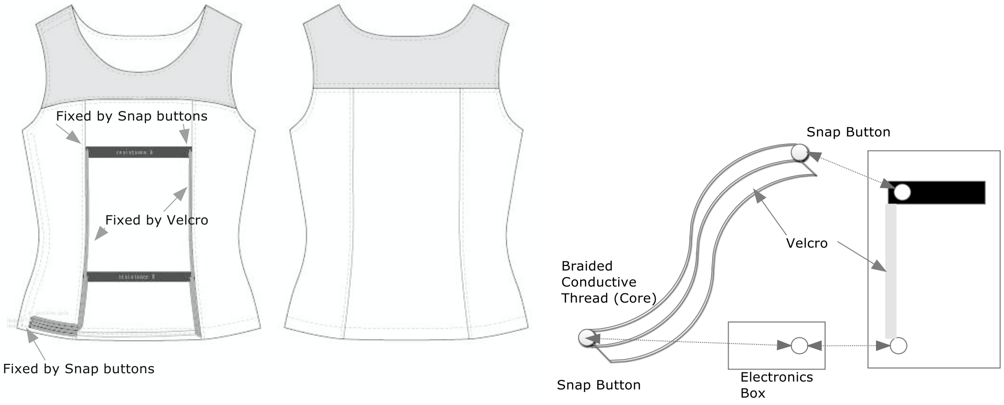


Figure 17. The arrangement of the data-bus and the electronic box (control unit).

5.2.5 Electronic interface design

Contact issues of clothing electronics was not considered in prototypes 1, 2, and 3. Crocodile clips were used for testing. In prototype 4 and 5, snap buttons were utilized for the interconnection. In this prototype, an attachable pocket was designed and fixed to the clothing by snap buttons as well. The control unit is placed in the side-pocket. The entire garment is washable, except the control unit; however, the data-bus is preferably removed when washing.

5.3 Electronic architecture

In the clothing system, the two conductive-coated straps function as strain gauges that are sensitive to the change in diameters of the chest and abdomen during respiration. Each coated strap is connected with a fixed resistor, whose value equals the initial resistance of the strap, and is connected to a 9-volt battery. The whole circuit acts as a voltage divider to transfer the changes in resistance to changes in voltage, enabling measurement of electrical signals. The schematic circuit of the prototype system is shown in Figure 18.

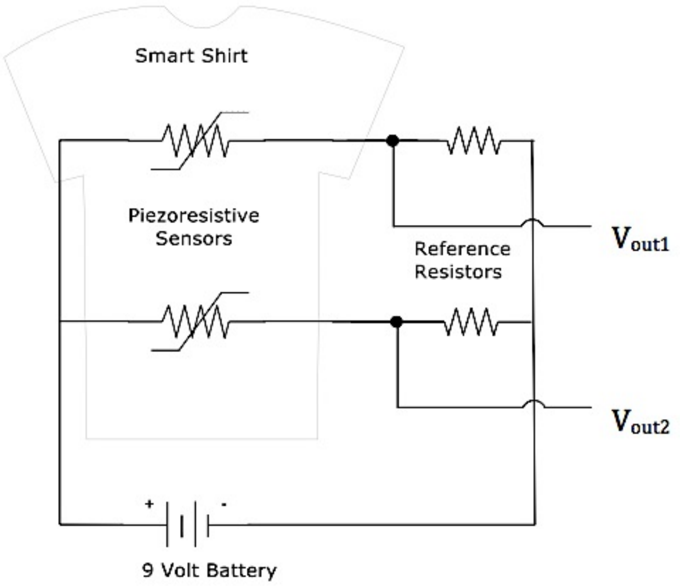


Figure 18. The voltage divider circuit for the clothing system.

5.4 Software implementation

A laptop was used as a control and monitoring unit in the implemented system, electrical cables were used for testing, and a wireless communication unit was used in the real monitoring situation. A LabVIEW graphical program was used to create a graphical user interface operating on the laptop to evaluate the signal online and analyse it offline. The algorithm of the LabVIEW programming flow chart is given in Figure 19. The coding diagram was implemented as the LabVIEW block diagram presented in Appendix B. The LabVIEW user interface is presented in Figure 20.

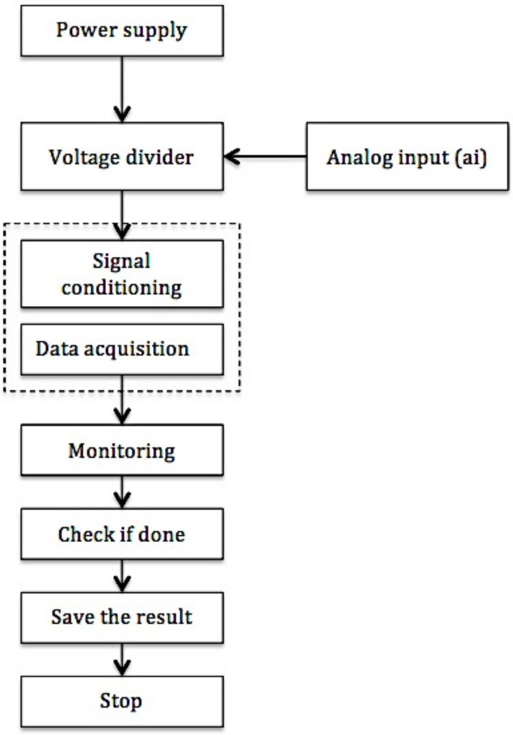
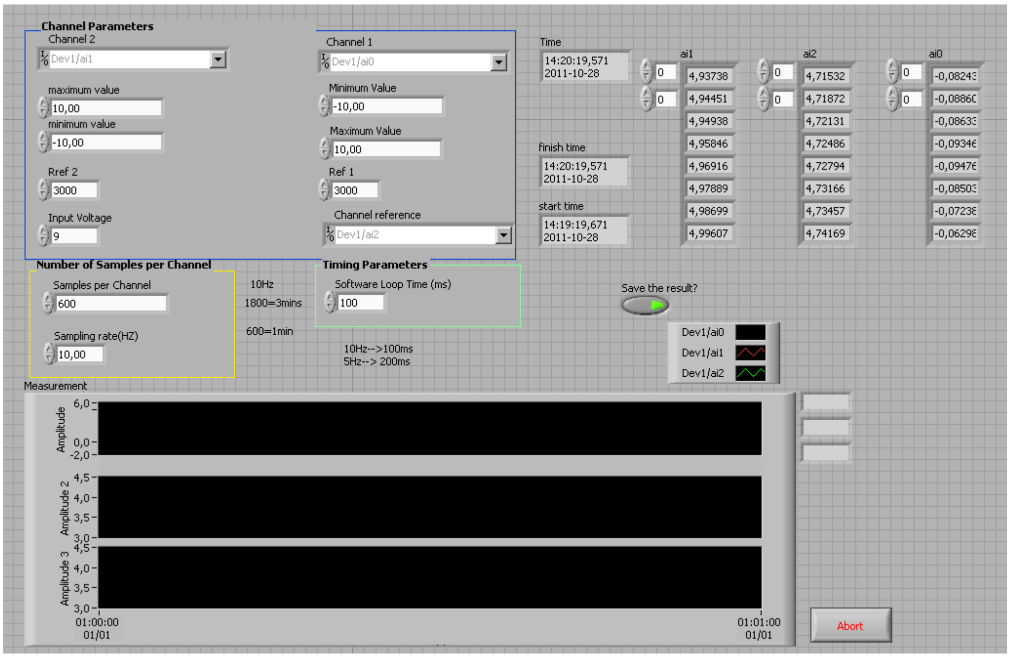


Figure 19. The algorithm of the LabVIEW programming flow chart.

The user interface allows the user to choose the channels of input signals. The maximum value and minimum value give the threshold values of the system and avoid the outflow of the circuit. Ref1 and Ref2 are predetermined in the voltage divider circuit and are associated with the resistance of the coated straps. The user can also select the number of samples per channel, the sampling rate, and the software loop time. The definition and relations of the three parameters are presented below.

The *sampling rate* (frequency) is determined according to the signal frequency. The sampling rate (f_s) must be greater than 2 times the signal frequency (f) in order to be measured and read. Usually the sampling rate is set at a value 10 times larger than the signal frequency. For example, the respiration signal has a frequency (f) around 1/3 Hz (20 breaths per min); therefore, the f_s can be equal or greater than $10 \times f = 3$Hz.



Channel Parameters

Channel 2: Dev1/ai1
maximum value: 10,00
minimum value: -10,00
Rref 2: 3000
Input Voltage: 9

Channel 1: Dev1/ai0
Minimum Value: -10,00
Maximum Value: 10,00
Ref 1: 3000
Channel reference: Dev1/ai2

Number of Samples per Channel

Samples per Channel: 600
Sampling rate(HZ): 10,00

10Hz
1800=3mins
600=1min

Timing Parameters

Software Loop Time (ms): 100

10Hz-->100ms
5Hz--> 200ms

Time: 14:20:19,571 2011-10-28
finish time: 14:20:19,571 2011-10-28
start time: 14:19:19,671 2011-10-28

ai1	ai2	ai0
4,93738	4,71532	-0,0824
4,94451	4,71872	-0,0886
4,94938	4,72131	-0,0863
4,95846	4,72486	-0,0934
4,96916	4,72794	-0,0947
4,97889	4,73166	-0,0850
4,98699	4,73457	-0,0723
4,99607	4,74169	-0,0629

Save the result?

Figure 20. The front panel of LabVIEW.

The *sample per channel* (N) is the total number of samples per channel. The testing duration can be calculated by the sampling per channel and sampling rate; for example, for f_s =10 Hz, and N =600:

$$T_S = \frac{1}{f_S} = \frac{1}{10} = 0.1\ s \text{ (Sampled every 0.1 s)}, \tag{7}$$

$$T_{total} = T_S \times N = 0.1 \times 600 = 60\ s\ , \tag{8}$$

Where T_s is time per sample and T_{total} is the total testing time.

Software loop time is the input specifying the time lapse (in milliseconds) when the program is run, and is used to synchronize different activities. When f_s equals to 10 Hz, the software loop time can be set as 100.

The amplitude of the respiration signal (in volts) can be seen in curves and digitals. The result can be saved once the ‘Save the result?’ switch is activated.

5.5 Sensor functionality study

5.5.1 Machine simulation

Cyclic performance is one of the important functions of sensor use for respiratory monitoring applications, as respiration can be seen as a cyclic activity of inhaling and exhaling. A *cyclic tester* has been designed by the author and produced for the purpose of simulating respiration patterns before on-body testing. The *cyclic tester* has been used in Articles 2, 3, and 4.

The *cyclic tester* has a fixed end and a movable end driven by magnetic force. The total length of the tester is 400 mm, and the speed of the movable end can vary from 0 mm/s to 50 mm/s to simulate different types of respiration signals applied to the system for measurement. A digital multimeter *Keithly* was coupled with the *cyclic tester* for continuously reading the variation of resistance of the sample during extension and retraction cycles. The testing setup is shown in Figure 21.

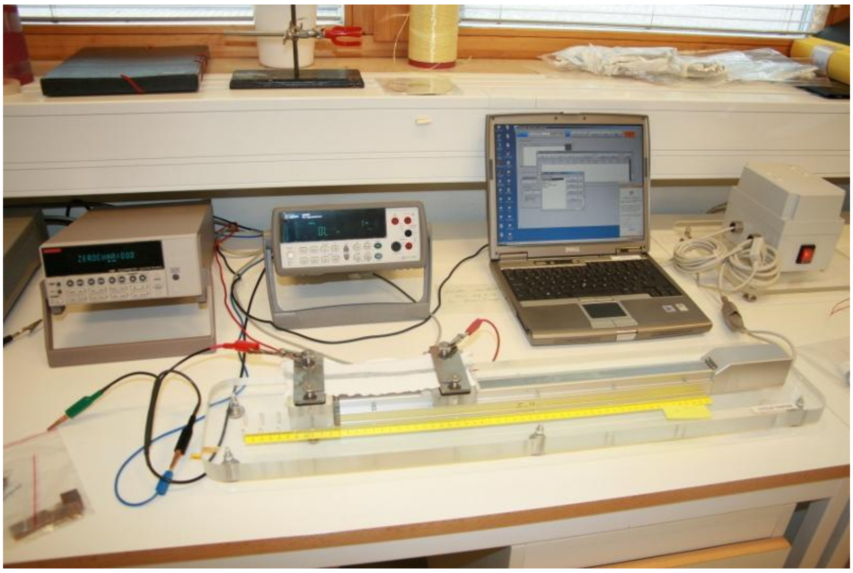


Figure 21. Cyclic tester with sample, and the resistance testing setup.

Respiration changes the torso circumference during the inhalation and exhalation phases, which can be simply simulated by the length change of the testing samples. For example, we can assume that the change of the half-breast circumference is 8 mm for a healthy adult (2% of the breast circumference), and the average respiration rate is 18 breaths/min. The inhaling time, as a ratio of total respiration time, is around 0.42 ± 0.02 [98]. By calculation, one respiration cycle can be interpreted as presented in Figure 22.

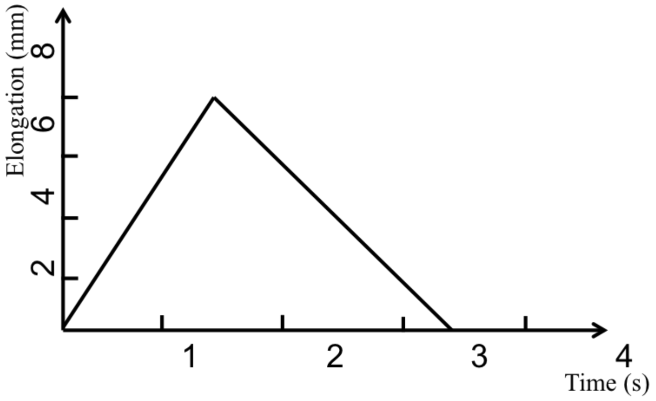


Figure 22. One simulated cycle of a respiration from a healthy adult.

5.5.2 On-body testing

In the simulation tests, the sensors stretched and deformed in one dimension; however, real respiration involves not only stretching but also bending along the chest and abdomen. In order to evaluate the sensor performance in the real case, on-body tests have been performed as detailed in Articles 2 and 5.

A single sensing channel was tested in Article 2. The prototype was worn by 10 subjects. They were taught to perform simultaneous breathing during sitting, walking, and jogging. In addition, the subjects performed deep breathing in a supine position and *athletic breathing* during running. *Athletic breathing* [A2] is a method used by some professional runners. The subjects manage their respiration by repeating three inhalations and three exhalations, instead of the usual one inhalation and one exhalation.

Double sensing channels were examined in Article 5. The prototype was worn by 5 subjects. All subjects were taught to wear the prototype tightly fixed by Velcro® to ensure the pre-stretch of approximately 2%. The subjects were instructed to follow a sequence of breathing manoeuvres as follows:

1. Breathing normally for three min in an upright position;
2. Breathing normally while reading a book for twenty min in a sitting position;
3. Breathing rapidly for one min in an upright position;
4. Breathing slowly for one min in an upright position;
5. Breathing normally three times and then hold the breath for approximately 10 s in a supine position.

In addition, the subjects were trained to perform chest-dominated breathing in an upright position and abdomen-dominated breathing in a supine position for one min, respectively.

The results of both machine simulation and on-body tests have been discussed in the appended articles in details, and the summary of the results is presented in Chapter 7.

5.6 Wearability and user acceptance study (SP4)

Smart textiles may be a promising solution for home care from a medical technology point of view. The use of smart clothing for medical reasons requires an understanding of the users' perspective and a willingness to use the products [99]. Functionality, wearability, and user acceptance are critical issues for the development and eventual commercialization [92, 100]. In this thesis study, wearability and user acceptance has been examined by surveys as a compliment to the appended articles.

5.6.1 Data collection methods

Questionnaire is the most common data collection method in a survey study. It consists of a series of questions for the purpose of gathering information from respondents [101]. Most questionnaires are designed for statistical analysis of the responses; however, open-ended questions can provide information for qualitative analysis as well. Questionnaires have advantages over some other types of surveys in that they are cheap and do not require as much effort from the questioner as verbal or telephone surveys.

In this thesis work, Survey A was conducted with a random group of participants to study the users' acceptance of using smart clothing systems. This survey was conducted in combination with a scenario technique [102], which introduced the participants into medical situation in which smart clothing may be used. The questionnaire was delivered to 100 randomly selected people from the Internet. 85 participants (45 women, 33 men; 20–70 years old, average age: 33 years) submitted responses within 2 weeks, and 63 responses were seen as effective answers. In this survey, gender, age, educational background and occupation were chosen as independent variable, while the pro- and con-arguments of using SmartShirt were designed as dependent variables. Only gender effects analysis is included in the thesis work. The correlation between other variables will be examined in future work.

Survey B has been delivered to a focus group of participants with basic knowledge of smart textiles, mainly, the students and the employees from a textile university (THS). The goal of the focus groups was to gather information of wearability regarding the prototypes (named SmartShirt). This questionnaire was given to 16 participants (13 women and 3 men) who have seen and/or tested the prototypes, with the purpose of studying and analysing the wearability of different clothing-based respiratory monitoring systems, including the ordinary respiration belt, and prototypes 3, 4, and 5[2].

5.6.2 Results from preliminary study

As the results from this study are not included in any of the appended publications, a short summary of the results is discussed hereafter.

User acceptance

The results of user acceptance were analyzed and given as follow:

In general, 51 participants (82.2% male, 77.8% female) accepted the use of the SmartShirt (Figure 23, left), and 10 participants (17.8% male, 13.5% female) rejected the use of the SmartShirt (Figure 23, right). We can see that no significant gender difference exists in the general acceptance of SmartShirt use. We found that when answering the con- arguments questions (general reject), more participants chosen 'Neutral' (46.4% male, 27.0% female), which indicates that they are not sure of, or have not considered, the answer.

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[2] Prototypes 3, 4, 5 were named as SmartShirt P1, P2, and P3, respectively, in the survey.

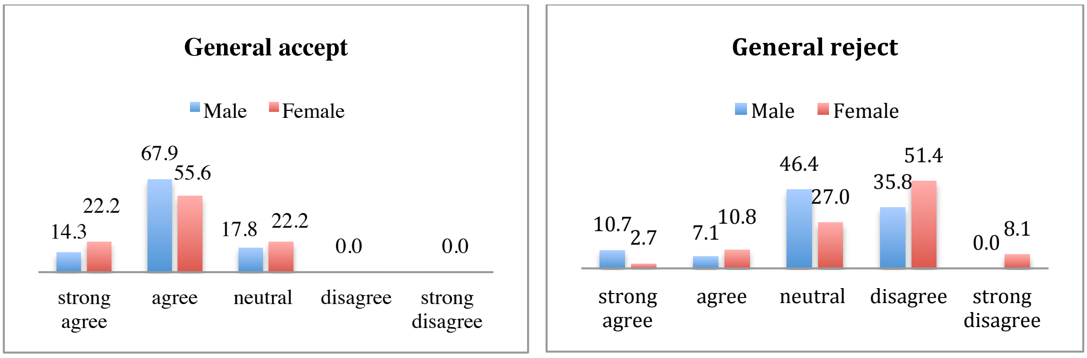

Figure 23. The general acceptance of using the SmartShirt for healthcare (in percentage).

Women report a low level of trust in using electronics on the body. 31 participants (57.1% male, 41.6% female) felt safe using the SmartShirt, while 29 participants (35.7% male, 55.9% female) participants feared having electronics on their bodies (Figure 24).

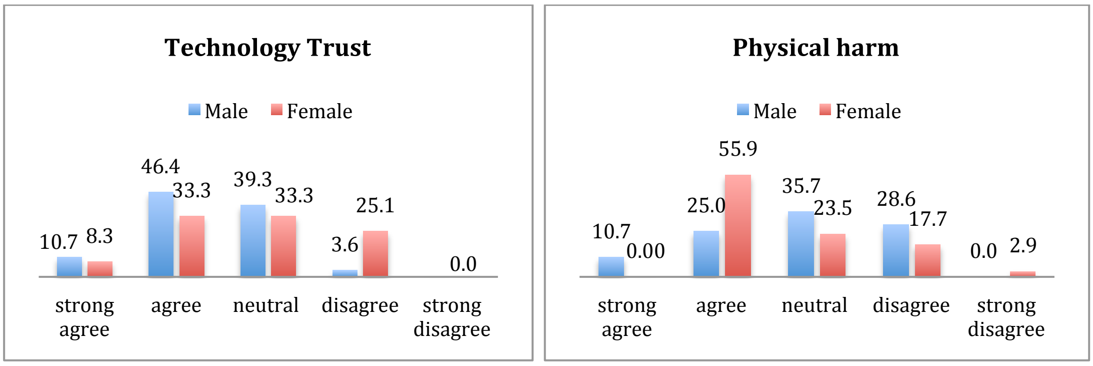

Figure 24. Trust in using SmartShirt technology (in percentage).

User friendly and washability

Regarding usability, men have a more negative view of the user friendly interface: one-half of the male participants hold a neutral view. However, 74.3% female participants believe the SmartShirt is easy to use. Around one-half of the participants in both the male and female groups believe the SmartShirt is able to be washed at home; however, the majority of both groups (53.6% men, 71.4% women) believe the sensing elements will be destroyed after several washing cycles (see Figure 25).

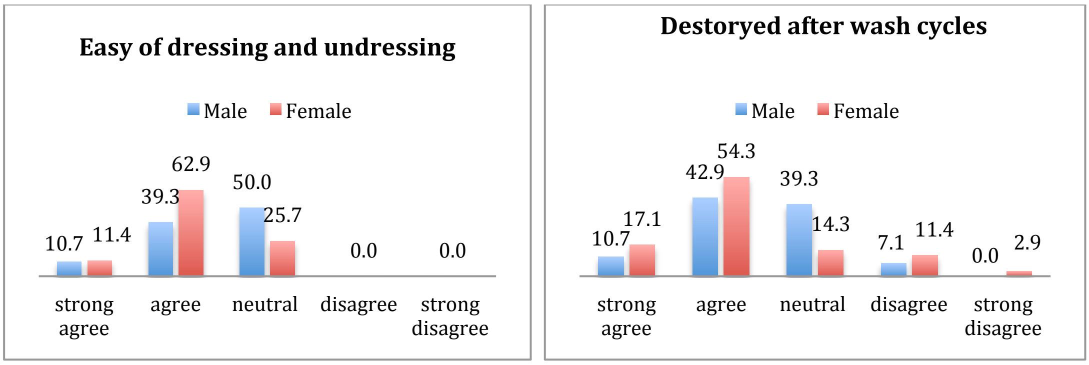

Figure 25. Ease of dressing and undressing and washability (in percentage).

Wearability

The survey results demonstrate that the clothing-based system offers significantly greater comfort compared to the respiratory belt (86.7% believe that wearing the SmartShirt was more comfortable than wearing the respiratory belt). However, the improvements in comfort from SmartShirt P1 to P2 and P3 were not as significant as the former comparison: nearly one-half of the participants felt that P2 was as comfortable as P1, while 40.0% of participants thought the same for P3. 68.8% participates agreed that SmartShirt P1 was easier to put on and take off, though the wearability of P2 was not significantly improved over that of P1. In Figure 26, we can see that 33.3% of participants believe that P2 is not easier to put on than P1, while one participant considered P2 more difficult to put on than P1. Almost half (46.6%) of the participants believe the comfort is not improved. This is most likely because the Velcro® underarm is difficult to align, and the stiffness of Velcro® renders the garment uncomfortable to the wearer. However, only one participant disagreed that the wearability of SmartShirt P3 was improved over that of SmartShirt P1.

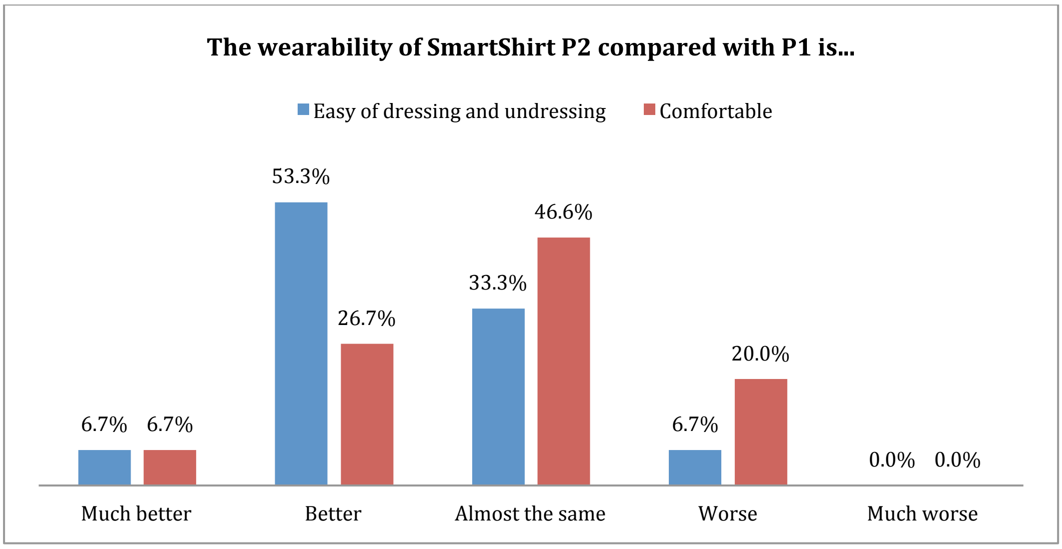

Figure 26. The wearability and comfort of SmartShirt P2 compared with SmartShirt P1 (in percentage).

In conclusion, the SmartShirt exhibited significantly improved comfort and wearability compared to the ordinary respiration belt. Both comfort and wearability could be further improved with better clothing design and construction.

6 SIGNAL PROCESSING AND DATA ANALYSIS METHODS

6.1 Signal processing methods

Signal processing is often used in the area of systems engineering and electrical engineering. The main purposes of signal processing are: 1) to reconstruct signals, 2) to improve the quality of signals, 3) to compress signals, and 4) to extract certain desired features from the raw signals. In this thesis study, all signal processing was performed in association with the MATLAB programme. The coding is presented in Appendix A, and the signal-processing methods used in this thesis are presented below.

6.1.1 Normalization

Normalization is the method to adjust measured values on different scales to a notionally common scale. It is commonly used in comparison studies and often prior to averaging. Figure 27 shows an example of a signal before and after normalization.

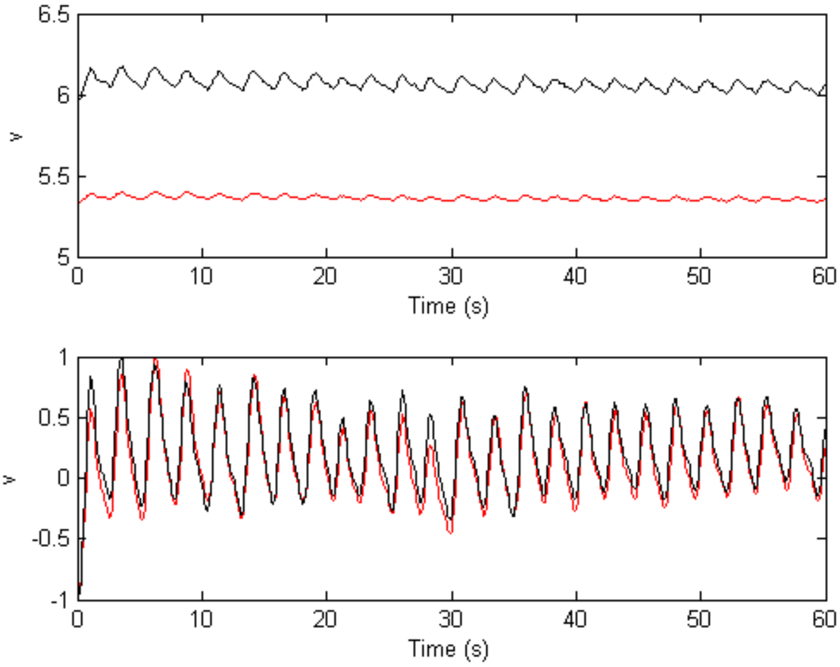

Figure 27. Signals before (top) and after (bottom) normalization. Signal from chest channel, red; signal from abdominal channel, black.

As shown in Figure 27, signal normalization modified the two signals to use the same scale, making the comparison easier. In Articles 4 and 5, the signal has been normalized for comparison. The signal amplitude was within the range of (-1, 1) after normalization.

6.1.2 Baseline drifting

When sensor systems were subjected to real situations, the respiration signals were analysed after processing to reduce the noise sources, including baseline noise, muscle artefact, user movement, and others [103]. Among these, baseline noise is the easiest to subtract from the real signal, due to the fact that baseline noise usually has a much higher frequency than the real signal [104]. Baseline noise is the short time variation of the baseline from a straight line caused by electrical signal fluctuations, lamp instability, temperature fluctuations, and other factors. It can be corrected by drift with the function *smooth* in MATLAB. As shown in Figure 28, the raw signal becomes more organized after normalization and smoothening.

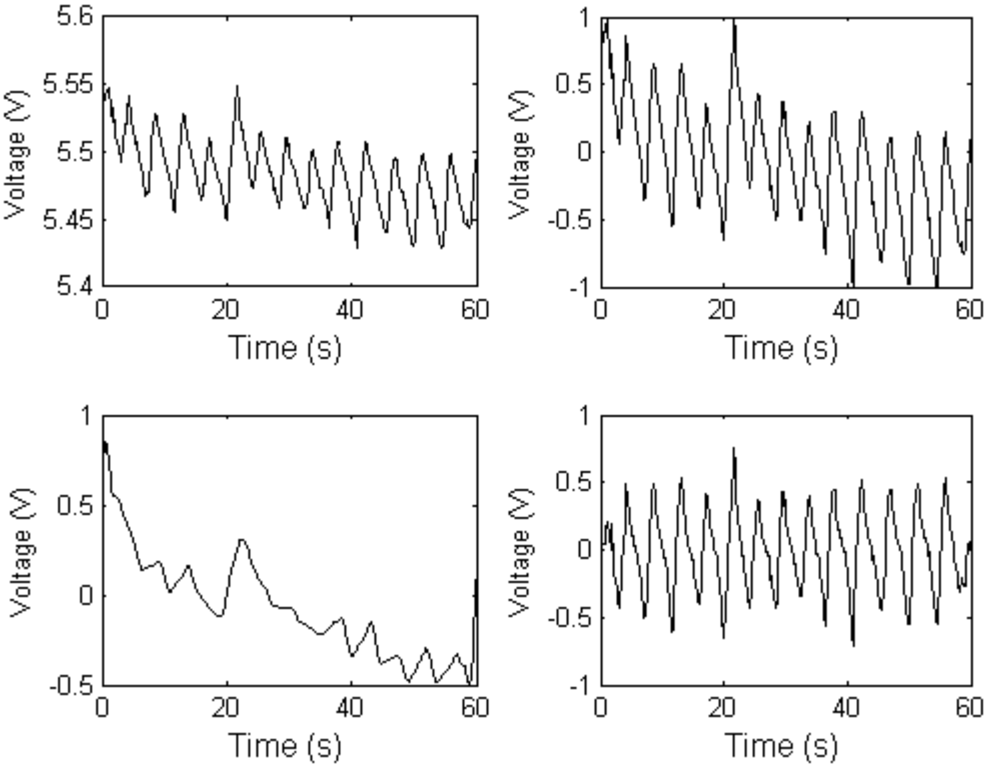

Figure 28. A normal respiration signal. The upper left pane displays the raw signal, while the upper right pane shows the normalized signal. The lower left pane displays the baseline drift and the lower right pane shows a smoothening subtracted.

6.1.3 Low-pass filtering

Another method to remove the high frequency noise is by application of low-pass filtering. In this thesis work, the cut-off frequency of the low-pass filter was selected depending on the measured respiration rate; increasing from 0.2Hz to 0.55Hz as the respiration rate rose. The filter function used in MATLAB was *butter* and *filtfilt*.

6.1.4 Root Mean Square calculation

Root mean square (RMS) is a statistical measurement of the magnitude of a varying quantity. In the case of a set of n values $\{x_1, x_2, \dots, x_n\}$, the RMS value is given by formula (9) [105]:

$$xrms = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + \cdots + x_n^2)}\ , \qquad (9)$$

In Article 5, the RMS was calculated by the amplitude of each respiration given by the subjects, and the predominate respiration compartment was determined accordingly.

6.1.5 Power spectral density estimation

Power spectral density is used to estimate the spectral density of a signal from a sequence of time samples of the signal. The spectral density indicates the frequency content of the signal. The purpose of estimating the spectral density is to detect any periodic signal in the data, by observing the peaks in frequency domain.

The most common method of spectral estimation is based on the Fast Fourier Transform (FFT). For many applications, FFT-based methods produce sufficiently good results [106]. In Article 5, power spectra of all the recorded signals were determined using the FFT method, which is realized using *pwelch* function in MATLAB.

6.2 Data analysis methods

Data analysis methods depend on the research topics and the methods, and data analysis in quantitative research is usually implemented with statistical analysis. In this thesis work, data were mostly analysed quantitatively with the methods listed below. Qualitative observation and comparison were also used in some cases.

6.2.1 Real time observation and qualitative comparisons

Biomedical signals such as blood pressure, ECG signals, and respiration rates are time varying. Therefore, real time observation is often used in diagnostic studies. In this case, the observers' experiments are included in the most important criteria.

In Article 2, real time observation and qualitative comparison was applied to compare the signal frequency and the amplitude to the real respiration made by the subjects, to evaluate the performance of the smart clothing system.

6.2.2 Linear regression

Regression is the study of dependence; it is used to answer questions regarding the relationship between the dependent variable y to the independent variable x_i [107]. Linear regression methods are most common used in regression; in which data are modelled using a linear predictor function. A linear regression model assumes that the relationship between the dependent variable y and the independent variables x_i is linear.

In Article 1 and Article 5, linear regression methods were applied to study the electro-mechanical transduction properties of the textile-based sensors, and the characteristic curve of the sensor was determined by plotting the fractional increase in electrical resistance value against the strain value. The linear range was calculated by means of a linear regression analysis and the coefficient of determination was estimated.

6.2.3 Correlation study

In statistics, the *correlation* refers to the statistical relationship between the variables; it shows weather and how strong pairs of variables are related [107]. There are several correlation coefficients; the most common of these is the Pearson correlation coefficient, which is sensitive only to a linear relationship between two variables. In Article 5, Pearson's correlation was studied to verify the agreement between the textile-based sensors and the reference respiratory belt.

Cross-correlation is a measure of similarity between two signals as a function of a time-lag applied to one of them. The response times of the textile-based sensors were compared with that of the reference belt by means of cross-correlation to determine if there was any delay between the sensors. The cross-correlation was determined by the function of *xcorr* in MATLAB.

6.2.4 ANOVA

Analysis of variance (ANOVA) is a useful technique to compare the significance of difference between the means of two or more samples [108].

In article 4, a one-way ANOVA between subjects was conducted to compare the effect of different experimental conditions (twists amount, selection of the core yarn and winding yarn) on the elongation at break and the breaking force of the hybrid yarns. However, the result from ANOVA can only indicate if this is a significant different between some of the conditions in the experiment, but not where this effect exists. Tukey's post hoc tests have been done in order to compare each of the experimental conditions to every other condition.

7 SUMMARY OF THE RESULTS

7.1 Overview of work done in each article

Article 1: Textile-based sensors were prepared by three different methods: conductive coating, weaving and knitting. The suitable measurement methods and devices were explored and the sensors were characterized according to the requirements of three different applications.

Article 2: The cyclic performance of the sensor made of conductive coating onto elastic textile substrates was studied, and different respiration patterns were simulated by a self-built device called a *cyclic tester*. Conductive coating was also applied to a prototype as sensors used for respiratory monitoring. The prototype was tested by ten healthy subjects and the performance was evaluated qualitatively.

Article 3: Knitted sensors were prepared with five different conductive yarns and four different knitting structures. The cyclic performances of prepared samples were examined. A prototype was manufactured by the fully-fashion technique and tested on one subject.

Article 4: Elastic-conductive hybrid yarns made of conductive winding yarns twisted around elastic core yarn were made. Two kinds of elastic core components and two kinds of conductive winding yarns were selected for our purpose. Different twist amounts were added into the hybrid yarns and the mechanical properties were tested and compared. Two hybrid yarns with better mechanical properties were selected for producing knitted strain sensors. Electro-mechanical properties of the prepared sensors were investigated in comparison with the sensors made of ordinary conductive yarns.

Article 5: A prototype with two sensing units was made for the purpose of monitoring respiratory function. The prototype was tested by five healthy subjects and compared with a conventional piezoelectric respiratory belt.

7.2 Textile-based sensors characterization – conductive coating and weaving (SP1; Article 1)[3]

In SP1, the electro-mechanical properties, e.g. the linear working range, sensitivity, stability, and hysteresis of prepared samples were studied. Conductive coating and weaving were the methods used to integrate sensors into the textile substrate. Both elastic and inelastic fabrics were selected as the textile substrate. The aim of Article 1 is to study the sensor characterization influenced by the textile substrate and the sensor integrating methods. Furthermore, two different testing methods were studied and compared.

7.2.1 Linear working range and sensitivity

Samples made of conductive coating were tested on two different lengths (150mm and 115mm indicated in the graph as R1 and R2) under the same continuous force increased from 2N to 4N. As seen in the dash-squared area in Figure 29, the resistance increases linearly with the increases of force. However, the resistance change (indicated by the slope of the curve) is independent on the initial length of the sample.

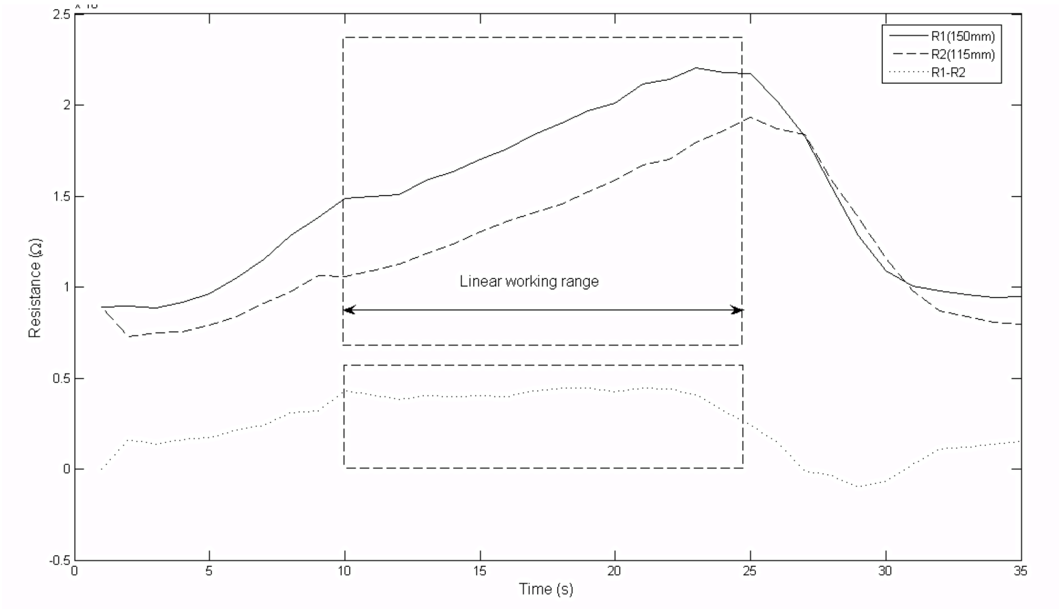

Figure 29. Resistance output under different testing length in conductive coated sensors [A1].

Linear working range (parts in the upper dash square in Figure 29) depends on the properties of the textile substrate and how the conductive part has been integrated into the textiles. The linear

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[3] The summary of study result from SP1 is a combination of results from Article 1 and results from paper, presented as reference [109] Guo, L., Berglin, L. and Mattila, H., (2010). Textile strain sensors characterization: Sensitivity, linearity, stability, and hysteresis, *Nordic Textile Journal,* **2**, 51-63.

working range of the elastic-coated samples was between 5% and 40% strain, while the inelastic samples performed linear below 6% strain. In woven samples, the linear working range of elastic samples was between 3.5% and 5% strain, while the inelastic sample had a linear range between 1% and 2.5%.

The gauge factor (GF) is used to indicate the sensor's sensitivity, which can be calculated by:

$$GF = \frac{\Delta R/R}{\Delta L/L} , \qquad (10)$$

Where R is the initial resistance, ΔR is the resistance difference between the final resistance and the initial resistance, L is the initial length, and ΔL is the difference between the final length and initial length.

Table 4 shows the testing results of conductive coated sensors under different force and gives the GF of the prepared samples:

Table 4. Measurement results of selected samples under different force [A1].

F (N)	**6**	**8**	**10**	**12**	**14**	**20**	**30**	**40**	**50**	**60**
ΔL/L (%)	16.2	20.7	23.7	25.9	27.5	32	35.7	37.1	39.1	39.2
R (Ω)	8960	9768	11908	11378	11157	11027	12165	12505	13069	12655
ΔR (Ω)	21998	29463	32443	38857	38726	45466	52580	55062	53349	59265
GF	15	14	11	13	13	13	15	12	11	12

As illustrated in Table 4, the GF of conductive coated sensor was around 13, the high gauge factor causes resistance drift (hysteresis) in time. This drift can be indicated by the difference of R in Table 4. The GF of inelastic-coated sensor was found to be 2.5, while it is 8.8 and 6.0 in elastic woven sensor and inelastic woven sensors, respectively [109].

7.2.2 Stability study

To study the stability, repeating stretch and release cycles were applied to the samples. The resistance-elongation property was recorded after 1 hour, 1 day, 5 days and 2 weeks. Results show that coated sensors perform constantly regardless of time (Figure 30, left). However, the resistance significantly decreased by approximately 10% in elastic woven and 25% in inelastic woven sensors (Figure 30, right). This decrease is probably caused by a slowly increasing of textile deformation. Due to lack of availability of the testing device, the stability of the inelastic woven samples could not be studied.

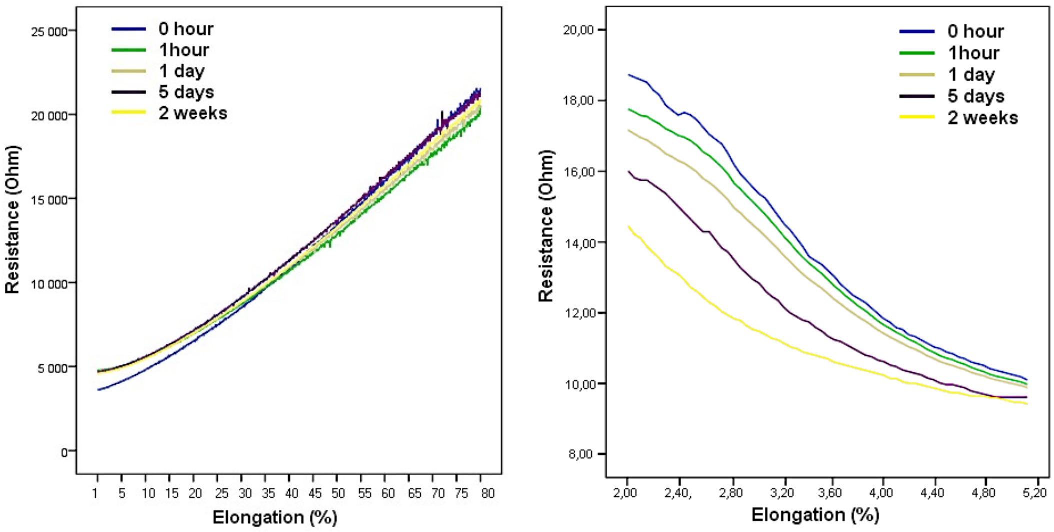

Figure 30. Stability test during 2 weeks. Elastic coated sensor S1 (left), and inelastic woven sensor S4 (right) [109].

7.2.3 Hysteresis study

Hysteresis is typically caused by the friction and structural change in materials [110]. Hysteresis is numerically indicated by hysteresis error; testing results demonstrated that the elastic materials had a rather high hysteresis error, while the inelastic materials exhibited smaller hysteresis errors. A typical resistance vs. elongation plot is shown in Figure 31, indicating the hysteresis behavior of a sensor. For the elastic coated sensor, the maximal hysteresis error is ±10% (in total 20%) at resistance of 7kΩ. Hysteresis effect can be easily eliminated by baseline drifting, which has been explained in section 6.1.2, figure 28.

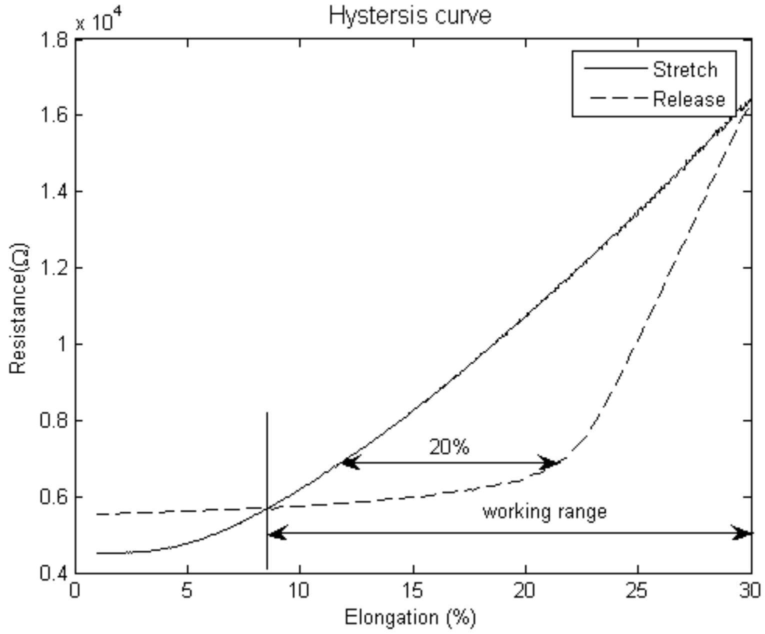

Figure 31. Hysteresis curve of elastic coated sensors, modified from [109].

7.2.4 Testing setups

Two different testing setups were built and compared in Article 1. Microprocessor was used in setup A (Figure 32, left), while instrumentation amplifier (LT1001) and oscilloscope were used in setup B. (Figure 32, right).

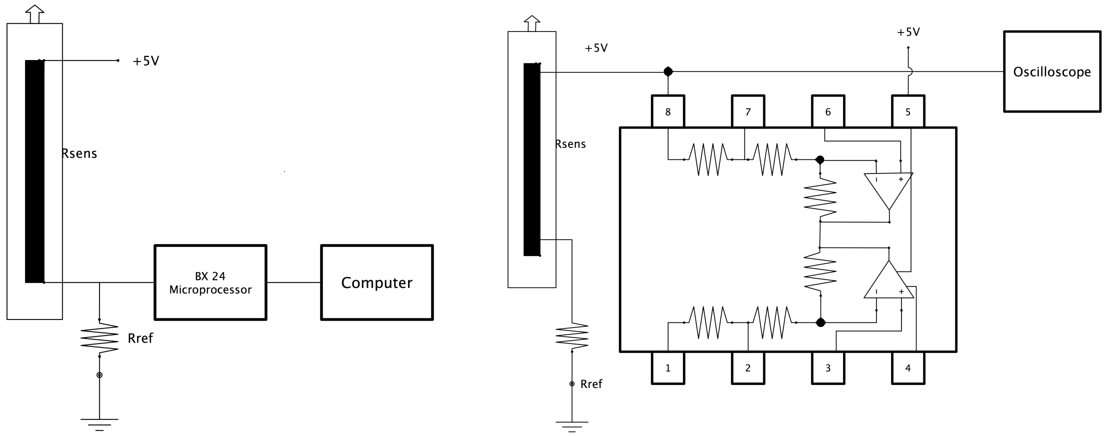

Figure 32. Testing setup, microprocessor connected with computer (left) and LT1001 amplifier connected with oscilloscope (right) [A1].

Both setups provide reliable testing results, however there are pros and cons in each setup. For example, setup A is preferable when mobility is required and setup B is better for measuring small and rapid force such as shaking or vibrational resonance. The comparison of the two setups is presented as follow in Table 5.

Table 5. Advantage and disadvantage of testing setup 1 and setup 2, modified from [A1].

Setup 1 Microprocessor + computer	Setup 2 Instrumentation amplifier + oscilloscope
+ Size of testing elements	+ Higher accuracy
+ No additional device needed	+ Better sensitivity
+ Simple circuit	+ Online measurement and data processing
+ Low costs	
- Lower accuracy	- Size of testing device
- Lower sensitivity	- High costs
- Offline data processing	

7.2.5 Application cases

In order to verify the sensor functionality according to the end applications, the conductive coated sensors were used in three different applications: a force sensor, a breathing sensor and a movement sensor. Preliminary tests have been done on all cases above.

In the applications where the force should be controlled within certain range, for example a cargo security strip, a stretch sensor can be used to indicate the force and activate the alarm when the force exceeds a pre-defined threshold value. On the other hand, conductive coated sensors are quite sensitive to small force/elongation changes, which makes it possible to sense the breathing rate. A prototype was made to register the breathing pattern. As the most interesting parameters in this case are the peak values, thresholds have been set up in order to simplify the testing. Stretch sensors can be used to measure joint movement as well. The conductive coated sensors could easily sense the step-wised resistance-elongation change, which corresponds to the degree of angle change.

7.2.6 Sub-conclusion

The flexibility of textiles allows their use in areas where large strains must be sensed and monitored. Common commercial metallic-based strain sensors work in the elongation range of 10^{-7} to 10^{-3} m [110]. With the textile-based sensors, one can achieve elongation typically in the elongation range of 10^{-2} to 10^{2} m.

The processability and quality are important issues to consider when designing a textile-based strain sensor. The conductive rubber used in this thesis work was difficult to apply using conventional coating technologies, due its high viscosity. Weaving the sensing element into the textile substrate seems to be a better alternative; however, the sensor performance must be improved. The development of conductive yarns that could be used as stain sensors in yarn-based manufacturing processes is of high interest.

7.3 Textile-based sensors characterization: knitting (SP2)

Knitting is another possible method for the application of conductive yarns into textile substrates. It has been considered an economical and effective textile manufacturing process. In addition, knitting produces less waste compared to weaving and coating.

7.3.1 Influence of yarns and structures (Article 3)

In Article 3, the knitted sensors were prepared with five different conductive yarns (Table 6) and four different knitting structures, namely: plain Jersey, 1×1 rib, interlock, and floating. The cyclic electro-mechanical properties have been studied and summarized below.

Table 6. Conductive yarns and their properties [A3].

Conductive yarn	Thickness	Linear resistivity (Ω/m)
Copper yarn	0.05 mm	10.5
Bekinox ® BK 50/2	400 dtex	5000
Shieldex®	235 dtex	100
Bekinox ® VN14/1	110 dtex	70
Beag EA1008	18 dtex	10

Preliminary testing results show that high conductive yarns such as copper are not among the best possible yarns for cyclic sensors, as the resistance-elongation dependence property is insignificant when small elongation is applied. Yarn made of BK 50/2, performed best among the selected yarns in terms of sensitivity. Sensors in different knitting structures made of BK 50/2 yarn were tested and presented in Figure 33. In the graphs, A0 and B0 represent the initial resistance of the sensor in the relaxed state and stretched state, respectively. Correspondingly, A1 and B1 represent the final resistance of the sensor. ΔA and ΔB represent the differences between A1 and A0, and B1 and B0, respectively, which gives an indication of sensor hysteresis. The ideal strain sensor should produce no hysteresis (ΔA = ΔB = 0), however, this is not the common case when the textile is used [67]. Therefore, a sensor that has constant change in resistance against elongation (B-A =constant) is a preferable solution, since the baseline shifting can be easily removed by post-processing. Taking this as a criterion, one could see in Figure 33 that the interlocking structure performs best, since the ΔA is almost equal to ΔB. In contrast, both 1×1 rib and floating structures have larger ΔB than ΔA. Another criterion is that the resistance in the stretched state (B) is preferably smaller than the resistance in the relaxed state (A), so that a threshold can be set to record the cycles. Both interlock and floating structures fulfil this requirement, while sensors with 1×1 rib structure are beyond the requirement (A1 >B0). Although 1 × 1 rib structure produces larger hysteresis effect, the difference between amplitudes of cycles was smaller than the floating one. As we mentioned before, the hysteresis effect can be easily eliminated by baseline drifting, 1×1 rib can still be a useful structure.

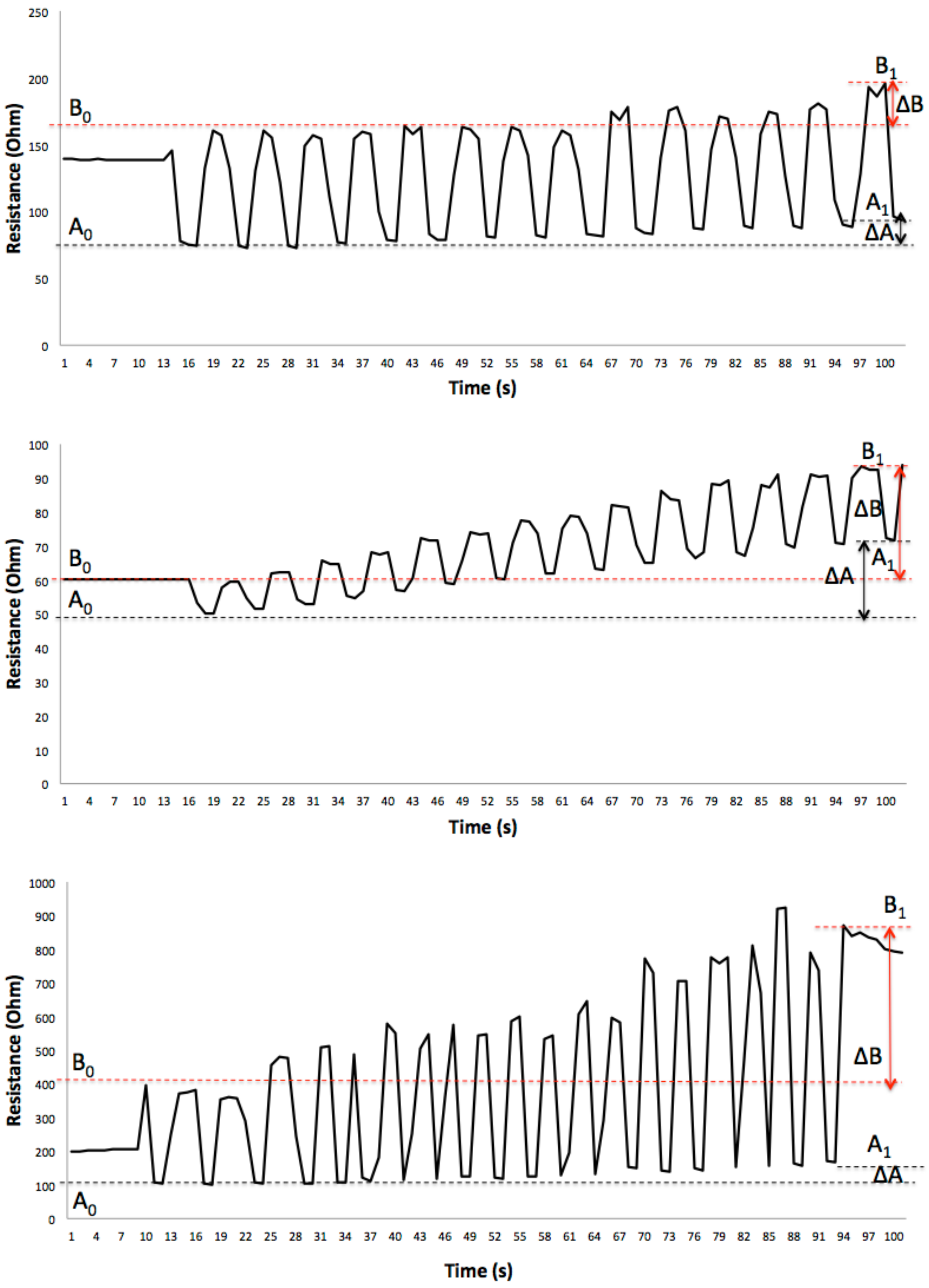

Figure 33. Resistance as a function of time for BK 50/2 with stretching speed of 20 mm/sec. Top: interlock; middle; 1×1 rib; bottom: floating [A3].

As a conclusion, the most practical structure is interlock. This is because the two sets of loops present in both sides of the fabric construct a dense and heavy fabric, which exhibits higher elastic recovery.

7.3.2 Improvement of electro-mechanical properties by elastic-conductive hybrid yarns (Article 4)

Mechanical properties of the hybrid yarns

Two kinds of elastic core components (PA/Lycra® and PA) and two kinds of conductive winding yarns (BK 50/1 and BK 50/2) were selected to produce hybrid yarns, the material properties are given in Table 7. The twisting was done with a constant twisting speed, and four different twisting amounts were applied to the hybrid yarns. Mechanical properties, such as breaking force, tenacity[4], and elongation at breaking of the hybrid yarns have been tested prior to integration into the fabric-based sensors. For each test, 10 randomly selected samples were measured. A special setup (see figure 34) was used in order to eliminate the false twists generated when high degree of twists was added to the hybrid yarns. In this setup, the hybrid yarn was placed in between two holders, and a calibration weight was hanging on both ends of the yarn, which was adjusted according to the fineness of the yarn (0.01±0.001cN/tex). The total length of the yarn was 50 cm and the space between the two holders was 26 cm. A mark was made at the centre of each holder (figure 34, left). When placing the yarn into the grips in tensile tester (figure 34. right), the marks should align to the starting point (A) and the ending point (B), respectively.

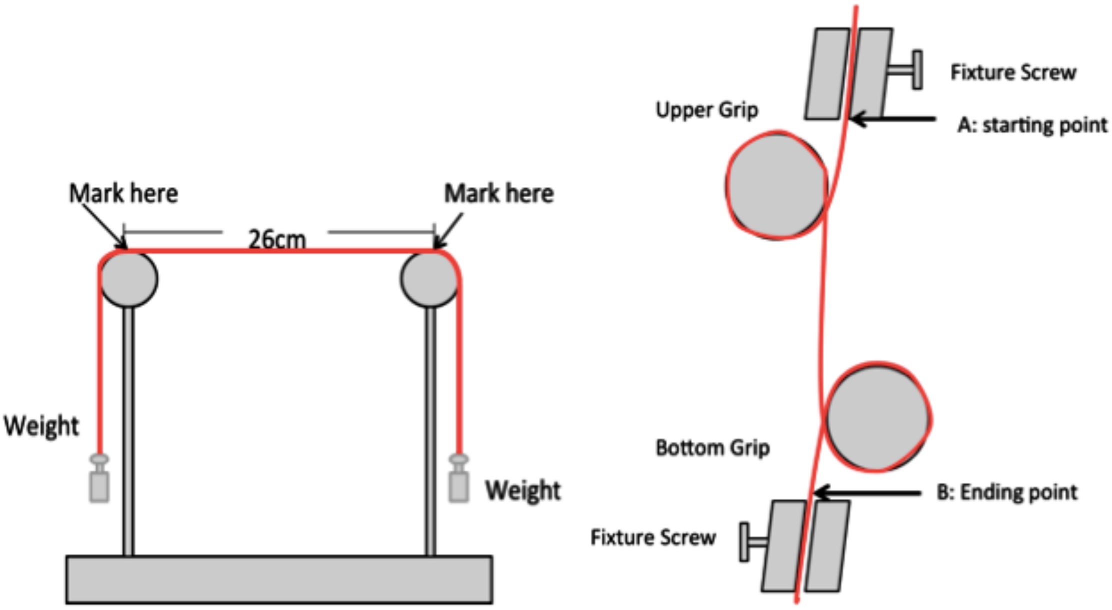

Figure 34. The yarn marking system (left) and the placement on tensile testing device (right) [A4].

The results of tensile properties of the hybrid yarns are given in Table 8. The results were analysed in comparison to sensors made of ordinary conductive yarn (see Table 7). The elongations at break of the hybrid yarns were generally improved. Taking BK 50/1 as an example, the elongation at

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[4] The study of the tenacity is not in the scope of this article.

break of BK 50/1 was 57.62%, while after twisting, this measurement increased 11.38% to 31.09% according to the number of twists added on. A similar phenomenon could be observed with BK 50/2 yarn. However, the improvement in elongation, in terms of the numbers of twists within each group, was insignificant in all groups (Figure 35, left).

Table 7. The materials used as core yarns and winding yarns and their properties [A4].

Materials		**Fineness (Tex)**	**Breaking force (cN)**		**Elongation at Break (%)**		**Linear Resistivity (Ω/cm)**	**Yarn specification**
			Mean	SD	Mean	SD		
Core yarns	PA/Lycra	78	3.59	0.21	235.31	11.68	-	#1
	PA	78	5.46	0.14	66.73	3.34	-	#2
Winding yarns	BK50/1	200	5.97	0.74	57.62	4.90	100	#3
	BK50/2	400	10.84	0.74	63.23	4.85	50	#4

Considering the breaking force (Figure 35, right), hybrid yarn exhibited reduced breaking force in groups #01 and #02. The reduction in breaking force is most likely due to the Lycra® filament in the core yarn, since it has a very low breaking force. Other observations from Figure 35 (right) are that breaking force increases with the number of twists in both groups, and that breaking force was comparable with that of the pure conductive yarn when the twist amounts reached 600 twists/m. Hybrid yarns generally exhibited improved strength in groups #03 and #04, and the peak was plotted at 450 t/m.

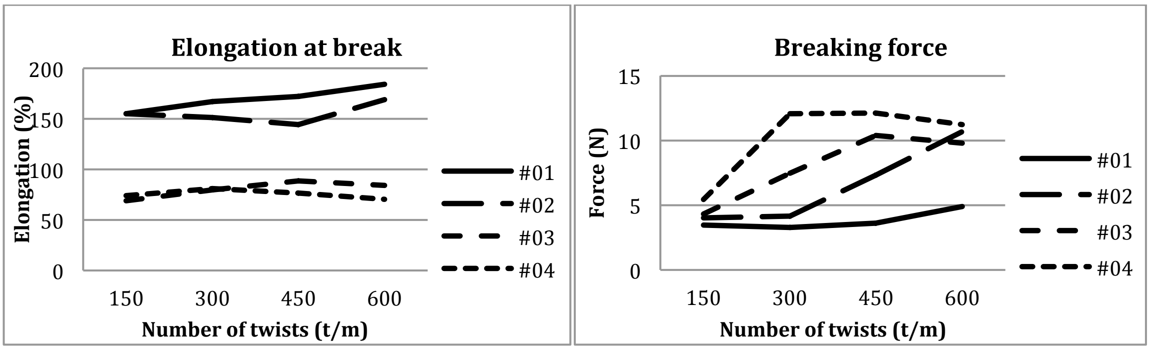

Figure 35. The elongation at break (left) and the breaking force (right) of the hybrid yarns [A4].

Table 8. Tensile properties of the manufactured hybrid yarns [A4].

Core yarns	**Winding yarns**	**Fineness (dTex)**	**Breaking force (N)**		**Elongation at Break (%)**		**Yarn specification**
			Mean	SD	Mean	SD	
PA/Lycra	BK50/1	278	3.45	0.19	155.13	16.72	#01a
			3.28	0.25	167.42	8.28	#01b
			3.63	1.01	172.48	8.90	#01c
			4.89	2.28	184.52	7.79	#01d
	BK50/2	478	4.02	3.44	170.61	12.14	#02a
			4.17	2.92	151.43	13.42	#02b
			7.31	2.62	144.28	18.02	#02c
			10.68	0.99	169.02	14.80	#02d
PA	BK50/1	278	4.32	1.48	69.00	6.74	#03a
			7.48	1.09	79.92	7.24	#03b
			10.38	1.99	88.71	7.83	#03c
			9.79	1.81	84.17	8.50	#03d
	BK50/2	478	5.43	4.35	74.33	6.19	#04a
			12.06	2.18	81.11	5.58	#04b
			12.12	1.85	76.58	1.84	#04c
			11.23	1.92	70.47	13.2	#04d

Result from 1-way ANOVA showed that there were significant effects of both twists amount and the yarn properties on breaking force at the $p<0.05$ level [F (4, 196)= 11.04, p=0.00 and F (7, 193) = 116.30, p=0.00]. In case of elongation at break, ANOVA result showed that there was a significant effect of the core yarns on the elongation at break at the $p>0.05$ level [F (2, 199)=600.361, p=0.00], however, the effect of twists amount on elongation was insignificant at the $p>0.05$ level [F (4, 196)=0.99, p=0.43]. In-group analyses were done by Post hoc comparison using the Tukey's HSD test. The results indicated that the difference of breaking force was insignificant when comparing no twists added with 150 twists/ meter, however, it became significant when twists are equal and larger than 300 per meter. In case of elongation at break, the difference between various winding yarns were insignificant, however, the elastic properties of the core yarns influence the elongation at break in most of the cases (statistically significant in all cases). As a conclusion, the elongation at break of the hybrid yarns was dependent on the elastic properties of the core yarns, rather than the number of twists applied. Conversely, the numbers of twists applied on the hybrid yarns strongly influenced the breaking force.

Electro-mechanical properties of the knitted strain sensor

Strain sensors were knitted with the selected hybrid yarns (#02d and #03c, Table 8). BK 50/1 and BK 50/2 were used to produce samples with the same parameters for the purpose of comparison. Resistance change ratios (RCR) were detected and used as an indication of sensor sensitivity. The RCR is calculated as:

$$RCR = \frac{R_f - R_0}{R_0}, \qquad (11)$$

Where R_0 is the initial resistance (the resistance before stretching), and R_f is the final resistance (the resistance after released from stretching).

The resistance change of a strain sensor indicates its total deformation, which can be divided into elastic deformation-related resistance change and plastic deformation-related resistance change. Because the elastic deformation is reversible after loading is removed, while the plastic deformation is permanent [111], the plastic deformation-related resistance change ratio (PD-RCR) can be used as a determinant of the sensor's elasticity. Results of RCR are presented in Table 9, from which we can see that, in most of the sensors, the RCR is negative in the first tension cycle, while mostly positive in the second tension cycle.

Table 9. The RCR of selected samples in the first and second tension cycles [A4].

	#3		#4		#03c		#02d	
	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle
2%	-0.55	6.05	2.74	2.74	-1.01	-0.38	1.25	0.99
5%	-2.86	1.18	6.93	0.87	-2.92	0.13	-1.21	2.97
10%	-0.83	4.02	-13.36	3.98	-2.46	1.50	-7.63	1.52
15%	-2.45	7.49	-14.71	0.52	-5.56	1.08	-9.40	1.62
20%	-5.66	2.13	-16.77	1.68	-6.50	1.83	-8.76	2.61
AVG	-2.47	4.17	-7.03	1.96	-3.69	0.83	-5.15	1.94
SD	2.042	2.63	11.00	1.42	2.27	0.93	4.84	0.82

Both positive RCR and negative RCR give indications of hysteresis behavior of sensors. In order to compare the magnitude of hysteresis in 1st and 2nd strain cycle, the absolute value of RCR was calculated and compared in Figure 36. In the first tension cycle (Figure 36, left), the value is highly dependent upon the magnitude of the elongation strain applied on the sample. This is because when the sample is under stretch, more contact points and greater pressure are created among the conductive yarns, so that the resistance drops significantly. When the strain is removed, the knitted structure cannot completely return to its initial state. However, in Figure 36 (right), we can see that the change in RCR value is irrelevant to the change of strain, proving that the plastic deformation has been totally or partially removed since and after the second cycle.

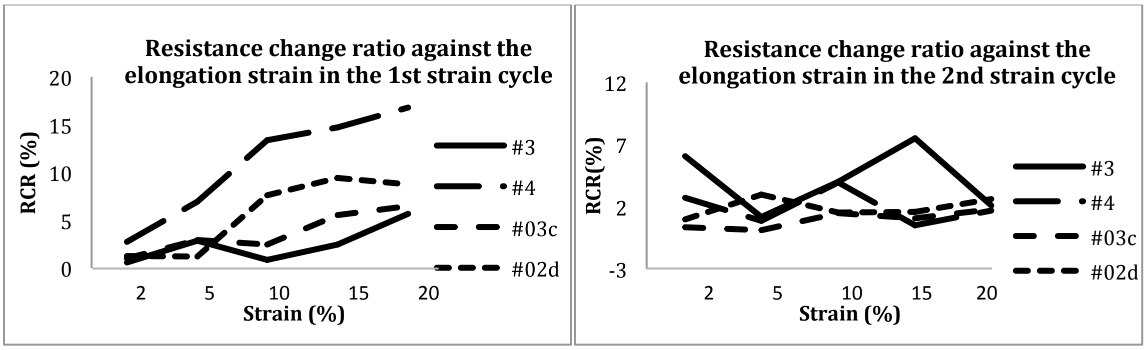

Figure 36. The absolute value of the resistance change ratio against the strain in the first (left) and second (right) cycles of specimens [A4].

A comparison was made between groups #3 and #03c, and groups # 4 and #02d. The RCR of specimen #3 was (4.17 ± 2.63)%, while the RCR was (0.83 ± 0.93)% for specimen #03c (see Table 9). The hybrid yarns improved the elasticity of the tested sample and consequently improved the sensor sensitivity. What's more, group #3 and #4 exhibit higher measure of dispersion, this is mainly caused by the inelastic character of the sensors. The magnitude of hysteresis increases with the increasing of elongation in inelastic materials. The elongation-dependent hysteresis effect could be removed by adding elasticity into the materials. As a result, the hybrid sensors (group #03c and #02d) exhibit a much lower standard deviation of RCR than the comparison group, which indicates that the sensors made of hybrid yarns exhibit a greater stability.

Cyclic electro-mechanical properties of the knitted strain sensor

The same comparison groups have been selected in the study of the cyclic electro-mechanical performance. Results are given in Figure 37 and Figure 38. From Figure 37 we can see that the cyclic pattern becomes more regular by using hybrid yarns when strain is greater than 5%, while in Figure 38, we can see that the hybrid yarns exhibited improved elasticity by giving a more homogeneous output over time when strain was 5%. When the strain was equal to or greater than 10%, the improvement in elasticity was not very significant; however, the signal strength was enhanced.

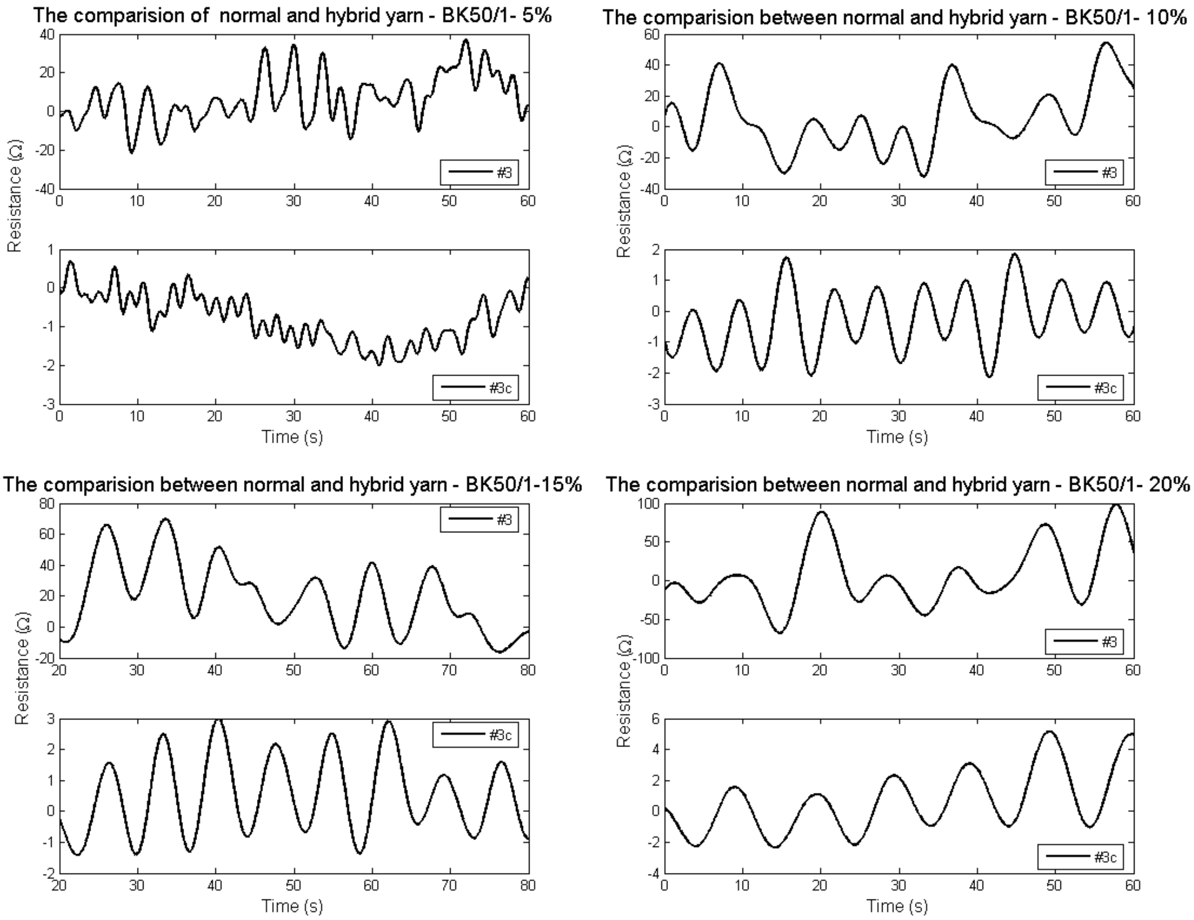

Figure 37. Cyclic electro-mechanical properties of specimens #3 and #03c under strains of 5, 10, 15, and 20% [A4].

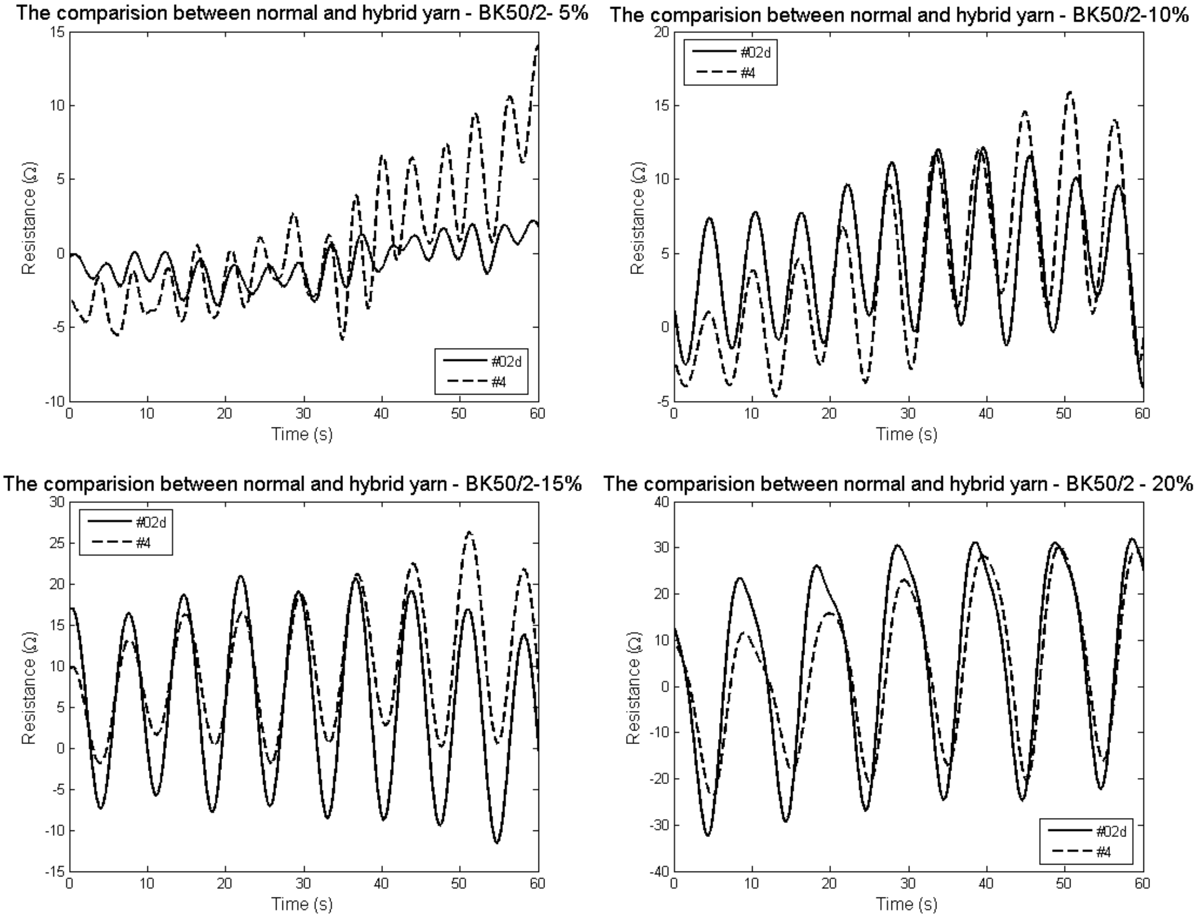

Figure 38. Cyclic electro-mechanical properties of specimens #4 and #02d under strains of 5, 10, 15, and 20% [A4].

7.4 Smart clothing system for respiratory monitoring (SP3)

In SP3, smart clothing systems were made for use in respiratory monitoring applications. Five prototypes were made, and two of them were selected for testing.

7.4.1 Mechanical simulation of respiration patterns (Article 2)

Mechanical simulation was applied on conductive coated samples prior to on-body tests. The simulation results of normal breathing and deep breathing are given in Figure 39.

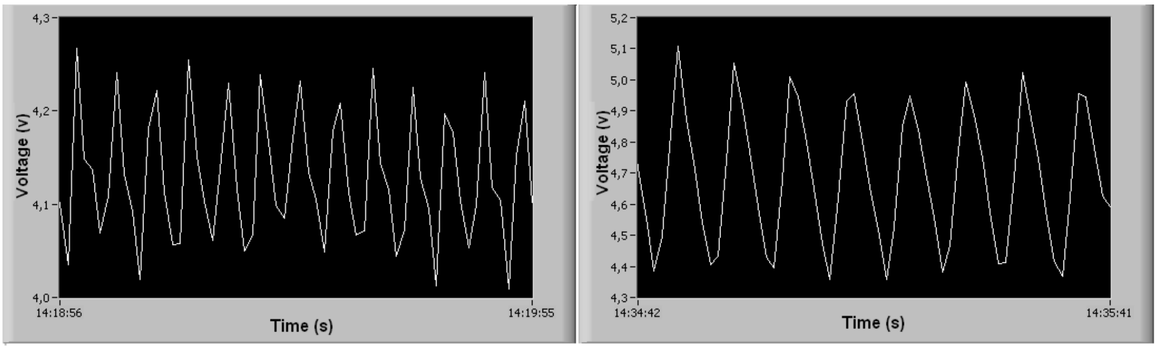

Figure 39. Machine simulation of normal breathing (left) and deep breathing (right) [A2].

Comparing the above-mentioned two simulation patterns, one can easily see that the magnitude of curve in the second pattern is greater than that in the first pattern, and the extension-releasing cycles in the first pattern are more frequent than in the second pattern. It is common knowledge that torso changes in deep breathing are larger than those in normal breathing, and that deep breathing are usually longer than normal breaths. The simulated results agree with these truths. Figure 40 illustrates the simulation results of four different patterns: normal breathing, deep breathing, hyperventilation, and apnea, and all patterns were distinguishable.

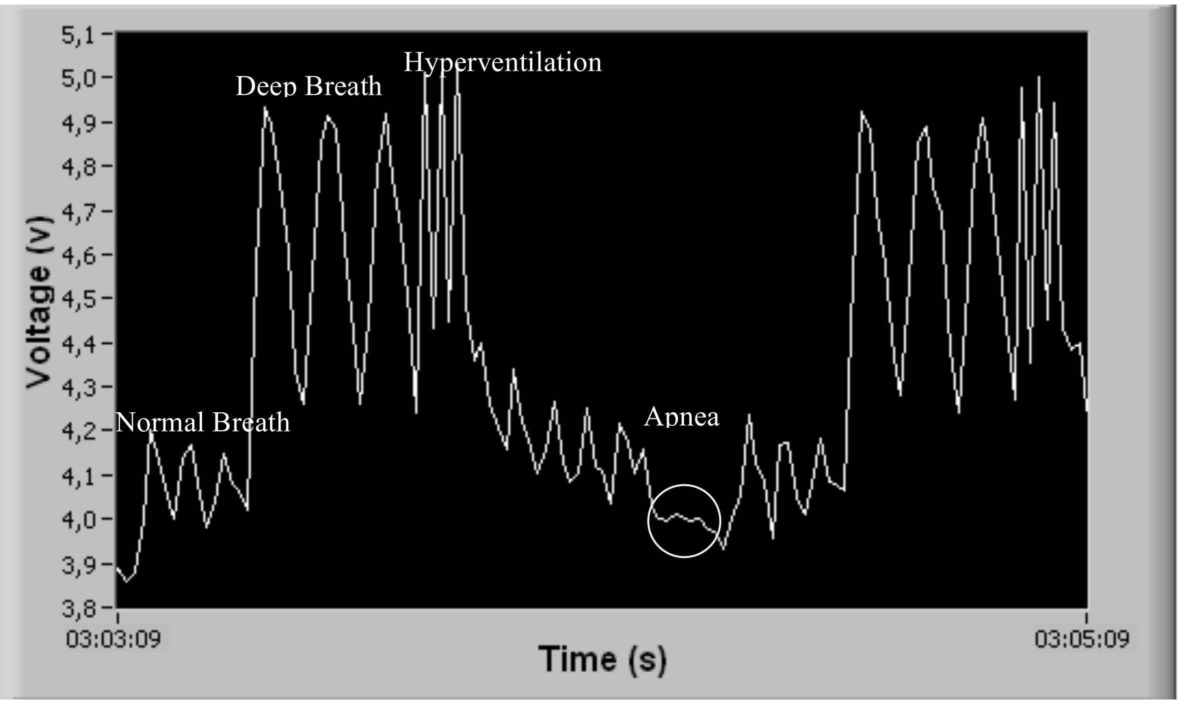

Figure 40. Machine simulation of normal breathing, deep breathing, hyperventilation and one apnea. The X-axis indicates the time in real-time scale, and the Y-axis indicates the voltage changes caused by stretching and recovering [A2].

7.4.2 On-body testing (Article 2 & Article 5)

Observation and comparison result (article 2)

In Article 2, prototype 2 was tested by ten subjects. The respiration patterns of the subjects were recorded during sitting still, walking, and jogging. In addition, deep breathing in a supine position and athletic breathing were studied. Results shown that the signals detected from the wearable sensor can be clearly distinguished among the different activities performed. Figure 41 gives examples of respiration signal collected when subject #5 in sitting still (a) and jogging (b). The sensor could register both the frequency change and the amplitude change that occur during testing. From figure 41 we can see that the amplitude in (b) is greater than it in (a), indicating that during jogging, the subject breathing was deeper than sitting still.

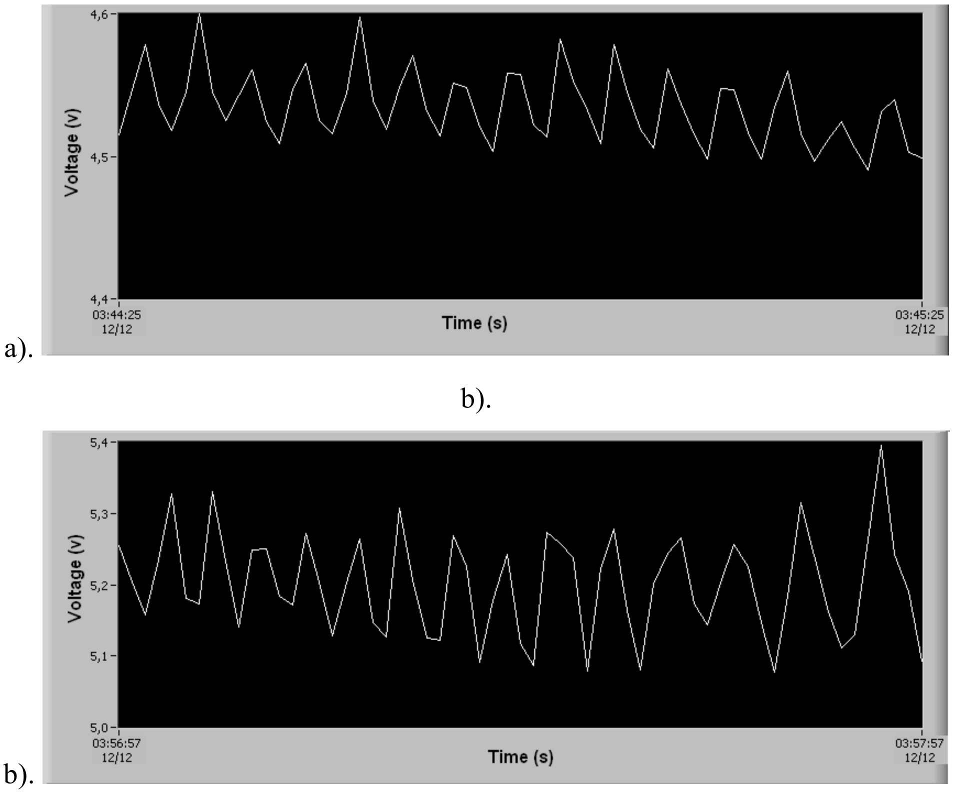

Figure 41. The breathing pattern of subject #5 while a) sitting still and b) jogging [A2].

Article 2 only provided a visual inspection of the respiration pattern, though a more thorough quantitative analysis was conducted in Article 5. In addition, a conventional respiratory belt was used to simultaneously record the respiration signal as a comparison.

Agreement between garment-based sensors and the reference respiratory belt (Article 5)

Agreement between garment-based sensors in the smart clothing system and the respiratory belt was analysed by Pearson’s correlation calculations, the results of which are presented in Table.10

Pearson's correlation between the garment-based and the reference belt were found to be: r = 0.70±0.12 for the chest sensor and r = 0.74±0.07 for the abdomen sensor, both significant at p< 0. 01. In addition, the intra-class correlation between the chest and abdomen data was r=0.92±0.05 (p <0.01), indicating that there is a strong relation between these two sensors.

Table 10. Pearson's correlation between garment-based sensors and the reference belt [A5].

	Ref−Ch[5]		Ref−Abd[6]		Ch−Abd[7]	
	mean[8]	SD	Mean[8]	SD	Mean[8]	SD
Normal breathing	0.70	0.12	0.74	0.07	0.93	0.08
Rapid breathing	0.48	0.25	0.67	0.38	0.72	0.29
Slow breathing	0.56	0.23	0.42	0.15	0.89	0.05

Figure 42 shows a typical respiration pattern collected from both garment-based sensors (Ch curve and Abd curve) and the reference belt (Ref curve). The other two curves, Ref−Ch and Ref−Abd, illustrate the differences between the reference belt and each garment sensor. The small amplitudes of Ref−Ch and Ref−Abd indicate less difference between the reference belt and the garment sensors.

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[5] Difference of signal from reference belt (Ref) and sensor placed in chest position (Ch).

[6] Difference of signal from reference belt (Ref) and sensor placed in abdomen position (Abd).

[7] Difference of signal from sensor place in chest position (Ch) and sensor placed in abdomen positon (Abd).

[8] The p-value for all observations is significant at the level of 0.01.

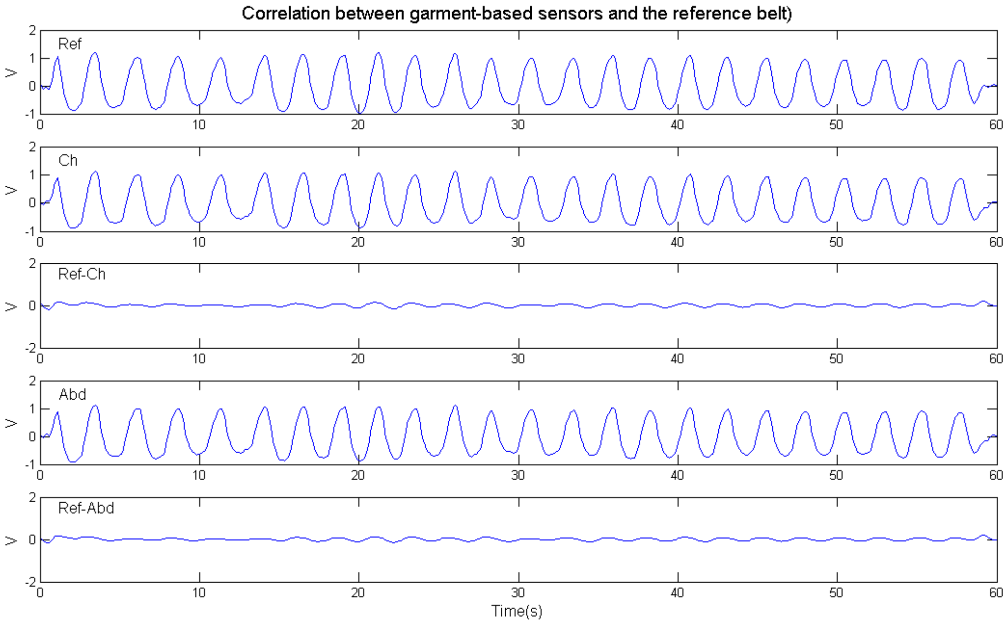

Figure 42. The recorded respiration pattern in a normal subject (subject #1). Ref, Ch, and Abd are signals from the reference belt, the sensor placed on the chest position, and the sensor placed on the abdomen position, respectively [A5].

Average respiration frequency determination

Figure 43 shows the recorded respiration signals in the time and frequency domains when a subject breathing normally.

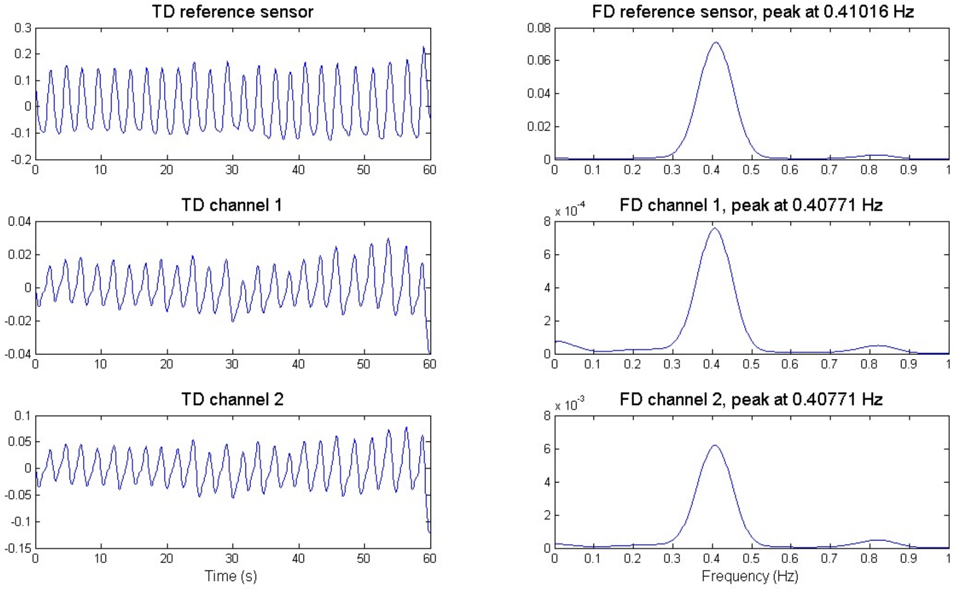

Figure 43. Normal breathing measured from the reference belt and the garment-based sensors in time and frequency domains. Channel 1: sensor placed in chest position; channel 2: sensor placed in abdomen position [A5].

Table 11 gives the frequency differences between the garment-based sensors and reference belt; the results show very small differences between all the respiration methods. The signals from the garment-based sensors agreed well with the reference one.

Table 11. Frequency differences (Hz) between garment-based sensors and the reference belt[9] [A5].

	$\Delta F_{ref\text{-}abd}$[10]		$\Delta F_{ref\text{-}ch}$[11]	
	Mean	SD	mean	SD
Normal breathing	0.003	0.0	0.001	0.004
Rapid breathing	0.002	0.004	0.001	0.007
Slow breathing	0.001	0.002	0.001	0.003

Time delay between sensors

The instantaneous respiration frequency is more meaningful than the average respiration frequency in most clinical situations. The delay of the garment-based sensors and the reference belt was observed in both chest and abdominal positions (Figure 44). The length of delay greatly depended on the respiration rate: slow breathing generates the longest delay (1 s), while fast breathing produced almost no delay (0.15 s) (Figure 45). However, we could not determine in which of the two sensor systems the delay was larger, compared to the actual respiratory movements.

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[9] Due to the large intra-individual variation in respiration frequency, the differences between estimated respiration and the measured respiration frequency has been reported instead of the absolute frequency of each breath.

[10] $\Delta F_{ref\text{-}abd} = F_{ref} - F_{abd}$

[11] $\Delta F_{ref\text{-}ch} = F_{ref} - F_{ch}$

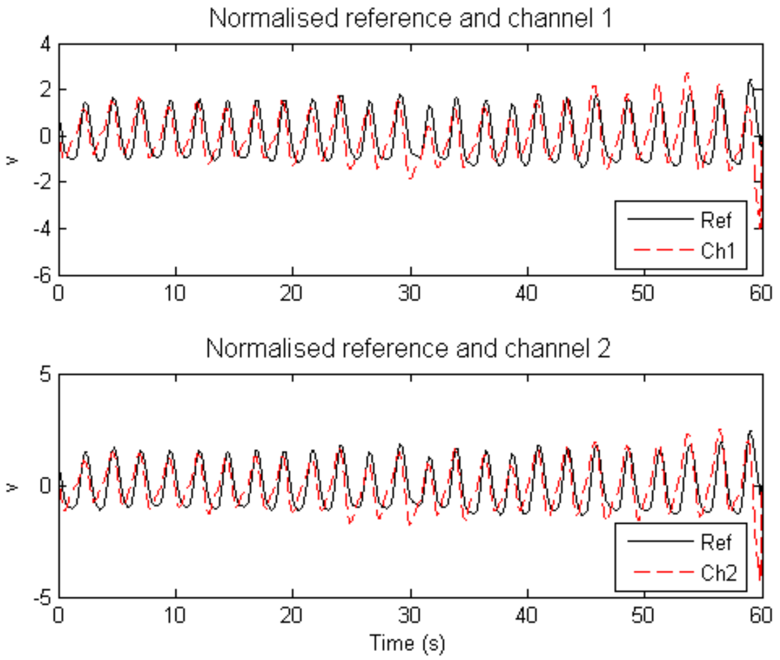

Figure 44. The delay of sensors placed in channel 1 and channel 2 [A5].

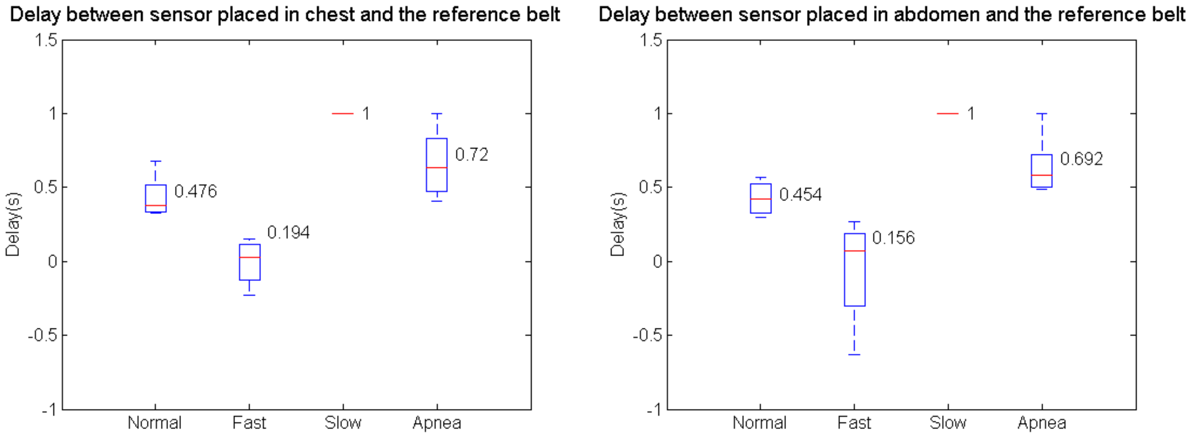

Figure 45. Delay between the garment-based sensors and the reference belt placed in the chest position (left) and the abdomen position (right) [A5].

Predominant respiration compartment determination

A general assumption is that the breathing maneouver consists of a balance between the chest and abdominal compartments of breathing [12]; however, this balance can be broken in different situations. Figure 46 represents chest-dominated breathing and abdomen-dominated breathing patterns a healthy subject. It can be seen that in chest-dominated breathing, the average signal amplitude collected from the chest position was larger than that from the abdomen position, and the opposite fact can be observed in abdomen-dominated breathing. Although two subjects (#2 and #5, Figure 47) failed to apply the chest-dominated breathing, the results indicate that the garment-based sensors could be used to determine the predominant breathing compartment.

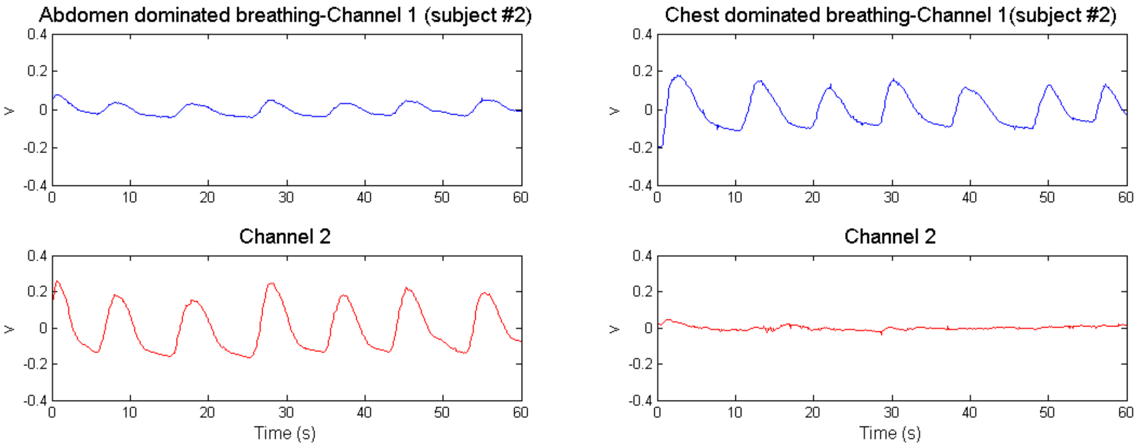

Figure 46. Chest-dominated breathing (left) and abdomen-dominated breathing (right) in subject #2. Channel 1: sensor placed in chest position; channel 2: sensor placed in abdomen position [A5].

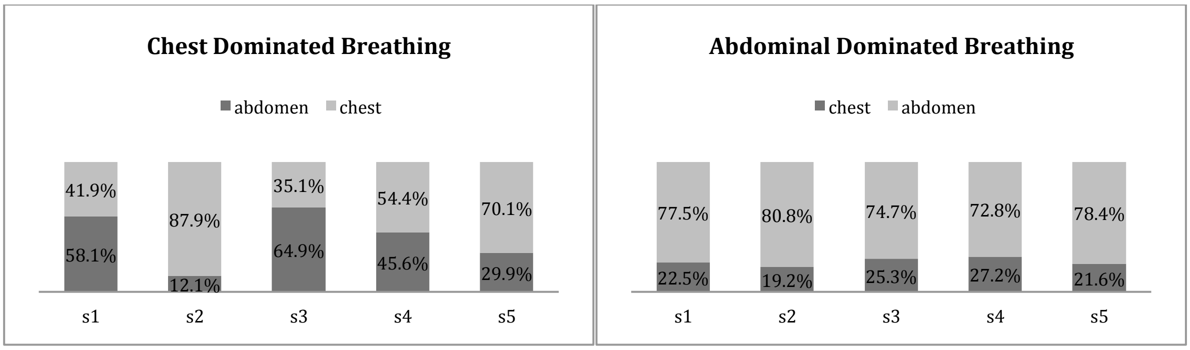

Figure 47. The percentage use of chest and abdomen compartments in chest-dominated breathing (left) and abdomen-dominated breathing (right), from five subjects [A5].

8 ANALYSIS AND DISCUSSIONS

This chapter analyses the appended articles in response to the research questions. The relationship between research questions and articles is illustrated in Table 12.

Table 12. The relationship between appended articles and research questions.

	RQ1	**RQ1**	**RQ2**	**RQ3**
	Materials Selection	Useful Technologies	Sensor Embedment	System Performance
A1	- Conductive yarns • Bekinox® BK 50/2 • Beag EA 1088 - Conductive rubber - Textile substrates • Elastic woven • Inelastic woven • 1×1 rib knitting	- Weaving - Coating - Knitting		
A2			- Single sensing unit - Placed on chest position	- Machine Simulation - On-body tests
A3	- Conductive yarns • Cooper • Bekinox® BK 50/2 • Shieldex® • Bekinox® NV 14/1	- Knitting • Single Jersey • 1 × 1 rib • Interlock • Floating -Fully-fashion	-Double sensing units -Placed on chest and abdomen positions	- Machine Simulation - On-body tests
A4	- Hybrid yarns -Elastic winding yarns • PA • PA/Lycra® - Conductive core yarns • Bekinox® BK 50/1 • Bekinox® BK 50/2	-Knitting • 1 × 1 rib		
A5			-Double sensing units -Placed on chest and abdomen positions	- On-body tests - Comparison with conventional respiratory belt

8.1 Analysis of research question 1

One purpose of this thesis was to study the existing methods for integrating the stretch function into the textile substrates and to study the suitable conductive materials that can be used in this application.

RQ 1: *Which materials and methods are suitable for integrating a stretch sensing function into clothing?*

8.1.1 Materials selection

CLR was found to be the most reliable material, which can be applied by the coating method onto the textile substrate. Sensors made of CLR exhibited high sensitivity, low hysteresis, and good stability in both the short-term and long-term. However, there are drawbacks to CLR. For example, applying CLR requires one additional process after the fabric production process and the waste materials/wastewater must be separated.

On the other hand, introducing conductive yarns into the woven or knitted fabrics reduces the process into a single step. Different conductive yarns were studied, and the main factors influencing the choice are: yarn resistivity, mechanical properties, and processability. Results show that the yarn with relatively high resistance is suitable for sensor applications. Therefore, the conductivity requirement is not so critical; metal staple fibre-spun yarns, metallic coated yarns and even conductive polymers may be used for this application. The mechanical properties are more important; as high tension is applied to the feeding yarns in both weaving and knitting processes, mechanical properties, such as the strength and the brittleness of the yarns, should be considered. In our experiments, Bekinox® BK 50/2 was most often used, as it has the best processability and sufficiently high resistance to be used as a sensor. However, the main problem of sensors made of conductive yarns is that the sensors have low stability and high hysteresis. Elastic-conductive hybrid yarns were produced in an effort to improve this problem. By introducing elastic yarns into the sensing units, the electro-mechanical properties improved significantly.

The choice of basic textile substrate was also studied. Results indicate that both elastic and inelastic substrate may be utilized. Due to different application requirements, the elasticity of fabrics is not essential; however, the elastic recovery properties are more important, since these affect the sensor stability and hysteresis.

8.1.2 Suitable methods

Coating was the method mainly used to apply sensing function into the clothing system. Sensors made of conductive coating have the greatest sensitivity. Respiration creates a signal of relatively low frequency and amplitude; sensors with low sensitivity may miss measurements.

Knitting, on the other hand, is an attractive method for the integration of sensing parts directly into the clothing by a single process. Due to time limitations, one prototype was produced by fully-fashion technique, though we believe that it is entirely possible to produce the prototype by complete garment technique. The prototype was tested on one healthy subject. The signals from both sensors were readable, but not stable enough for long-term monitoring. This is because the knitted loops in the garment were not compact enough to ensure ample sensitivity of both sensors. Future work should focus on improving the elastic recovery properties of the basic structure. This can be achieved by increasing the stitch density and by using elastic yarns as the basic materials. Another improvement for better sensitivity could be the use of elastic-conductive hybrid yarns.

8.2 Analysis of research question 2

RQ2: *How can sensors be embedded into the clothing system?*

RQ2 addressed the problems of sensor placement, the transmission method of data collected from sensors, and the contact between the clothing and electronics interface. This question cannot be answered quantitatively and no standard answer exists. In this thesis work, different attempts were made to achieve a system that fulfils most of the requirements mentioned in Section 5.1.

Sensor placement decides whether the system is capable to be used as the breathing detection device. Sensors must be placed on top of the chest or/and abdomen position so that the change of the corresponding respiratory compartment may be sensed and indicated by the resistance change of the sensors. Placement on both chest and abdomen positions provides information of certain illnesses, e.g. muscle fatigue; this double sensing unit was utilized in prototypes 3, 4, and 5.

Signals collected by sensors must be sent out via data-bus; therefore, the data-bus must be protected from regular usage and maintenance, as well as the electrical interference. In prototypes 3 and 4, piping was used as the protective layer of the data-bus, however, piping was not resistant to long-term washing. In prototype 5, the final solution was to make the data-bus piping detachable, so that data-bus could be detached before washing.

Reliable contacts are achieved by the use of snap buttons. Snap buttons were used in the clothing industry for many years; to have them on clothing in any circumstance is no problem.

8.3 Analysis of Research question 3

RQ3: *How does the clothing system perform, in terms of sensor functionality and wearability?*

RQ3 consists of two study parts: sensor functionality and wearability. Sensor functionality was the major concern in Articles 2 and 5, and the wearability was studied in Section 5.6.

8.3.1 Sensor functionality

Results from Article 2 show that the signals detected from the clothing system can be clearly distinguished between different activities. Sensors could register changes in both the frequency and the amplitude of breathing patterns.

Article 5 provided quantitative analysis information of the clothing system in comparison to the clinical respiratory belt. The Pearson's correlation results indicate that the majority of normal and slow breathing patterns can be registered by the clothing system; neglected errors occurred only when the subjects breath rapidly. FFT analysis revealed that the signal frequency detected by the clothing system strongly agreed with that of the respiratory belt. There are slight delays between the clothing system and the belt (1s) when monitoring slow breathing; however, we could not determine in which of the two sensor systems the delay was larger, compared to the actual respiratory movements.

8.3.2 Wearability performance

Wearability was achieved by the usage of Velcro®. This simple design made 86.76% of survey respondents believe that wearing the SmartShirt was more comfortable than wearing the respiratory belt; while 68.75% of the respondents agreed that the SmartShirt was is easier to put on and take off,

Answering RQ3, a smart clothing system can provide reliable respiratory measurements, with signals of comparable quality to the conventional respiratory belt. The users were more comfortable with the smart clothing system and most of them believe that using a smart clothing system will improve their health condition and their quality of life.

9 CONCLUSIONS

In this thesis work, textile-based sensors and a smart clothing system for respiratory monitoring were introduced, with a focus on sensor and clothing design and subsequent system evaluation.

This thesis begins with the establishment of the research area. Due to the interdisciplinary nature of the research topic, basic knowledge of ubiquitous healthcare, smart textiles, and wearable computers is introduced and the definitions of useful items are presented. In order to understand the theory behind sensor performance, the sensing mechanism is presented in Chapter 3. The knowledge of sensing mechanisms is not included in the appended articles. In Chapter 4, sensors made of knitted fabric were studied, as knitting is an attractive method for integrating sensing functions into textile architecture. The purpose of this study was to evaluate different conductive yarns and knitted structures, and to determine the optimal combination for designing knitted-based sensors for respiratory monitoring use. Smart clothing system requirements, according to functionality, system configuration, and component requirements, are discussed together with the design flow in Chapter 5. Issues related to wearability, maintenance, and aesthetic requirements, as well as the environment and health, are also discussed. Sensors and clothing made by knitting technique are studied in Chapter 5. Data collection, signal processing, and analysis methods are presented in Chapter 6. LabVIEW was used for software implementation, and MATLAB was mainly used for the data analysis. A summary and analysis of the results from publications are presented in Chapter 7 and Chapter 8, and the main contribution of the publications can be summarized as follows:

- Different methods of introducing sensor function into textiles have been explored, and the sensor performances in terms of sensitivity, stability, and hysteresis have been studied. Advantages and drawbacks of different technologies have been reviewed.
- Sensors have been evaluated, both as one single element and as a component of a clothing system. Sensor performance is not only influenced by the materials and manufacturing methods, but also by the built-in environments. Sensors integrated into clothing for respiratory monitoring have been tested by five subjects during different scenarios in comparison with a conventional respiratory belt. To the author's knowledge, similar work has not been reported before these publications.
- The development of a smart clothing system, considering not only the sensor performance, but the wearability, user acceptance, and related environmental issues, has been discussed. A novel clothing construction was discovered on the study. Clothing-like electronics are utilized as much as possible, including the sensor, data-bus, and the interface between the clothing and the control unit.
- A *cyclic tester* has been invented to study the cyclic electro-mechanical properties of the

sensor. The special design of the *cyclic tester* allows large contact surfaces and high contact pressure between the testing samples and the device, so that significant elongation and high speed cycles could be applied to the sample without affecting the accuracy of the testing results. To the author's knowledge, the device is novel and contributes to the research society. Since smart textiles is a fairly new area, more testing devices for specific uses are in demand.

- Novel elastic-conductive hybrid yarns were produced to improve the electro-mechanical properties of knitted strain sensors. Knitting is an effective and economical process, and is therefore a promising method for making the strain sensor. However, existing conductive yarn has low processability in flat knitting machines. The novelty of the hybrid yarn is its excellent elasticity and conductivity while still allowing reasonable processability.

Despite promising results obtained in this thesis work, more research is needed and the development of smart clothing system can be further improved in several ways:

- **Sensor and system development**: new conductive materials and textile manufacturing or finishing technologies are needed to improve sensor sensitivity and to simplify the processes.
- **Energy consumption**: heating effects and energy consumptions are important aspects to be considered in the system development. When an electrical system is working, heating is always generated as a side effect, and this part of energy is usually wasted. The total energy consumption in a system can be reduced by lowering the heating generated in the working system. This can be done by using novel materials and/or improving electrical circuits.
- **Interconnection between rigid and flexible structures**: textiles are flexible materials, while most electronics are rigid. Since difficulties lie in constructing all components from textile materials, a connector between textiles and electronics is needed. The connector should have a stable connection as well as display resistance to usage and maintenance.
- **Clothing-like electronics**: clothing-like sensors and actuators are mainly discussed in the current studies; however, for example, the processor and control units are constructed of non-textile materials. The future of smart clothing should incorporate clothing-like electronics as much as possible.
- **Intrinsic conductive polymer:** conductive yarns that exist in the market are mainly based on materials such as metals and carbon black-filled polymers. Yet, none of these is environmental friendly. Use of intrinsic conductive polymer is a better alternative [112]. However, achieving good mechanical properties and high conductivity is a challenge.

- **Measurement device:** the author is dedicated to the development of new devices that can be used to measure the new functionality and performance. Smart textiles is an area that brings added value to the products in terms of new functionality and performance; however, these should be tested and evaluated before market launch.
- **Standard for testing:** new devices and methods to measure functionality and performance should be standardized to have comparable testing outcomes [48], [113].
- **Long-term validity and reliability:** clinical tests are needed to study the long-term system validity and reliability.
- **User acceptance study:** The field of wearable systems is still quite young, and no data are available on the physical and/or mental effects of long-term use in humans. This is an area for further research.

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Appendix A-MATLAB coding

Sensor characterize

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 %%%%%%      Experimental has been done by place the sensor on tensile tester  %%%%%%%%%
%%%%%%%%%%       and record the signal with a digital multi-meter     %%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% import the data %%%%
R=importdata('Resistance5.dat'); % resistance v.s strain until 10%
R2=importdata('Resistance.dat'); % resistance v.s strain until 40%


%%% normalizing procedure %%%
miniR= min(R);   %get the minimal of R and R2
miniR2= min(R2);
 Rzero = R-miniR;  %set the zero level
normR = Rzero/max(Rzero);
R2zero = R2-miniR2;
normR2 = R2zero/max(R2zero);

%%%set the time scale%%%
t1=linspace(0,10,length(R));
t2=linspace(0,40,length(R2));


% plot the resistance -strain curve %%
figure
subplot (2,1,1)
scatter (t1,normR,'*')
subplot (2,1,2)
scatter (t2,normR2,'*')
 xlabel('Elongation [%]')
ylabel('Normalized Resistance[R/Rmax]','fontsize',10)
```

System performance

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%   experimental has been done by place wearing the smart shirt    %%%%%
%%%%%         and place the reference sensor on the top of channel 1  %%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


[FileNames,PathNames,FilterIndex]=uigetfile('*.dat','MultiSelect','on');
n_files= size(FileNames,2);
if n_files~=3
```

```
    error('Three files must be selected')
    return
end
for ix=1:n_files
    which_filename=char(FileNames(ix));
    if findstr(which_filename,'ch1')
        ch1_datafile=which_filename;
    end
    if findstr(which_filename,'ch2')
        ch2_datafile=which_filename;
    end
    if findstr(which_filename,'ref')
        ref_datafile=which_filename;
    end
end

% Extract the name of the subject
 ixdot=findstr(ch1_datafile,'ch1.');
 filename=ch1_datafile(1:ixdot-1)

% Print pathname and filenames to verify that correct files are used
disp('******************************')
disp(PathNames)
disp(['Reference: ' ref_datafile]);
disp(['Ch1: ' ch1_datafile]);
disp(['Ch2: ' ch2_datafile]);

% Load data from the folder
chrefraw=importdata([PathNames ref_datafile]);
ch1raw=importdata([PathNames ch1_datafile]);
ch2raw=importdata([PathNames ch2_datafile]);

% create vector of times
Ts=0.1;
ti=linspace (0,60,length(chrefraw));

%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% correlation study %%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%

%% reverse data in time scale
ref=chrefraw(end:-1:1);
ch=cha1raw(end:-1:1);
abd=cha2raw(end:-1:1);
```

```
%% normalization
maxref=max(ref);
minref=min(ref);
Nref=((ref-minref)./(maxref-minref) - 0.5 ) *2;
 maxch=max(ch);
minch=min(ch);
Nch=((ch-minch)./(maxch-minch) - 0.5 ) *2;
maxabd=max(abd);
minabd=min(abd);
Nabd=((abd-minabd)./(maxabd-minabd) - 0.5 ) *2;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%% finding the drift and smoothing the signal from abdominal channel %%%%%
%%%%%%% same procedure applied on reference channel and chest channel %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%finding the drift%
 Dabd=smooth (Nabd,30);


%substract the drift%
for i=1:length(Nabd)
    subabd(i)=Nabd(i)-Dabd(i);
end
 figure
clf
subplot (2,2,1)
plot (t,abd,'K')
xlabel ('raw data','fontsize',14)
 subplot (2,2,2)
plot (t,Nabd, 'k')
xlabel ('Normalized data','fontsize',14)
subplot (2,2,3)
plot (t,Dabd,'k')
xlabel ('Baseline drift','fontsize',14)
subplot (2,2,4)
plot (t,subabd,'k')
xlabel ('data smoothening','fontsize',14)
```

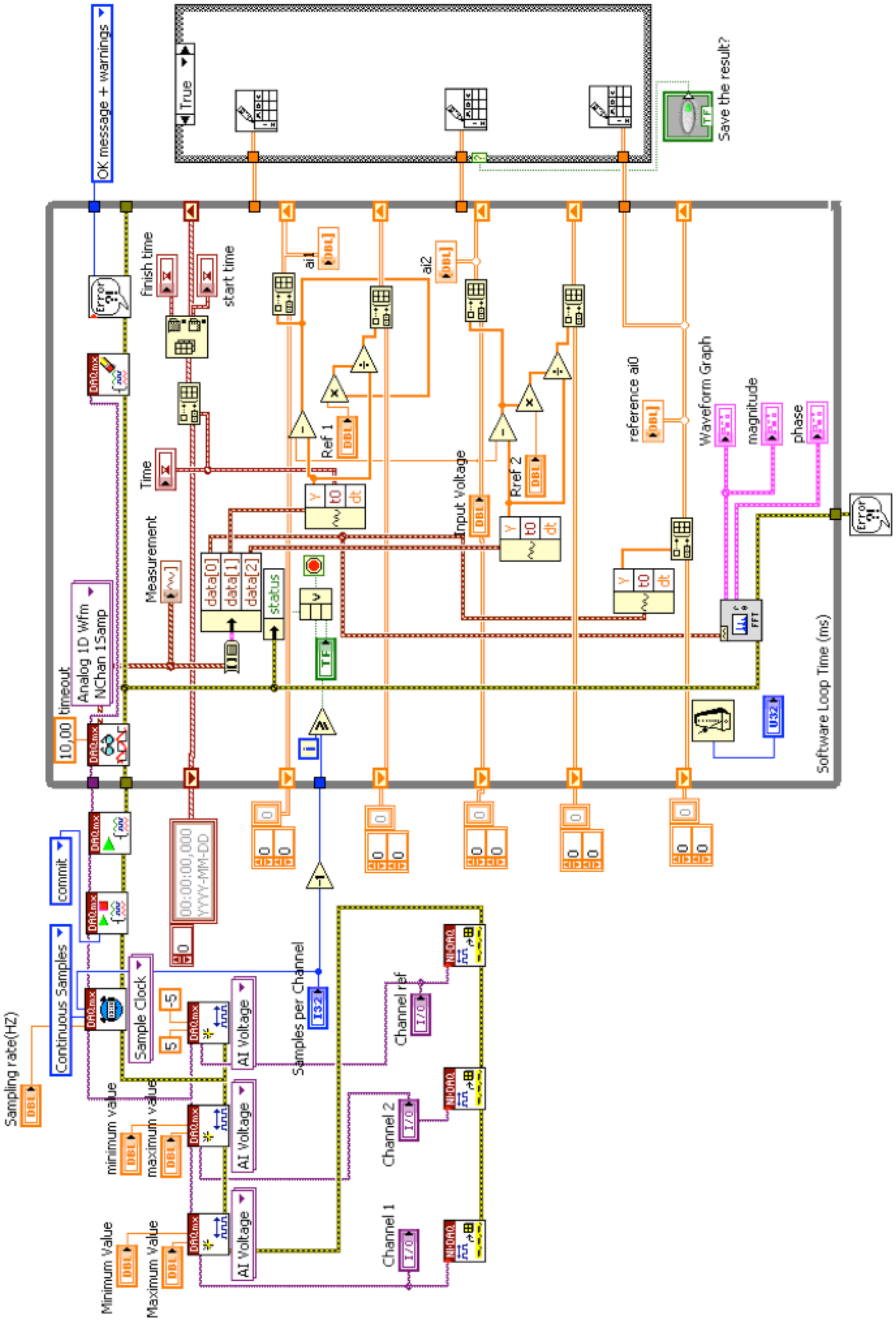
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% a further smoothening, only apply when needed%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

c=subabd;
D2abd=smooth(c,30);
for i=1:length(c)
   sub2abd(i)=c(i)-D2abd(i);
end
figure
subplot (2,1,1)
plot (t,subabd,'k')
xlabel ('Data smoothing','fontsize',14)
subplot (2,1,2)
plot (t,sub2abd,'k')
xlabel ('A further smoothening','fontsize',14)

%%% plot the correlation %%
corr_ref_ch=sub2ref-sub2ch;
corr_ref_abd=sub2ref-sub2abd;
figure
subplot (5,1,1)
plot (t,sub2ref)
text(1.2,1.5,'Ref','fontsize',8)
ylabel('V','fontsize',6)
title ('Correlation between garment-based sensors and the reference belt)')
subplot (5,1,2)
plot (t,sub2ch)
text(1.2,1.5,'Ch','fontsize',8)
ylabel('V','fontsize',6)
subplot (5,1,4)
plot (t,sub2abd)
text(1.2,1.5,'Abd','fontsize',8)
ylabel('V','fontsize',6)
subplot (5,1,5)
plot (t,corr_ref_abd)
text(1.2,1.5,'Ref-Abd','fontsize',8)
ylabel('V','fontsize',6)
axis([0 60 -2 2])
xlabel('Time(s)')
subplot (5,1,3)
plot (t,corr_ref_ch)
text(1.2,1.5,'Ref-Ch','fontsize',8)
ylabel('V','fontsize',6)
axis([0 60 -2 2])
```

```
%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% Delay and FFT study %%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%

ti=0:Ts:(length(chrefraw)-1)*Ts; % create vector of times
figure % plot the raw signals
subplot(3,1,1)
plot(ti,chrefraw)
title([filename ' Recorded signal - Reference sensor']);
subplot(3,1,2)
plot(ti,ch1raw)
title('Channel 1')
subplot(3,1,3)
plot(ti,ch2raw)
title('Channel 2');
xlabel('Time (seconds)')  %%% plot detrended signals and the filtered signals

% remove some high-frequency noise by low-pass filtering all signals
[a b]=butter(5,1/((1/Ts)/2),'low');
% 5x2 order low pass filter, cut off frequency is 0.2 (Ts=0.1)

chref= filtfilt(a,b,detrend(chrefraw));
ch1= filtfilt(a,b,detrend(ch1raw));
ch2= filtfilt(a,b,detrend(ch2raw));
figure
subplot(3,1,1)
plot(ti,detrend(chrefraw),'r--')
hold on
plot(ti,chref)
title([filename ' Filtering of Reference sensor']);
subplot(3,1,2)
plot(ti,detrend(ch1raw),'r--')
hold on
plot(ti,ch1)
title('Channel 1')
 subplot(3,1,3)
plot(ti,detrend(ch2raw),'r--')
hold on
plot(ti,ch2)
title('Channel 2')
xlabel('Time (seconds)')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% Delay estimation based on cross correlation  %%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% Estimate delay by finding the max of the cross-correlation function.
% To increase the resolution in time, the signals are resampled,
% where Ts is reduced 10 times


Ts_new=Ts/10;
sref=resample(chref,10,1);
sch1=resample(ch1,10,1);
sch2=resample(ch2,10,1);
sti=(0:Ts/10:(length(sref)-1)*Ts/10);
figure
subplot(2,1,1)
plot(sti,zscore(sref),'k')
hold on
plot(sti,zscore(sch1),'r--')
title([filename ' Normalised reference and channel 1'])
subplot(2,1,2)
plot(sti,zscore(sref),'k')
hold on
plot(sti,zscore(sch2),'r--')
title('Normalised reference and channel 2')
xlabel('Time (seconds)')


% **************** delay between ref and ch1 *************************
[corr_ref_ch1,lags]=xcorr(sref,sch1,'coeff');
ix_zero=find(lags==0);   % find lag for zero delay between signals
[cmax,lag_max]=max(corr_ref_ch1(ix_zero-100:ix_zero+100));
delay_ref_ch1=(lag_max-101)*Ts/10;
disp(['Delay between ref and ch1:' 9 num2str(delay_ref_ch1)])
 figure
subplot(2,1,1)
plot(lags,corr_ref_ch1);
 title([filename ' Cross-correlation between ref and ch1, delay=' num2str(delay_ref_ch1)]);


% ******************  delay between ref and ch2 **********************
[corr_ref_ch2,lags]=xcorr(sref,sch2,'coeff');
ix_zero=find(lags==0);   % find lag for zero delay between signals
[cmax,lag_max]=max(corr_ref_ch2(ix_zero-100:ix_zero+100));
delay_ref_ch2=(lag_max-101)*Ts/10;
disp(['Delay between ref and ch2:' 9 num2str(delay_ref_ch2)])
 subplot(2,1,2)
```

```
plot(lags,corr_ref_ch2);
 title(['Cross-correlation between ref and ch2, delay=' num2str(delay_ref_ch2) ' s']);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%   FFT analysis    %%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
npsd=4096;
[Pref,fref]= pwelch(chref,[],[],npsd,1/Ts,'onesided');
%determine frequency of respiration peak
[Pmax,fmax_ref]=max(Pref);
resp_freq_ref=fref(fmax_ref);
subplot(3,2,2)
plot(fref,abs(Pref))
title([filename ' PSD reference sensor, respiration peak at ' num2str(resp_freq_ref) ' Hz'])
xlim([0 1])
disp(['Respiration freq in reference:' 9 num2str(resp_freq_ref)])
subplot(3,2,4)
[Pch1,fref]= pwelch(ch1,[],[],npsd,1/Ts,'onesided');
[Pmax,fmax_ch1]=max(Pch1);
resp_freq_ch1=fref(fmax_ch1);
plot(fref,abs(Pch1))
title(['PSD channel 1, respiration peak at ' num2str(resp_freq_ch1) ' Hz'])
xlim([0 1])
disp(['Respiration freq in ch1:' 9 num2str(resp_freq_ch1)])
subplot(3,2,6)
[Pch2,fref]= pwelch(ch2,[],[],npsd,1/Ts,'onesided');
[Pmax,fmax_ch2]=max(Pch2);
resp_freq_ch2=fref(fmax_ch2);
plot(fref,abs(Pch2))
xlim([0 1])
title(['PSD channel 2, respiration peak at ' num2str(resp_freq_ch2) ' Hz'])
disp(['Respiration freq in ch2:' 9 num2str(resp_freq_ch2)])
xlabel('Frequency (Hz)')
subplot(3,2,1)
plot(ti,detrend(chref))
title([filename 'Time domain signal: Reference sensor']);
subplot(3,2,3)
plot(ti,detrend(ch1))
title('Channel 1')
subplot(3,2,5)
plot(ti,detrend(ch2))
title('Channel 2')
xlabel('Time (seconds)')
```

Appendix B- LabVIEW Block diagram



PUBLICATIONS

ARTICLE 1

Guo, L., & Berglin, L. Test and Evaluation of Textile-based Stretch Sensors. In *AUTEX 2009 World Textile Conference,* Izmir, Turkey. 26-28 May, 2009.

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ARTICLE 2

Guo, L., Berglin, L., Li, Y.J., Mattila, H., Mehrjerdi, A.K. & Skrifvars, M.
'Disappearing Sensor-Textile-Based Sensors for Monitoring Breathing'. In *Control, Automation and Systems Engineering (CASE), 2011 International Conference*, Singapore, 30-31 July, 2011, pp. 1-4.

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ARTICLE 3

Qureshi W., Guo L., Peterson J., Berglin L., Mehrjerdi A. K., & Skrifvars, M. ‘Knitted wearable stretch sensor for breathing monitoring application’. In *Ambience* 2011*,* Borås, Sweden, 28-30 November, 2011, pp.72–6.

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ARTICLE 4

Guo L., Berglin L., & Mattila H. (2012). Improvement of electro-mechanical properties of strain sensors made of elastic-conductive hybrid yarns. *Textile Research Journal* **82(19)**, 1937-47.

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ARTICLE 5

Guo L., Berglin L., Wiklund U., & Mattila H. (2013). Design of a garment-based sensing system for breathing monitoring. *Textile Research Journal* **83(5)**, 499-509.

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ISBN 978-952-15-3280-1
ISSN 1459-2045