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Quality Inspection and Evaluation of Smart or Functional Textile Fabric Surface by Skin Contact Mechanics

Melkie Getnet Tadesse

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Abstract

The rapid progress in consuming e-textiles has made a huge uprising in the researcher's track on the course of smart and functional textile development. Consumption of functional and smart textiles in the wearable e-textile is fetching extra eye-catching scheme owing to its lightweight property, flexibility, stretchability, and the ability to be integrated into wearable apparel. This platform makes wearable e-textile arena to be more user-friendly, but at the same time, it sets a limit to some of the real desires of the tactile comfort during skin contact. So far, many researchers have attempted to provide the consumers with a real sense of ordinary fabric hand through subjective and objective evaluation techniques. However, few or no attempts have been achieved to evaluate the tactile comfort of functional and smart fabrics.

In this current thesis, we propose for the first time a systematic methodology to study the functional and smart textile fabric's tactile comfort properties through subjective and objective evaluation using skin contact mechanics principle. First, various functional and smart textile fabrics were produced, developed and collected using different state of the art technologies such as 3D printing, coating, inkjet printing, screen printing, incorporation of smart fiber during knitting operation. The samples produced using the above mentioned technologies were thermochromic, conductive, and photochromic type. Then, we investigated the physiological and psychological aspect with regards to the tactile comfort on the basis of visual and blind subjective evaluation for the tactile properties and interpreted utilizing different statistical techniques. Sensory experiments employing a trained panel of experts were carried out to verify the tactile handle. We followed a novel approach to verify the hypothesis obtained from different tactile attributes. From this study, we conclude that it is likely to perceive the tactile comfort properties through visual and blind scenarios.

In order to explore further, objective measurements of tactile properties of the samples were conducted using the Kawabata evaluation system (KES). Low-stress mechanical properties related to the tactile comfort of the fabrics were measured using KES. The KES result confirmed that it is credible to measure the tactile properties using objective evaluation methods to interpret the tactile properties of the samples. Sets of relevant intelligent systems such as fuzzy logic and artificial neural network (ANN) were implemented to interpret and analyze the subjective and objective sensory datasets and to compare the results obtained by both methods.

Keywords: tactile comfort; expert; subjective evalaution; objective evalaution; smart fabric; functional fabric; skin contact; KES; sensory evalaution; sensory perception.

Kvalitet inspektion och utvärdering av smarta eller funktionella textilväv yta genom hudkontaktmekanik

Sammanfattning

Den snabba utvecklingen av e-textil för konsumtion har gett forskarna ett stort uppsving mot utvecklingen av smarta och funktionella textilier. Konsumtionen av funktionella och smarta textilier för bärbara e-textilier är extra iögonfallande tack vare egenskaperna: lättvikt, flexibilitet (böjbarhet/följsamhet), töjbarhet och för att de kan integreras i kläder. Denna plattform gör arenan för bärbara e-textilier mer användarvänlig, men sätter samtidigt en gräns för den önskvärda taktila komforten vid hudkontakt. Hittills har många forskare försökt förse konsumenterna med känslan av ett normalt tyg genom subjektiva och objektiva utvärderingsmetoder. Däremot har få eller inga försök lyckats att utvärdera den taktila komforten hos funktionella och smarta textilier.

I denna avhandling föreslås, för första gången, en systematisk metod för att studera de taktila komfortegenskaperna hos funktionella och smarta textilier genom subjektiv och objektiv utvärdering utifrån principen om mekaniken hos hudkontakt Först producerades, utvecklades och samlades olika funktionella och smarta textilvävnader med hjälp av olika toppmoderna teknologier, såsom 3D-tryckning, beläggning, bläckstråleskrivning, skärmutskrift, införlivande av smart fiber med användning av stickning. Proverna var termokroma, ledande och fotokroma. Sedan undersöktes de fysiologiska och psykologiska aspekterna beträffande taktil komfort genom visuell och blind subjektiv utvärdering. Resultatet tolkades med olika statistiska tekniker. Taktila experiment med en tränad expertpanel utfördes för att verifiera tygest taktila känsla. Vi följde ett nytt tillvägagångssätt för att verifiera hypotesen som uppkom från olika taktila attribut. Utifrån denna studie drar vi slutsatsen att det är troligt att taktila komfortegenskaper kan uppfattas genom visuella och blinda scenarier.

Ytterligare objektiva mätningar av provernas taktila egenskaper gjordes med utvärderingssystemet Kawabata (KES – Kawabata evaluation system). Mekaniska egenskaper vid låg spänning, relaterade till tygernas taktila komfort, mättes med KES. KES-resultatet bekräftade att det är tillförlitligt att mäta de taktila egenskaperna med objektiva metoder för att tolka provernas taktila egenskaper. Ett antal relevanta intelligenta system såsom ”fuzzy logic” och ”artificial neural network” (ANN) implementerades för att tolka och analysera de subjektiva och objektiva taktila dataserierna, samt för att jämföra resultaten som uppnåtts med de olika metoderna.

Nyckelord: taktil komfort, expert, subjektiv utvärdering, objektiv utvärdering, smart tyg/textil, funktionell(t) tyg/textil, hudkontakt, KES, taktil utvärdering, taktil uppfattning/förnimmelse

Calităţii Inspecţia şi Evaluarea Inteligente sau Funcţionale Suprafaţă Tesătură Folosind Mecanica de Contact a Pielii

Rezumat

Progresul rapid in ceea ce priveste consumul de e-textile a condus la dezvoltarea foarte rapidă, in lumea cercetătorilor, a domeniului textilelor inteligente şi funcţionalite. Consumul de textile inteligente şi funcţionale din domeniul e-textilelor atrage atenţia în mod suplimentar asupra posesiei acestor articole, în special datorită proprietăţilor privind flexibilitatea, masa redusă, extensibilitatea şi posibilitatea de integrare în produse ce pot fi purtate.

Această platformă permite ca scena e-textilelor purtabile să fie mai prietenoasă, dar în acelaşi timp, stabileşte limite în ceea ce priveşte câteva din cerinţele reale în ceea ce priveşte confortul sensorial la contactul cu pielea. Până în prezent, mulţi cercetători au încercat să furnizeze consumatorilor informaţii privind tuşeul materialelor obişnuite, utilizând tehnici de evaluare subiective şi obiective. Totuşi, au fost realizate foarte puţine încercări de evaluare a confortului tactil al materialelor inteligente sau funcţionale.

In această teză se propune, în premieră, o metodologie sistemică de studiu a proprietăţilor de confort sensorial al materialelor funţionale şi inteligente, prin evaluări subiective şi obiective, utilizând principiul contactului mecanic cu pielea. În primul rând, diferite materiale funcţionale şi inteligente au fost produse, dezvoltate şi colectate utilizând diverse tehnologii de ultima generaţie, cum ar fi imprimarea 3D, acoperirea, imprimarea cu jet de cerneală, imprimarea în serigrafie, încorporarea fibrei inteligente prin operaţiuni de tricotat. Probele au fost termochromice, conductive şi fotochromice. Apoi, au fost investigate aspecte fiziologice şi psihologice referitoare la confortul senzorial, pe baza evaluării bazată pe evaluarea subiectivă, cu sau fără vizualizarea materialelor, urmate de interpretarea rezultatelor prin utilizarea diferitelor tehnici statistice. Experimentele senzoriale, desfășurate cu ajutorul unui grup de experți, au fost executate pentru verificarea sensibilității tactile. A fost folosită o nouă abordare pentru verificarea ipotezelor obținute din diferite atribute tactile. Ca urmare a acestui studiu, s-a concluzionat că este posibilă aprecierea proprietăților referitoare la confortul senzorial prin scenarii cu sau fără vizualizarea probelor.

În vederea explorării ulterioare, au fost desfășurate măsurători obiective ale proprietăților psihosenzoriale, utilizând sistemul de evaluare Kawabata (KES). Proprietățile mecanice la solicitări de mică intensitate, referitor la confortul senzorial al materialelor au fost măsurate utilizând KES. Rezultatele KES au confirmat faptul că măsurarea proprietăților senzoriale prin folosirea metodelor de evaluare obiectivă este credibilă pentru interpretarea proprietăților senzoriale ale mostrelor. Seturi de sisteme inteligente, cum ar fi fuzzy logic și rețele neuronale artificiale (ANN), au fost implementate pentru interpretarea și analiza subiectivă și obiectivă a seturilor de date și pentru compararea rezultatelor obținute prin ambele metode.

Cuvinte cheie: comfort senzorial; expert; evaluare subiectivă; evaluare obiectivă; materiale inteligente; materiale funcționale; contactul cu pielea; KES; evaluare senzoriala; percepție senzorială

皮肤接触力学对智能或功能性纺织品表面的质量检测与评价

摘要

随着电子纺织品消费的快速发展，有关纺织智能化、功能化的研究得到了普遍的关注。由于其具备重量轻、柔韧、可伸缩以及能够集成到可穿戴服装中的优点，功能化和智能化纺织品在可穿戴电子纺织品中的消费而备受瞩目。这个平台使得可穿戴的电子纺织品显示出用户友好的特点，但同时，它也在与皮肤接触过程中对触觉舒适性产生影响。迄今为止，许多研究者试图通过主、客观评价技术为消费者提供真实的织物手感信息。然而，对于评估功能性和智能织物的触觉舒适性方面的研究还比较少。

本文首次采用皮肤接触力学原理，通过主观和客观评价相结合的方法，对功能**性、智能化**纺织品的触觉舒适性进行了系统研究。**首先，使用不同的**现有技术生产，开发和收集各种功能性和智能纺织品，例如**3D打印，涂布**，喷墨印刷，丝网印刷，使用针织操作的结合智能纤维。样品是热致变色的，导电的和光致变色的。然后，在对触觉特性进行视觉和视觉隔离主观评价的基础上，对触觉舒适性的生理和心理两个方面进行了研究，并利用不同的统计技术加以解释。利用训练有素的专家小组进行感官实验，以验证触觉手感。采用了一种新的方法来验证从不同的触觉属性获得的结果。通过本研究，我们发现，可能通过视觉和视觉隔离的场景感知触觉舒适特性。

为了进行深入研究，使用川端评估系统（KES）对样品的触觉特性进行了客观测量。利用KES测试了织物触觉舒适性相**关的低**应力力学性能。KES结果证实了用客观评价方法来评价样品的触觉特性是可靠的。本文利用模糊逻辑和人工神经网络等相关智能系统对主客观感觉数据进行解释和分析，并对两种方法得到的结果进行比较。

关键词：触觉舒适性；专家；主观回避；客观回避；智能织物；功能性织物；皮肤接触；KES；**感**觉评价；感觉知觉

Motto: "Do my best, so that I can't blame myself for anything."

Magdalena Neuner

If an idea disturbs while you are sleeping, wake up and kill it before it disappears.

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I dedicate this work to my family for their constant encouragement, understanding, and moral support they gave me throughout my study.

IASI, Romania

Sincerely

Melkie Getnet Tadesse

May 10, 2019

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List of Abbreviations

HV	hand value
THV	total hand value
BSE	blind subjective evaluation
VSE	visual subjective evaluation
KES	Kawabata's Evaluation System
PEDOT-PSS	poly (ethylenedioxythiophene) –poly (styrene sulfonate)
3D	three-dimensional
DoD	Drop-on-Demand
ANN	Artificial Neural-Network
FLM	Fuzzy Logic Modeling
EL	Electroluminescnce
UV	Ultraviolet
CAD	Computer Aided Design
QC	Quality Control
TGA	Thermogravimetric Analysis
SEM	Scanning Electron Microscopy
ICP	Intrinsically Conductive Polymers
FTIR	Fourier Transform Infrared
AM	Additive manufacturing
WC	Warm/Cool
IS	Itchy/Silky

SS	Sticky/Slippery
RS	Rough/Smooth
HS	Hard/Soft
NCC	Non-compressible/Compressible
NSS	Non-stretchable/ Stretchable
HL	Heavy/Light
SF	Stiff/Flexible
FAST	Fabric Assurance by Simple Testing
FTT	Fabric Touch Tester
ANN	Artificial neural network
ANFIS	Adaptive neuro-fuzzy inference systems
ISO	international standard organization
IEC	international electrotechnical commission

General Introduction

Development of smart and functional fabrics using different state of the art technologies such as 3D printing, inkjet printing, coating, screen printing and incorporation of smart fibers during knitting are currently investigated by many researchers. These smart and functional fabrics have been used for several applications such as in the fields of sport, medical, and entertainment. Eventhoguh this functional finishing brought specific functionality to the textile goods; it can affect the handle of the product.

Clothing materials played and will carry on delivering an indispensable impact on human life. Human surroundings are enclosed by clothing materials starting from the early age (even if difficult to conclude when the human being started wearing clothing materials) to the contemporary world. Clothing is not only affords insurance, graceful as a fashion and life but should also provide a comfortable sensation. Smart textiles are now produced as if we can wear and used as an additional function of it. This is because, most recently, functionality or smartness to the clothing materials has been introduced by the inclusion of functional or smart materials in part using either mechanically (weaving, knitting) or chemically (coating, printing, and dyeing). Therefore, when studying comfort, the effect of the added materials or processes should not be forgotten. This means the comfort of smart textiles could be evaluated and should fit the comfort quality. If not then, the well-being of the wearer feels pain or discomfort. Evaluating smart and functional textile fabric handle (tactile perception) could be a huge interest for the smart textile fabric industry in order to match the quality needs of the user and the framework of the augmentation and manufacturing processes. Due to the increasing sales of smart and functional textiles, clothing tactile comfort and the related evaluation methods became very paramount in recent years. Clothing material user desires depends on a large extent on the hand of the clothing material worn next to the skin. Intuitively, consumers use the sense of touch, vision, and even smell when choosing a clothing material in order to assess the quality and fitness of the materials they are going to buy. In this feature, tactile comfort is the most suitable and relevant for the quality inspection of smart and functional textiles that worn next to the skin.

In practice, before purchasing a textile product, customers have a tendency to check the quality of the product by touching great parts of it. So, in addition to other evaluation techniques, tactile sensation plays an essential role in turning aside the purchasing decisions. The quality of the smart fabric is a question that alarms its appeal to the quality checks of the buyer on the evidence of his/her senses. The judgment depends on gender, environment, geography, time, season, and personal experiences. So, that it would be impractical to pretend to replace the subject by the numerical result of the low-stress mechanical test. This means, on the other hand, subjective tests mainly depend on the physical properties of the material, so that the measurements of the low-stress mechanical properties can be of great value in providing data upon which the exercise on judging the quality. However, the smart textile manufacturing industries dearth standardized systems of producing their product on the feature of tactile sensing.

In addition to the subjective evaluation of the functional fabrics, measuring the mechanical properties of the textile-based material also provides the quality of the fabrics in terms of sensory properties.

Research in smart and functional textile typically focuses on scientific and technological problems or technological sense of interaction of the wearer. However, as per our knowledge very few have been done on the tactile sensation of technical textiles fabric using skin contact mechanics principle. Depending on the type and application of smart and functional textile fabrics, most are used in direct contact with the human skin. Some of them have few contact areas for example like zipper and clothing tags, and they are manufactured for the most part from e-textiles. Needless to state, the quality of these smart textile fabrics directly affects both the human physiological and the psychological comfort of the human being. For this reason, it is compulsory to have a system which allows the industry to accurately and thoroughly evaluate/assess the quality of smart and functional textiles.

Therefore, the motivations in selecting the research in quality inspection and evaluation of functional and smart textile fabric by skin contact mechanics are:

- The research in smart and functional textile fabric is growing rapidly;
- Even though the research in smart and functional textile fabric is growing rapidly, the main focus area has been in the functionality aspect;
- The quality inspection and evaluation of smart and functional textile fabric has no standards yet;
- The smart and functional textile fabric marketing is not growing rapidly due to lack of quality in the comfort and reliability;
- Fabric handle can change the purchasing decisions;
- To set sensory profile data for the manufacturing of smart and functional textile fabrics.

Therefore, this thesis envisioned to change the smart and the functional textile fabrics manufacturing systems from experienced-based into an engineered oriented manufacturing so that best quality smart and functional textile fabrics can be manufactured. The subjective and the objective evaluation and inspection of the functional and smart fabrics would aim to satisfy the consumer perception especially in the case of tactile comfort properties of the functional fabrics. The tactile assessment of the textile-based product is provoked by the careful inspection of human hands in which the skin touch instigation and the instantaneous reply of the textile material against our skin. In many research works, the use of the tactile sense is quite different and has different thoughts. However, in our thesis we used the term tactile it means comprehensively to all sensory perceptions initiated by cutaneous sensibility (like warmth, cold, heavy, light or any other contact related senses created when we touch the fabric with our hands-stimulation of end organs in the skin-more specifically with our hands). All of the work performed is related to these definitions.

Furthermore, the data obtained in this thesis work could be progress in standardization of the quality inspection and evaluation of the smart and functional textiles fabrics. In the state of the art technology part, we present the theoretical bases that are concerned in our practical approach.

Thesis Purpose and Objectives

The aim of this research is twofold, and divided into two parts; the first part is to develop and collect various functional and smart textile fabrics using different state of the art technologies. The second part comprises evaluation and inspection of functional and smart textile fabrics using skin contact mechanics. The main focuses of this thesis are:

- Development of various functional and smart textile fabric using different state of the art technologies such as inkjet printing, screen printing, coating, and 3D printing;
- Collection of functional and smart textile fabrics produced using incorporation of smart fibers during knitting;
- Assessing the tactile perceptions of the functional and smart textile fabrics using subjective evaluation with human experts; and
- Evaluating the low-stress mechanical properties of the functional and smart textile fabrics using Kawabata's evaluation systems (KES-F);
- Investigating the effect of functional finishing on the tactile comfort of the product;
- Comparing the tactile comfort of the functional fabric obtained using subjective evaluation and Kawabata’s evaluation system (objective evaluation);
- Predicting the tactile comfort of the functional fabrics using fuzzy logic, artificial neural-network; an adaptive neuro-fuzzy inference systems; and
- Providing the sensory profile data to the smart and functional textile developers and manufacturers so that they can use the quality control and inspection of their products.

The above mentioned concepts are the main focus of this thesis work.

Thesis Summary

This thesis has two parts: **The first part**- state of the art technologies and **the second part**-Research outcomes and is divided into 7 chapters including the recommendations and future work.

The basis of this thesis is to analyze people's tactile perceptions towards the smart and functional textile products when touching with the skin. Thus, in the first chapter, we present the fundamental history and literature survey of the thesis. In this section, two primary points are discussed. Firstly, we provide a general introduction about how smart and functional textiles developed where the main focus is given on: coating, 3D-printing, inkjet-printing, and screen-printing methods. Then, accustomed introduction about each section where the development of smart and functional textiles is briefly discussed.

Secondly, we introduced the current and future trends in the smart and functional clothing (related to comfort assessment), quality inspection and evaluation in smart and functional textile products. Furthermore, we discoursed about human perception on sensorial comfort of textile-based product associated with skin contact. The key emphasis of the thesis is tactile comfort evaluation and inspection of smart and functional textile fabric using skin contact mechanics scheme. For this reason, we present issues related to skin contact mechanics such as physiological and psychological perceptions of the textile-based goods, and tactile comfort characteristics of smart and functional textile fabrics. In tactile comfort aspect, sense of touch and the structure of the brain in kin to the tactile comfort are discussed.

In this **chapter**, we mark on the discussion about the feasibility of defining the smart and functional textile fabric properties using blind subjective evaluation and visual subjective evaluation techniques from the perspective of physiological perception. First, we describe the basic concept of sensory comfort of clothing materials. Then, we

present the numerous types of subjective evaluation methods that contract with textile-based product. At the same time, we discussed the recruitment process of panels, the approaches of training, and evaluation techniques; and some definitions of the handle of the textile-based products were given based on certain protocols.

As a result of the subjective evaluation, we implemented Kawabata's evaluation system in point for the objective evaluation of the samples. We introduced the basic mechanical properties measured by Kawabata Evaluation System (KES) for textile fabrics under low-load conditions. We discussed how the low-stress mechanical properties of the samples can be measured using Kawabata evaluation system.

In the final section of **chapter 1,** we present intelligent systems that have been frequently used in analyzing and interpreting the subjective and the objective evaluation of textile-based products in terms of tactile comfort. In this section, we presented fuzzy logic and artificial neural network that have been often used in the modelling of the human perception data. So, in this subdivision, we first introduced fuzzy logic with compressed theories. Then, The ANN structure, the fuzzy membership feature, degree of membership function; fuzzification and defuzzification methods are explained concisely.

The second part of the thesis is the main part of our thesis, as it comprises of the **research and its outcomes**. This part in turn consists of **two** main sections and divided into **six** chapters. Each research part except **chapter 7** has its own introduction, experimental part, and result and conclusion subdivision. Each section has discussed as follows:

Development of Smart and Functional Textile Fabrics *(Chapter 2)*

In this section, we present three experimental sub-sections. These are:

Effect of Liquid Immersion on the Conductivity of PEDOT-PSS-Coated PET Fabrics *(Experiment I) (chapter 2.1)*

In this chapter, we aimed to yield the conductive functional fabrics using poly (3, 4-ethylenedioxythiophene): poly (styrene sulfonate)–PEDOT-PSS. Coating of polyester fabric with PEDOT-PSS and some compounds such as polyethylene glycol (PEG), methanol (MeOH), and ethylene glycol (EG) as a conductivity accompaniment was performed. This approach is based on the flexible textile-based conductive materials that bring wireless connection and showed sufficient electrical conductivity as measured by four-probe surface resistance measurement principles. The results in **Experiment I** was accompanied by surface resistance measurement, FTIR and SEM analysis, washing stability test; and confirm that it is possible to introduce the conductivity into textile materials using simple coating applications with better performance and durability against the environment.

Printing of TPU using 3D-printing for Electroluminescence applications *(Experiment II) (Chapter 2.2)*

In this chapter, we extend the application of coating **(experiment I)** accompanying with 3D printing to produce smart and flexible electroluminescence device. Coating of textile fabrics with PEDOT-PSS and 3D printing of TPU on top were carried out, aiming to produce a lightweight and flexible electroluminescence device. Extra mechanical properties of the electroluminescence device and thermal analysis using TGA of the filament were performed. This experiment proved that, it is achievable to produce textile-based electroluminescence device with cost-effective coating and 3D printing method that has the capability to be integrated into wearable garments.

Characterization and Application of Conductive Elastic Knitted Textile Fabrics
(Experiment III) (Chapter 2.3)

This chapter prolongs the application of coating and immersion technologies applied in chapter 1, experiment I, to design energy storage devices using flexible substrates (polyamide/lycra fabrics). Coating and immersion of the textile substrate were achieved intending to produce the conductive textile materials that will be invoked as a thermoelectric (convert the body and the environmental temperature into electrical energy). Various characterization methods including SEM, Seebeck coefficient measurement, electrical conductivity characterization, electromechanical analysis (stretchability against surface resistance; cyclic stretching against the surface resistance) and durability study against washing were performed. This all confirmed the potential applications of the coating and immersing techniques to yield thermoelectrics on the textile materials with conductive polymers so that it can be used as energy storage devices.

Tactile Evaluation of Functional Fabrics Using Subjective Assessment (*Experiment IV) (Chapter 3)*

In this chapter, we are addressing the blind and the visual interpretability of the functional fabric's tactile properties using human subjects. Subjective evaluation experiments were carried out by a trained panel of experts, on a number of functional textile fabrics produced using coating, 3D printing, inkjet printing, screen printing and knitting processes using blind subjective and visual subjective evaluation scenarios. The main aim of this chapter is to investigate the tactile perceptions of the functional fabrics utilizing blind and visual subjective evaluations so that to verify that subjective evaluation can be used to evaluate functional fabrics, and to evaluate the difference in the perceptions of the comfort of individual panel of experts. This experiment proved that both blind subjective evaluation and visual subjective evaluation could be used to evaluate the tactile comfort of functional fabrics. The sensory profile data provided by this thesis could be used to check the quality of the functional fabric before inducing the next step.

Objective Evaluation of Functional Fabrics Using KES-F
(Experiment V) (Chapter 4)

In this chapter, we further study the tactile comfort of the functional fabrics through measuring the low-stress mechanical properties using Kawabata's evaluation system (KES). Sensory analysis of the functional fabrics was explored by measuring the sixteen/seventeen low-stress mechanical properties using KES. Hand values and the total hand values were calculated and presented. The effect of functional fabrics on the mechanical properties discussed. The interpretation of the functional fabric properties via the Kawabata's evaluation system is accomplished. Thus, our work has come to the conclusive point that is possible to interpret the functional fabric's sensory perception from the results of the low-stress mechanical properties of the fabric. This data can be used for the functional fabric developers and manufacturers for quality evaluation and inspection of their products and to communicate quality of the artifact.

Prediction of the Tactile Comfort using Intelligent Systems
(Experiment VI) (Chapter 5)

In this chapter, we present the appraisal of the hand and the total hand value of the functional fabrics by means of fuzzy logic and artificial neural-network simulation software. After measuring the subjective evaluation of the functional fabrics (in chapter 3), the obtained hand values (HV) and total hand values (THV) were used to predict the tactile comfort of the functional fabrics using intelligent system models. The effect of finishing on the sensory comfort of the samples was explored using input parameters. This approach proved to be an excellent model for the prediction of the sensory comfort of the functional fabrics.

Comparison between Subjective and Objective Hand Evaluation of Functional Fabrics for Tactile Comfort Evaluation *(Experiment VII) (chapter 6)*

In this chapter, two issues are presented. First, we compared the hand values of the functional fabrics obtained using human expert's subjectively and the objective results obtained by measuring the mechanical properties of the samples under low-load regions using Kawabata's evaluation systems. The results confirmed that it is practicable to apply subjective evaluation using human experts and objective mechanical properties of the functional fabrics using KES-F methods for the tactile evaluation of functional fabrics. The correlation between the two methods was an indication of a strong association between them in the hand evaluation of the functional fabrics. Secondly, we applied the equation previously developed to equate the hand and the total hand values of the men's suiting to predict that hand value and the total hand value of the functional fabric and the results confirmed that such kinds of equations could be applied to predict the handle of the functional fabrics without any modification.

Conclusions and Future Works *(chapter 7)*

In this chapter, we present the summary of the conclusions described at the end of each chapter, the original contributions appeared at the full length of the doctoral study period and potential and future research directions and recommendations.

Thesis Structure

The thesis is divided into two basic categories: Smart and functional textile fabrics development and quality inspection and evaluation of smart and functional textile fabrics. The overall this structure is shown in Figure 0.1.

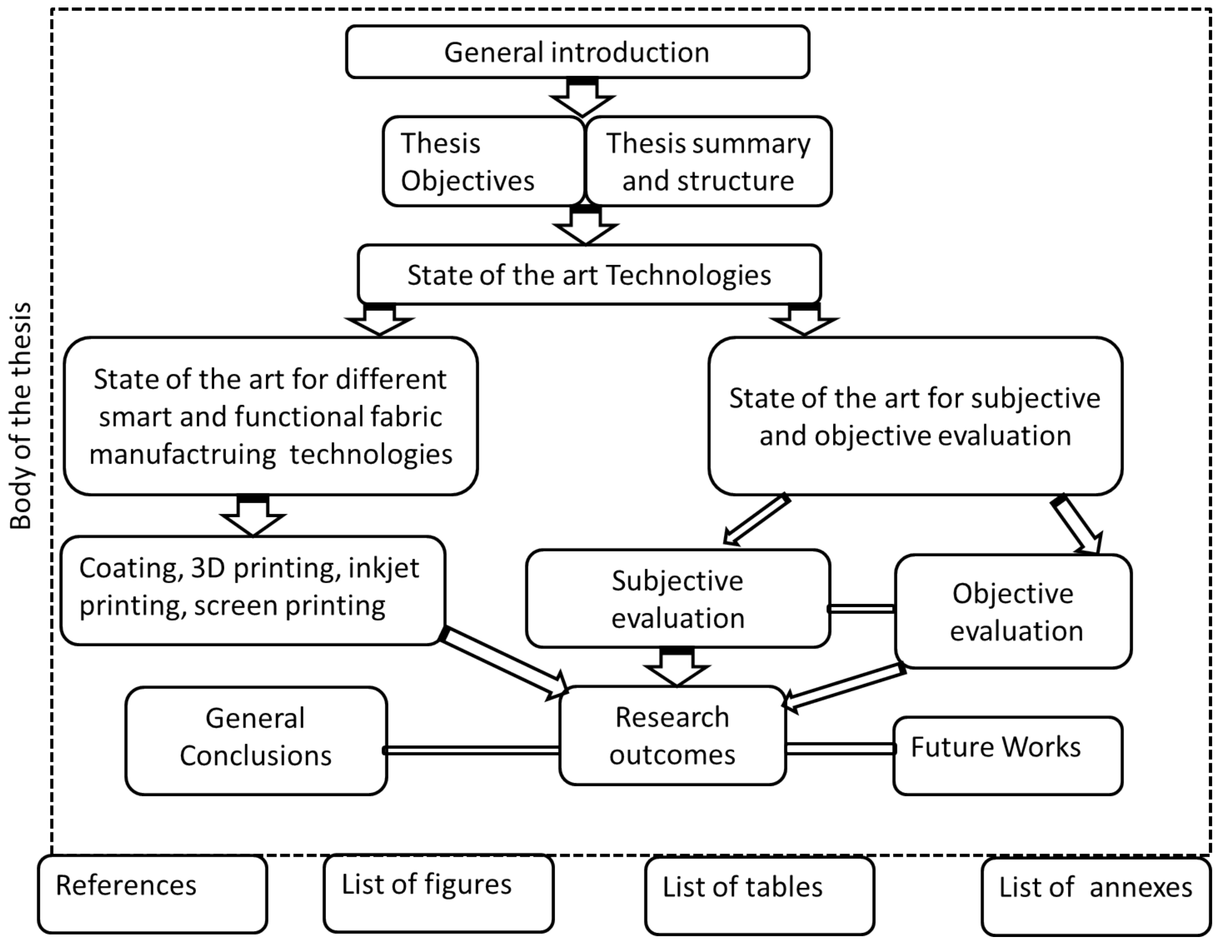


Figure 0.1 Thesis structure

STATE OF THE ART

Chapter 1 State of the Art Technologies

1.1 Introduction

Quality inspection and evaluation of smart/functional fabrics is presently an imperative and crucial step to escalate the market share of the fabric's value in the domain. This is the basic objective of our thesis work. Therefore, in this thesis work, we did on two fundamental concepts. The tactile evaluation was performed using subjective techniques using expert's method and objectively by measuring the low-stress mechanical properties of the fabric using Kawabata evaluation system (KES). Therefore, first, we introduced certain basic functional and smart textile fabric production and development techniques. Then, we present the basic concepts of the human sensory systems towards external stimuli especially when touch to the skin. Last but not least, the basic relationship between human perception and functional textile fabrics are discussed with an emphasis had been given to blind subjective and visual subjective evaluation scenarios. The most vital feature is the tactile feeling is when the user is in touch and visual observation with a textile material during buying.

For the final intended use of the goods, the interaction of the functional and smart textile fabrics with the wearer's skin shall be assessed in addition to its functionality. In our thesis, sensorial studies of the samples obtained using various technologies are assessed subjectively (using the human perception knowledge) and objectively (KES) and analyzed using soft computing models in addition to the surface property analysis of the functional and smart fabrics.

Furthermore, rudimentary soft computing algorithms that ca be utilized to model the sensory investigations of the functional and smart textile fabrics are discussed that help the easier interpretation of subjective and objective sensory data.

1.2 Functional and Smart Clothing Development

Functional/smart (next generation textiles) clothing represents the upgraded version of the technical textiles when clothing crosses the customary confines and consolidated with the healthcare, electronics, computing, and other engineering and science domain applications. Functional textile has the capacity to replace the harsh metallic wire in connection with electrical conductivity. The terms functional and smart textiles need to be defined and distinguished with respect to each other first. The so-called "smart textiles" are defined as those textile materials that are capable of sensing (passive smart), responding the stimuli (active smart) from the environment (pressure, temperature, electrical, chemical, thermal or other types); and adapting (very active smart) them by adopting of the functionality in the textile structure (Van Langenhove, 2007). While, functional clothing is defined as clothing designed to fit the performance specification such as protective clothing, sports clothing or medical clothing for the user (Gupta, 2011).

In our thesis, we utilized the term functional fabric in a sense that as it is a passive and an active smart fabrics category. Thus, smart and functional textile fabrics are exploited interchangeably if one of them in not mentioned alongside. Therefore, smart textile is a dynamic thinking textile material that serves the user for security purposes, delivers comfort, or used as communication tools; smart textiles introduce a shift from passive functionality into active and reactive behaviors to the environment. The high customer expectations, the crumbled niche market, and the development of new technologies are just some of the factors that drive the researcher to work anxiously on numerous controversies of smart and functional textiles. The chain and the relationship between smart and functional textile are illustrated in Figure 1.1.

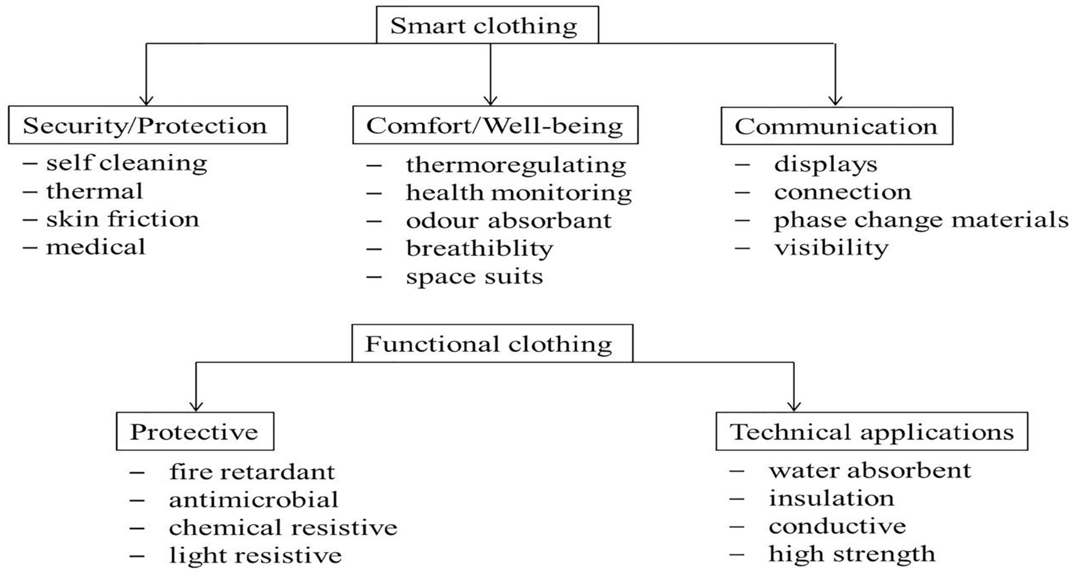


Figure 1.1 The smart and functional clothing-various issues

The smart and functional clothing-various issues

Furthermore, smart textiles are now becoming the most integral part of human's life as wearable technology so that they simplify human life (Tao, 2015) to the environmental stimuli. Conventionally, functional textiles fall into the first category as said earlier.

Smart and functional textiles can be developed using diverse approaches such as coating and laminating (Ghosh, 2006; Smith, 2010), 3D printing (Khoo et al., 2015; Sanatgar et al., 2017), screen printing (Wei et al., 2013), incorporation of smart fibers using knitting technology (Li et al., 2010), and other techniques. In recent years, most research focuses on producing conductive functional textile fabrics that might be used in several applications. Electrically-conducting textiles are the most portable and integral parts of smart textiles. They are generally manufactured by integrating the non-conducting fabrics with conducting materials, using various application processes such as coating, printing, spraying, in-situ polymerization, chemical vapor deposition (CVD), and plasma treatment and other several means (Bonaldi, 2017). In the following sub-chapter, we will look at the production techniques that have been used to produce our samples during the development stage.

1.2.1 Coating Technologies

The coatings of textile materials are an industrial finishing process that changes the conventional applications of the textiles to a specific function or aesthetic value. By coating, textile materials converted into functional, smart, or intelligent, which allows the textile materials to react to the environmental stimuli by earning specific properties to the textile materials such as antimicrobial, UV protection, electrical conductivity, and other functions (Mahltig et al., 2005). The textile coatings have been found to have high potential applications to develop various functional applications such as textile sensors (Lee et al., 2015; Pacelli et al., 2006; Tsang, 2007), connectors and actuators (Hutchison et al., 2000), stimuli-responsive products (Lavrič et al., 2012), electrical conducting materials (Collins and Buckley, 1996; Tadesse et al., 2017), etc.. The practical coating principle can be shown as in Figure 1.2.

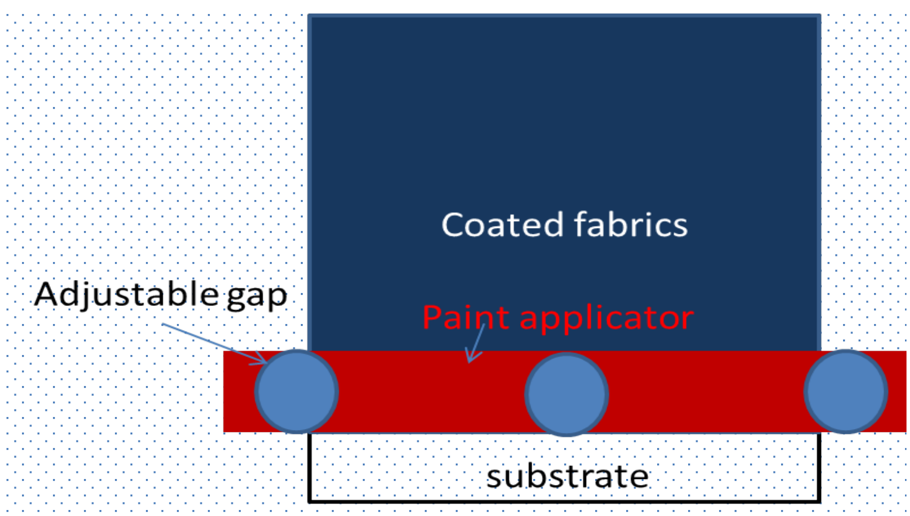


Figure 1.2 The simple manual coating process

The coating process can be prepared using various techniques such as direct coating, blade coating, reverse roll coating, roller coating, rotary screen coating, spray coating, and other coating techniques (Conway, 2015). This is because the coating is simple and cost effective process. New functionally-finished and present product shall continue being developed using a new and the current technologies. The increasing demand for consumer expectations would further propel step ahead of the development of different coating formulations and invention of new technologies in the coating industry.

Among various strategies, coating of textiles with conducting polymers have got a wide attention and more emphasis has been given the coating of textiles with intrinsically conductive polymers (ICP) such dispersions of poly (3,4-ethylenedioxythiophene)-poly(styrene sulfonate) (PEDOT-PSS) (Daoud et al., 2005; Lipomi et al., 2012; Takamatsu et al., 2011; Åkerfeldt et al., 2013), polypyrrole (PPy) (Avloni et al., 2008; Mičušík et al., 2007), polyaniline (PANI) (B. Kim et al., 2006), and other conducting polymers to bring special function to the textile materials. However, among these polymers, PEDOT-PSS has got great consideration due to its electromechanical properties as witnessed by some researchers (Cairns and Crawford, 2005; Okuzaki et al., 2009). Hence, the present study is proposed to examine the electrical characterization, effect of liquid immersion on electrical conductivity; study applications in the electroluminescence and thermoelectric of the PEDOT-PSS-coated polyester fabrics. When PEDOT-PSS is treated with conductive enhancers like ethylene glycol and sorbitol, the coil structures are changed into linear structures due to the removal of hydrophilic PSS to the outer surfaces of the PEDOT chain (Ouyang et al., 2004). This structural conformation change is illustrated as showed in Figure 1.3.

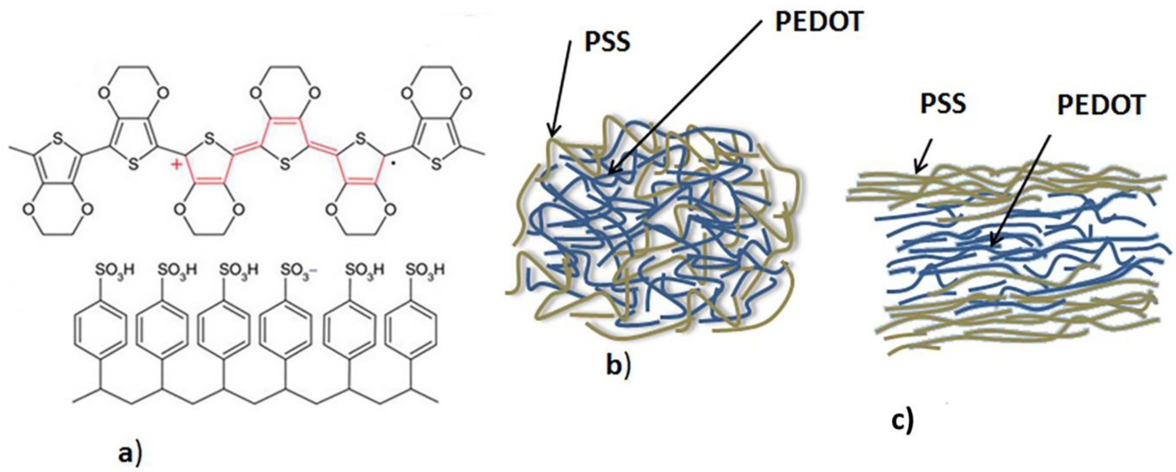


Figure 1.3 The structure of PEDOT-PSS a) chemical structure of PEDOT & PSS, b) formation of PEDOT-PSS dispersion and c) conductivity enhancement by adding organic liquids

When PSS anion is added to the PEDOT cation, the insoluble PEDOT transformed into a water dispersion (soluble) phase. However, the insulator PSS anion reduces the conductivity of PEDOT. Hence, several mechanisms have been proposed to enhance the conductivity of the PEDOT-PSS dispersion after and before applying to the substrate. Among these, immersion of PEDOT-PSS-coated fabric with organic liquids such as ethylene glycol, polyethylene glycol and methanol (Tadesse et al., 2017), adding ethylene glycol into an aqueous solution of PEDOT-PSS (Ouyang et al., 2004), treating the PEDOT-PSS dispersion using sorbitol (Nardes et al., 2008), PEDOT-PSS film treatment using dimethyl sulfate (Reyes-Reyes et al., 2010) are some of them. Among several ICPs, we nominated PEDOT-PSS in our work due to several reasons such outstanding environmental stability (Nardes et al., 2008) and excellent electro-mechanical properties (Okuzaki et al., 2009). Therefore, most of the functional textiles used in the subjective and objective evaluation were developed by utilizing PEDOT-PSS on polyester fabrics using coating and several printing methods.

1.2.2 3D Printing Process

Another exciting new option to create smart materials is using 3-dimensional (3D) printing technology and otherwise known as additive manufacturing (AM). 3D-printing, that was introduced around the 1980s, is defined as the manufacturing of a three-dimensional product from a computer-directed digital model and the process is additive, where number of layers from computer-aided-design (CAD) drawings are positioned alternatively to create various forms (Noorani, 2017). 3D-printing empowers us to search for new ways of thinking about crafting new artifacts. 3D-printing has a promise of taking such product development much more efficient, user and environmentally friendly, cost-effective, and enabling distributed manufacturing system. The process that we followed in our work is shown in Figure 1.4.

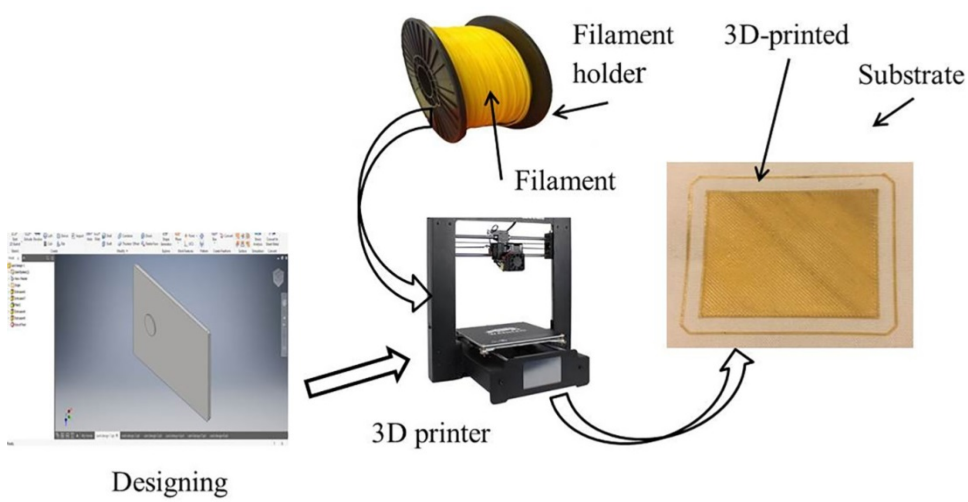


Figure 1.4 The simple 3D printing process

Furthermore, 3D printing tools are accessible at low-cost price. Therefore, nowadays, 3D printing is making an outburst in all areas of engineering and science. Over the last years, various polymers have served in 3D printing technology. Various polymer filaments can be 3D-printed onto the textile substrates. Lots of thermoplastic polymers that have been used on printing on textile materials are illustrated in Figure 1.5. Most of them are very stretchy in nature some others are not. This flexibility allowed us to maintain the stretchability of the substrate materials, textile fabrics. This established the likelihood of 3D-printing in creating wearable smart fabrics.

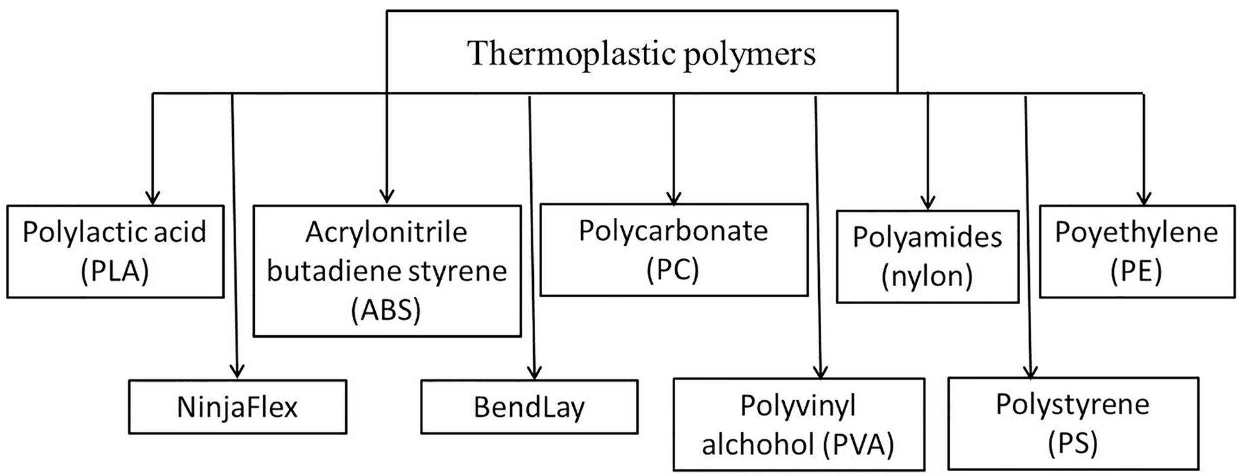


Figure 1.5 Some of the thermoplastics filaments used in 3D printing

There are several types of 3D-printing processes such as Fused Deposition Modeling (FDM), Stereolithography (SLA), Digital Light Processing (DLP), Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Selective Laser Melting (SLM), and other types. Among these types, FDM which places a material where you want it by melting the filament and then engaging the melted plastic to create an object precisely is the core of this thesis. FDM uses the filament-based polymers as a raw material. The polymer-based materials have been applied on to textiles substrates to produce conductive materials using FDM technique (Sanatgar et al., 2017). It has been shown that a possibility of enhancing production time and allowing to create lightweight and flexible textile-based structures. However, there are a few challenges that occurred when polymer filaments 3D-printed onto the textile substrates such as clogging arisen during melting of the polymers in the printing process unless otherwise controlled by adjusting the printing parameters. This is the most common challenge in printing flexible filaments using 3D-printing techniques. Adjusting the printing parameters such as printing speed, printing temperature could reduce the challenges.

1.2.3 Inkjet Printing Techniques

Inkjet printing which is also known as digital printing is a process by which charged droplets of ink supplying from the nozzles are heading for printing onto a substrate material under computer control scenarios. Inkjet printing could be achieved on a textile substrate and an ink should achieve the various properties (Cie, 2015). Among these properties:

- *Hydrodynamics:* to make it happen an inkjet printing process; the ink droplet has to form so that the ink being printed dropwise;
- *Elasticity*: an ink droplet should be strained before it breaks;
- *Viscosity*: the ink should have an ample resistance to movement; ≤ 20 cps;
- *Electricity*: the ink fluid should come out of nozzle; and
- *Surface tension:* the elastic tendency of the ink surface should obtain the least surface area possible; usually the most acceptable value ranges from 20 to 40mNm^{-1}. The inkjet printing process is shown in Figure 1.6.

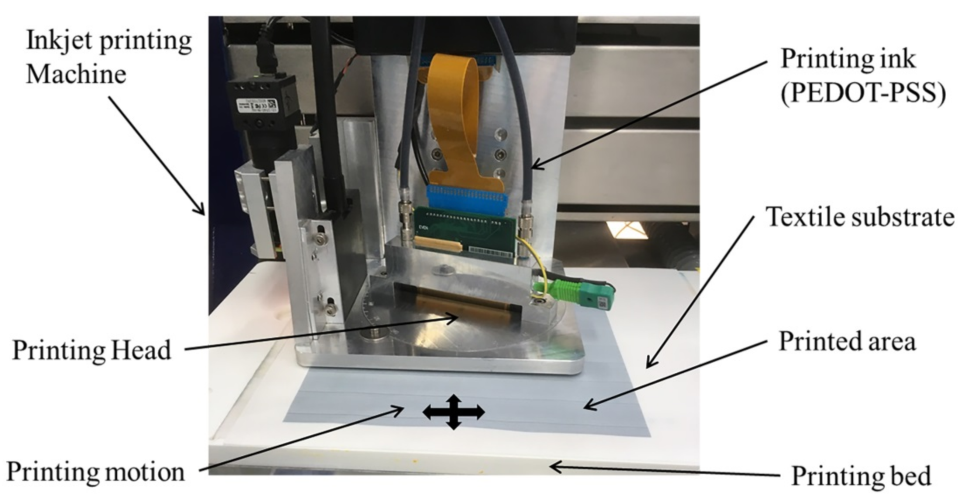


Figure 1.6 The inkjet printing process

In addition, pH scale, particle size (PS) distribution, total solids, ink mass density, ink filterability, foaming, air content in the ink and degassing, and drying rate at controlled temperature and pressure are the key features which disturb the dropping ability of an inkjet ink onto a textile substrate surface (Ujiie, 2006). Recently, inkjet printing has been applied to generate functional properties on the textile substrate using electrically-conducting polymers such as PEDOT-PSS (Hoath et al., 2012). Stephen D et al. claimed that the effect of the formation of satellite droplet formation and its solution using a drop-on-demand (DoD) inkjet printing process would be more appropriate.

1.2.4 Screen Printing Process

Screen printing on a textile substrate is a traditional way of locating a design whereby a mesh is used to transfer an ink onto the substrate materials, other than in areas made impermeable to the ink by blocking the mesh as showed in Figure 1.7. Screen printing has been used for several years since its appearance during the Song Dynasty in China (960-1279 AD) (Watt and Wardwell, 1997). However, textile designers began to make use of screen printing technology starting from the late 1920s (Russell, 2011). Screen printing technology has been used for many years for the making of electronic products (Suganuma, 2014) in addition to the traditional painting technology. Screen printing technology is preferable than other types of printing because of its straightforward process and low cost of manufacturing.

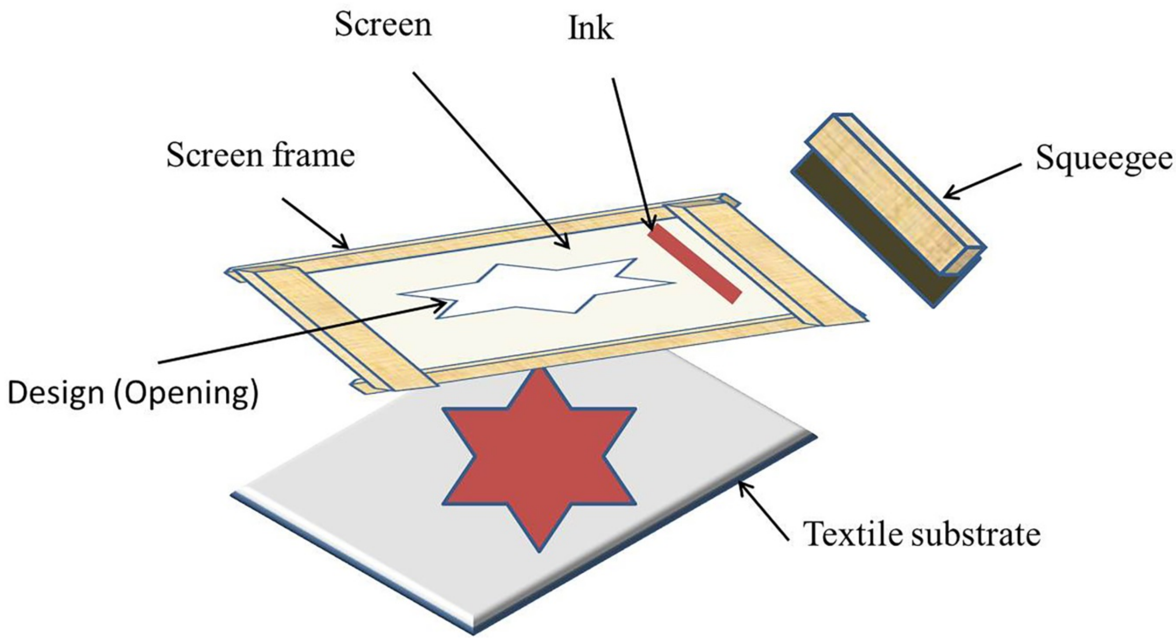


Figure 1.7 Screen printing process illustrations

Because of the permeable nature of the screen materials (most used are silk and polyester), the traditional screen printing process is commercially compliant to many other substances including polymer materials like PEDOT-PSS (Sriprachuabwong et al., 2012), PPy (Li et al., 2007), and whenever the thick film is required (Aegerter and Mennig, 2013). The screen printing technology is often served to accumulate various inks onto numerous substrates such as clothing, papers, plastic, and other considerable materials (Shi et al., 2011). The evolution of using flexible electronics has been growing for the last five decades ranging from flexible solar cells to organic light-emitting devices (LEDs) on flexible substrates notably on plastics and textiles (Wong and Salleo, 2009). In this regard, screen printing played lots of contribution in producing flexible large area solar cells (Krebs et al., 2009), flexible large area array sensors (Chang et al., 2009), and flexible organic light-emitting devices (Pardo et al., 2000). Due to the above mentioned motives, we meant to produce functional textile fabrics using a screen printing technology for e-textile (smart textile) applications. We applied with a simple hand-prepared screen frame with a polyester mesh and the inks were ready according to the prescription. Smooth, evenly distributed, and highly electrical-conducting functional fabrics were obtained.

1.3 Quality Inspection and Evaluation of Textile Product

It is extremely difficult to define quality in a single statement. However, Juran in 1998 (Juran and Godfrey, 1999) defined quality as those features of products, services, and processes which meet customer needs and thereby provide customer satisfaction or conformance to specification. In addition to the aforementioned managerial processes, quality inspection that uses a pre-established tool to check the quality of the product is a mandatory one. In this sense, the quality of smart and functional textiles fabrics with attention to the comfort wear can be regarded as those fabrics free from comfort deficiencies during wearing.

He added that, sensory measurement methods are unique in regards to quality inspection programs in such a way that sensory methods give the direct measurement of perceived attributes; the consumer can easily understand the process, and possible to integrate subjective measurements by experts and objective measurements using instruments. However, sensory evaluation of a product mainly dependent on environmental and emotional factors, physiological and psychological bias, geographical location, personal experience, professional background and training (Das and Alagirusamy, 2010). Hence, sensory evaluation is vulnerable to possible lack of accuracy and precision. Therefore, sensory evaluation needs time and extensive data for accuracy.

Quality inspection of smart and functional fabrics involves the evaluation of tactile perceptions of fabrics based on tactile attributes and using intrinsic senses of the human being (in this case sense of touch and feel). The purpose of the quality inspection is to determine the conformance of the textile product against the comfort standards (Juran and Godfrey, 1999). In this thesis work, we employed the subjective and objective evaluation of some smart and functional textile fabrics using a trained panel of experts and Kawabata evaluation system, respectively. The sensory profile dataset obtained by these methods will be used for e-textile developers and manufacturers for quality inspection and evaluation of their product.

1.4 Human Perceptions of Sensorial Comfort of the Textile Product

Comfort is one of the most important parameters on the desirability of consumer's preference during purchasing decisions. Consumers assess the comfort of clothing not only with a sense of touch but also with a sense of smell, inherent tendency, and emotion during the purchase of the garment product (Li, 2001). Clothing comfort which is a fundamental need for quality of life is a complex subject and is difficult to define (Li and Dai, 2006). However, Slater (1985) (Slater, 1985) defined comfort as an "acceptable state of physiological, psychological, and physical conformity between the human being and the surrounding situation." Therefore, clothing is influenced by both the physical characteristics of clothing as well as by attitudinal and psychological perceptions of the wearer (Das and Alagirusamy, 2010). Kawabata (1991) (Kawabata and Niwa, 1998) relates comfort of clothing with the quality of the fabrics. Therefore, in addition to the attitudes of human being, the physical properties of clothing in terms of subjective and quantitative measurements are able to determine the comfort of clothing. Today consumer's demand on the smart and functional textile fabrics is to fulfill multifunctional properties and comfort to satisfy their physiological and psychological needs. In the following three chapters we shall deal with these topics.

1.4.1 Physiological Perceptions

In recent times, the use of sensory analysis is becoming frequently performed for the quality assessment of textile products (Chollakup et al., 2004) even though the sensory evaluation for quality control has been started in the food industry (Stone et al., 2012). A consumer always touches and senses the handle of the textile product during purchasing and their buying decision mostly taken into account their preferences and personality which they experienced from the multi-sensory, emotional, and physiological incident (Schacher et al., 2011). Physiological perception measurements in the clothing comfort grow up rapidly (Yan Li and Anthony S. W. Wong, 2006).

According to Song (2011) (Song, 2011), physiological perception is an important dimension of clothing comfort and can be predicted when the environmental systems become constant. He defined physiological comfort as a union of tactile comfort, thermophysiological comfort, and garment fit. As he said, subjective evaluation of the physiological comfort of a textile product involves a complex process in which a big number of stimuli from clothing and external environments pass to the brain via various communication channels of sensory responses of the subjective perception of the human skin. The most communication channel in tactile comfort is the finger.

1.4.2 Psychological Perceptions

The psychological feelings of sensorial comfort could be explained as by virtue of what the human brain collects each sensory perception, interprets and measures the perceptions to specify systematically a subjective perception of comprehensive comfort and choice of the textile product.

Psychological perception is the basic constituent of the clothing comfort and is a very challenging task to measure and make an analysis on it (Slater, 1986). However, Pineau in 1982 (Pineau, 1982) has been addressed how to assess the psychological perception of comfort by developing some questionnaires and he winded up that the comfort is not a universal concept because it has the psychological dimension which could not be evaluated by the use of purely material criteria. In 1984, Elder and his co-workers (Elder et al., 1984) have carried out a psychophysical subjective evaluation of fabrics using human experts from psychology department by selecting various linguistic terms of softness.

Later, the study in 2002 (Wong et al., 2002) has claimed that it is possible to simulate the psychological perceptions of clothing using some statistical methods. Many type of research have shown that it is possible to relate the psychological perceptions of a fabric with that of the objective measurement results obtained by measuring the mechanical properties of the fabrics using various numerical solutions and models (Lun Yick et al., 1995; McGregor et al., 2015; Ozcelik et al., 2008; Rombaldoni et al., 2010).

1.4.3 Tactile Perceptions of the smart and functional fabrics

Tactile sensations are the feelings of the garment material (fabric) when it is brought next to the skin (Song, 2011). During wear, the clothing touches our skin dynamically, vigorously, and continuously (Li and Dai, 2006) and hence committed to change its physiological parameters such as skin temperature, sweating rate, and often induces several mechanical stimuli (Li and Dai, 2006). The mechanical stimuli triggers responses from various sensory receptors and formulate various perceptions including tactile senses. Since smart and functional textile fabrics get additional finishing treatments, the tactile perceptions of these fabrics are distinct from the usual fabric.

Wearability features of the e-textile address the factors that affect the degree of comfort, the wearer confronts when wearing a cloth material made from e-textiles including tactile, physiological, psychological, and thermal dimensions. The use of tactile properties of textile-based materials is still a myth and there is not still defined well.

Even though wearable e-textiles become increasingly applied in the smart and the functional textile market, the tactile aspects are still not investigated. Only the functionality aspects examined and of course would still be explored. Tactile/sensorial comfort is perceived when a textile material is in close contact with the human skin (Song, 2011). For textile product that has an explicit contact with the human skin, tactile sensation is very pivotal and the textile material stimulates the various mechanoreceptors like free nerve endings. Meissner's corpuscles, Ruffini corpuscles, Pacinian corpuscles, Tactile disks, and end bulbs of Krause that are present in the various layers of the skin (Das and Alagirusamy, 2010) (see **Figure 1.11)**.

1.4.3.1 Sense of Touch

Touching is very important sensing property for decision making during purchasing apparel in addition to seeing and smelling as claimed by Schacher L et al. (Schacher et al., 2011). They said that touching includes the response to touch, pressure, and vibrations when a part of our body in contact with the external materials and the sensibility mainly depends on combinations of shape, surface, color, duration, and the intensity of the perception. The mechanoreceptors (Merkel disks, the tactile disks, the hair follicles, the Meissner corpuscles, the Ruffini corpuscles, and the Pacini corpuscles-see Figure 1.10) are essential to the sensibility and perception. Moreover, when wearing, garments perpetually contact and touch vigorously with the skin of the full body parts or some parts of the body. Several portions of a body where sensory functions concentrated are laid out in Figure 1.9.

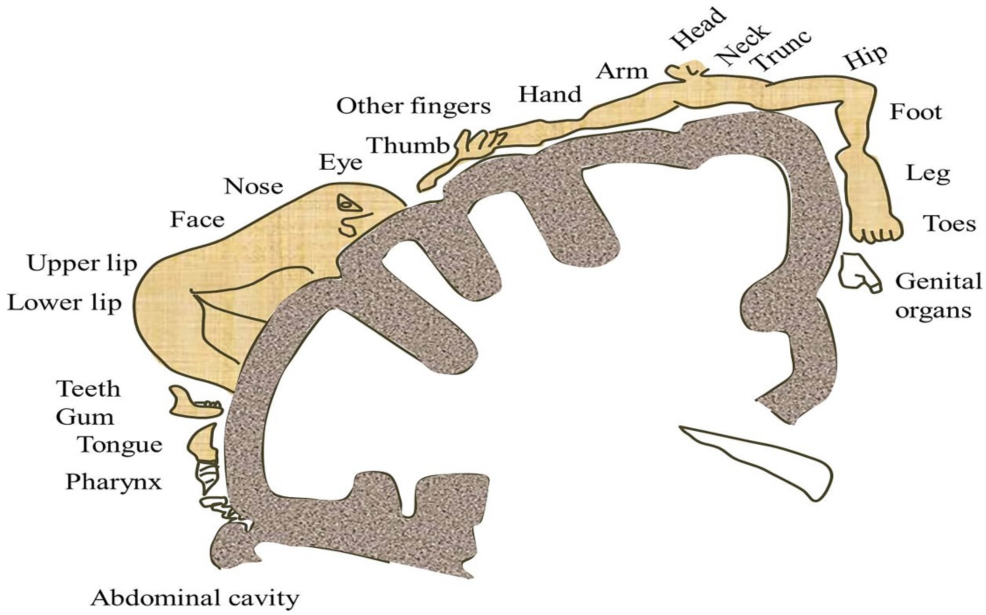


Figure 1.8 Parts of body dedicated to sensory functions (Schacher et al., 2011)

The psychological perceptions of the textile fabric that led to a pleasant feel when wear (Militký, 2005) could be judged when the fabric is being touched and the usual way of expression for this is "hand" of the textile materials. The expression hand has no accurate definitions; however, the fabric hand could be used to evaluate the quality index of the textile goods when squeezed or touched. The fabric hand can be assessed mostly using holding considerable parts of the fabric either with the thumb and fingers or by wearing the fabric (Das and Alagirusamy, 2010).

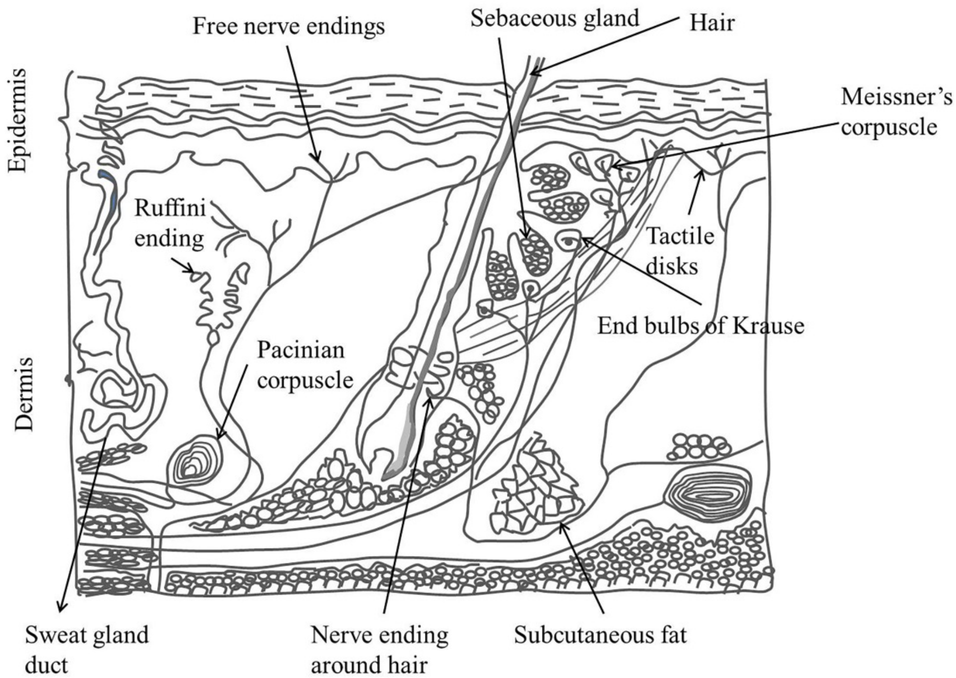


Figure 1.9 Various mechanoreceptors in the skin (Song, 2011)

1.4.3.2 The Brain

In interrogating and perceiving the comfort of textile materials, the brain plays the central role on account of the hands more specifically the fingers have to lead sensitivity and complexity to the brain (Song, 2011). The basic communication channel existed between the brain and the fingers in terms of touch sensations. Considering that fingers are the most used parts to evaluate the comfort of the textile goods during buying as dictated in Figure 1.10. Neuron cells are further divided into dendrites and an axon. Dendrites receive information from other cells and give this to the cell body while axon helps the neurons to transmit the message. The structure of the neuron can be shown in Figure 1.11.

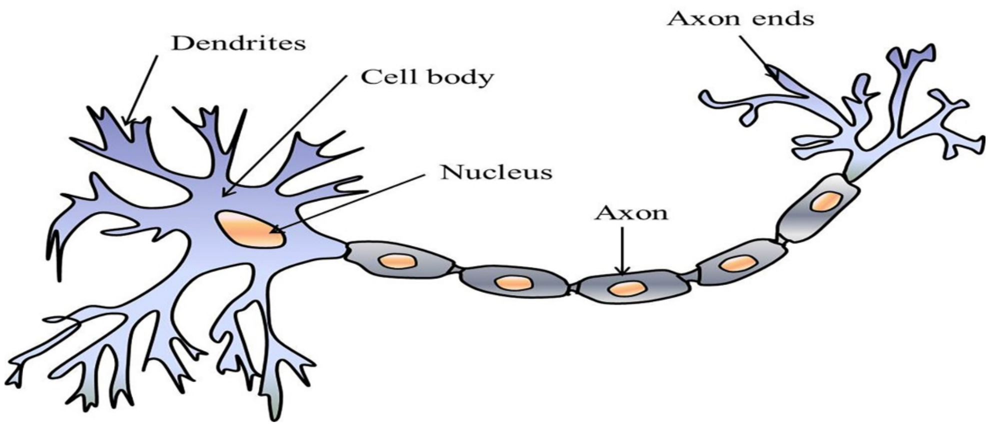


Figure 1.10 The structure of neuron (source: 21 Century Tech)

As Allerkamp claimed, the neurons need extra neurotransmitters to communicate the perceptions to each other. The physical stimuli created during touch of the textile product can be translated into comfort perception and transfers into the neuron using some transducers and back to the brain for complete translation and finally the subjective perception can be taken as an output value.

1.5 Tactile Comfort Investigation

Tactile comfort of the textile-based materials can be investigated using two methods viz subjective and objective evaluation methods by measuring or evaluating the handle of the product. In the following sub-sections, these two hand evalaution methods have been discussed.

1.5.1 Subjective Evaluation Techniques

The subjective evaluation of the clothing comfort can be determined by physiological and psychological processes using human experts induced by various physical stimuli (Yan Li and Anthony S. W. Wong, 2006). Subjective evaluation determines the fabric hand which is influenced by various characteristics of the fabric components (fiber and yarn) such as flexural rigidity, count, friction, hairiness, stiffness, and other physical features (Peykamian and Rust, 1999). Subjective evaluation comprises many steps such as expert panel selection, panel training, conducting the subjective evaluation, and interpreting the subjective data into quantitative data using numerical and other reliable analysis systems. As the name indicates, subjective evaluation is wide-open to bias due to the experience and other human being related issues.

1.5.1.1 Panel Selection

Sensory evaluation can be carried out by few or several sensory panels according to the type of sensory panels. Few sensory panels may be sufficient enough for industry experts and several required for others to the reputability and validity of the obtained data. These groups of sensory panelists are supposed to evaluate the tactile sensations for textile materials against the skin most preferably touching and gripping with their hand.

Dijksterhuis (Dijksterhuis, 2008) has classified the panelist according to the following categories based on the training they get:

- Field (street) panels: consumers randomly selected like around the shopping mall, to answer the pre-defined questionnaires;
- The panel of consumers: inexperienced consumers are recruited at least in a controlled environment for example at a laboratory to judge the products; and
- Panels of experts: those panels that get intensive training in which they are supposed to judge about.

In the subjective evaluation of the functional fabrics, experts or panels are selected to function as instruments to measure the product differences, characteristics or preferences levels (Stone, 2012). Sensory skills vary from person to person. Henceforth, it should be diagnosed carefully. Failure to these differences may create difference in subjective perception results. Therefore, panel selection is an important practice is a subjective evaluation.

1.5.1.2 Training and Evaluation

The successful application of the subjective evaluation of the fabric's hand mainly depends on establishing reliable and reproducible hand perceptions of the fabric hand and this intern majorly depends on whether the human experts have similar perceptions towards the hand descriptions and reproducibility of the test. Training and brainstorming about the descriptors, evaluation methods, and some technical terms play a crucial role to have comparable hand perception outputs (Naima et al., 2013b). The subjective evaluation of fabric hand composes the existing textile assessment method, mentioning the total sensation, experienced when a fabric is touched, squeezed, rubbed or otherwise handled and rated by human subjects. Hand evaluation is the inspection of the comfort-related properties of a fabric using subjective evaluation as claimed by Mark and Borch (Mark and Borch, 2001). Mark et al. have defined fabric properties which are related to fabric tactile handle for winter/autumn suiting as:

- *Stiffness (Koshi)*: in fabric sensory evaluation, this property is linked with fabric bending and stiffness. Fabrics that are easily bent are characterized as flexible, whereas those resistant to bending are described as stiff or inflexible.
- *Smoothness (Numeri)*: the smoothness is characterized by the indentations and ridges on the fabric surface. The fewer the ridges, the smoothness the fabric is; otherwise, the fabric is bumpy.
- *Fullness (Fukurami):* a fabric feeling from the mingle sense of bulkiness, richness, and well-formed perceptions. It possesses a springy property in compression and thickness, accompanied by a warm feeling. Is characterized by

the interval between the face and the back side of the fabric. The smaller the distance the finer the fabric is.

Fabric physical and mechanical properties such as softness, hardness, scratchiness, looseness, stretchability, stickiness, prickliness, and itchiness (Y. Li and Anthony S. W. Wong, 2006) for tactile sensations and warmness coolness for thermal sensations could be considered based on the application of the fabrics.

1.5.2 Fabric Objective Hand Evaluation Techniques

After the introduction of fabric hand evaluation in 1930s by Peirce (Peirce, 1930), lots of research have been accomplished for the fabric using objective measurement using several methods such as KES-FB and phabrOmeter (Yim and Kan, 2014), SiroFAST (De Boos and Tester, 1994), and some other relevant techniques. The objective measurement has been established well by Kawabata in 1980 (Kawabata, 1980). Ellis et al. in 1980 (Ellis and Garnsworthy, 1980) claimed that the introduction of novel finishing techniques to the textile fabric has a strong influence on the hand of textiles. Literally, the empirical measurement of fabric to quantify the handle of textile fabric is related to the low-stress mechanical properties of the fabric such as tensile property, bending, shearing, surface friction and bending (Behery, 2005). Fabric quantitative measurement of low-stress mechanical properties and surface properties represents a very persuasive apparatus for the quality evaluation, inspection, and control of fabric development, manufacturing, finishing and re-finishing operations as claimed by Hu in 2004 (Hu, 2004). Hu summaries the advantages of using objective measurement using KES despite of the high cost of the machines:

- Direct the end uses of the textile-based fabrics by giving an optimized fabric properties in regard to its quality and performance attributes;

- Enables to develop a new finishes, finishing chemicals, finishing equipment for the textile product based on the previous objective assessment data as a standard;
- Quality inspection, control of the products by adjusting the finishing and re-finishing of fabric to fit the fabric properties related to quality more specifically tactile comfort;
- Provide a standard and fabric specification to the fabric manufacturers so that process of manufacturing shall be controlled; and
- Provide the quality profile data to the fabric developers so that new products shall be developed and tailored accordingly.

In addition, the results can create the powerful tool to interconnect between fabric developers, manufacturers, finishers and sellers. Among the objective measurement techniques, Kawabata's evaluation system gives precise and reproducible fabric mechanical properties under low-load conditions. The KES measurement method doesn't damage the fabric samples. Therefore, the handle of the textile material relies on the data obtained by measuring these mechanical properties. In the following section, the mechanical properties of the fabric related to tactile handle using Kawabata's evaluation systems are being discussed.

1.5.2.1 Tensile Properties

Peirce (Peirce, 1930) stated that the sensory perception of clothing is dependent on the physical properties of the fabric. Tensile property is the vital physical properties of the fabric in this feature. Liable on the types of purpose in which the fabric intended for, there are numerous types of tensile tests. When tensile tests executed under low-stress conditions, the result obtained by applying a tensile strain is utilized to make an analysis of the handle (comfort) of the textile materials (Sun, 2017). To measure the handle of the textile fabric, tensile distortion (basically called “strip biaxial deformation”) is applied alongside the length direction only according to Kawabata in 1980 (Kawabata, 1980). For this deformation, the strain rate is kept persistent and is about 4.00×10^{-3}/sec. The recovery is measured after the tensile strain reaches 500*gf/cm* (*Fm*) as showed in Figure 1.12. The increased demand of functional fabric production rate to fulfil the consumer requirements demanded the quality evaluation and inspection in terms of tactile comfort. In this regard, measuring the tensile properties that have a direct kin to the tactile comfort of the product is a thoughtful step. Therefore, one of the steps in inspecting the quality of the tactile comfort of the functional fabrics is measuring the tensile properties under low-load regions. Each of the tensile properties is interrelated to the comfort properties and further investigated.

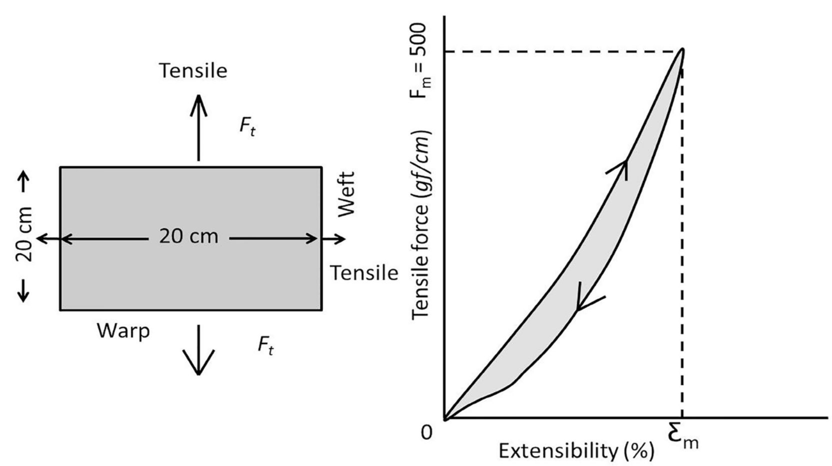


Figure 1.11 A typical tensile curve for polyester fabric

Tensile characteristic values need to be measured conferring to Kawabata are LT: Linearity [no unit]; WT: tensile energy per unit area [gf.cm/cm^2]; and RT: Resilience [%]. These tensile properties are needed to be measured using Kawabata evaluation system (KES-FB1). Tensile distortions applied along the length direction. That is stripped biaxial deformations (warp and weft). As showed in the figure, the tensile deformation has two segments. The deformation of the material by strip axial stress (→) and the recovery phase (←).

Working out:

WT Tensile energy per unit area [N.m/m^2] $WT = \int_0^{Em} F.dE$ (1.1)

LT Linearity [-] $LT = \frac{WT}{Fm.Em/2}$ (1.2)

RT Resilience [%] $RT = \frac{WT'}{WT} * 100$ (1.3)

Where WT' is recovery energy [N.m/m^2].

1.5.2.2 Shearing Properties

During putting on the clothing materials, the clothing twists along with the body movement. It fits the bowed shapes of the body and touches several parts of the skin. As a result, clothing material deforms as per the curved parts of the body. This deformation comprises the shearing action of the clothing materials (Sun, 2017). The shearing property is obtained by measuring shear rigidity (G) and is the ease which the yarn within the fabric slides against each other. The shear properties of the fabric relate to the handle of the fabric and are measured using KES-FB1, Kawabata 1980 (Kawabata, 1980). According to Kawabata's evaluation system, persistent shear tension of 10gf/cm (woven fabric) is applied along the direction orthogonal to the shearing force (see Figure 1.13).

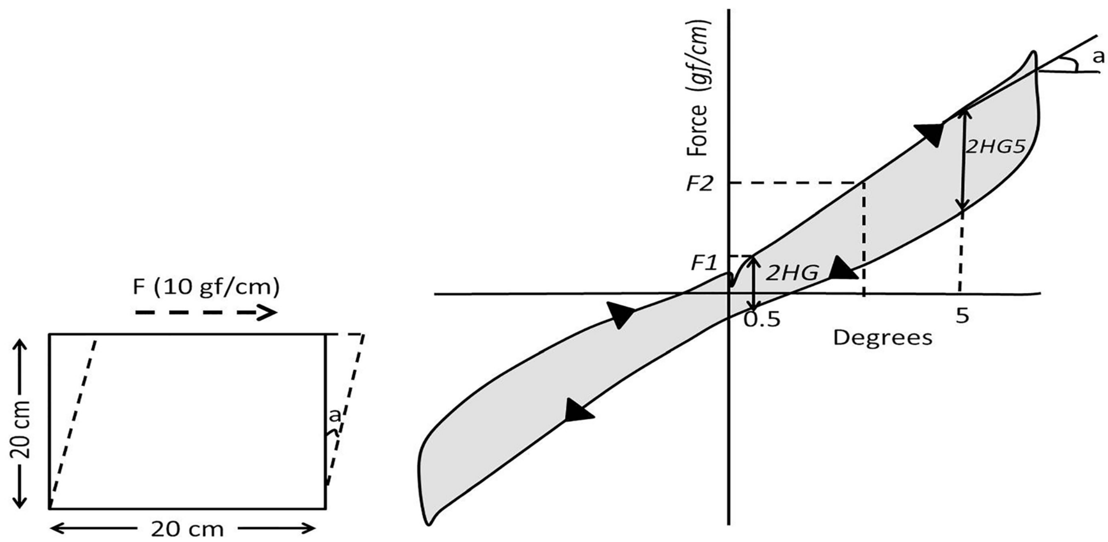


Figure 1.12 The shear properties of polyester fabric

In addition to shear rigidity G[gf/cm.degree], shear hysteresis 2HG[gf/cm] and 2HG5[gf/cm] are the hysteresis of the shear force at 0.5 and 5 degrees, respectively; and the greater the shear hysteresis values the inferior the recovering ability of the fabric will be (Sun, 2017). Shearing properties are also related to the comfort of clothing materials when measured under low-load regions.

1.5.2.3 Bending Properties

The bending property of a fabric is one of the key properties of a fabric that governs the fabric handle (Hu, 2004). Figure 1.14 demonstrates the linking between the bending movement M and the bending curvature and can be obtained by measuring the bending property using KES-FB2 (Kawabata, 1980; Sun, 2017).

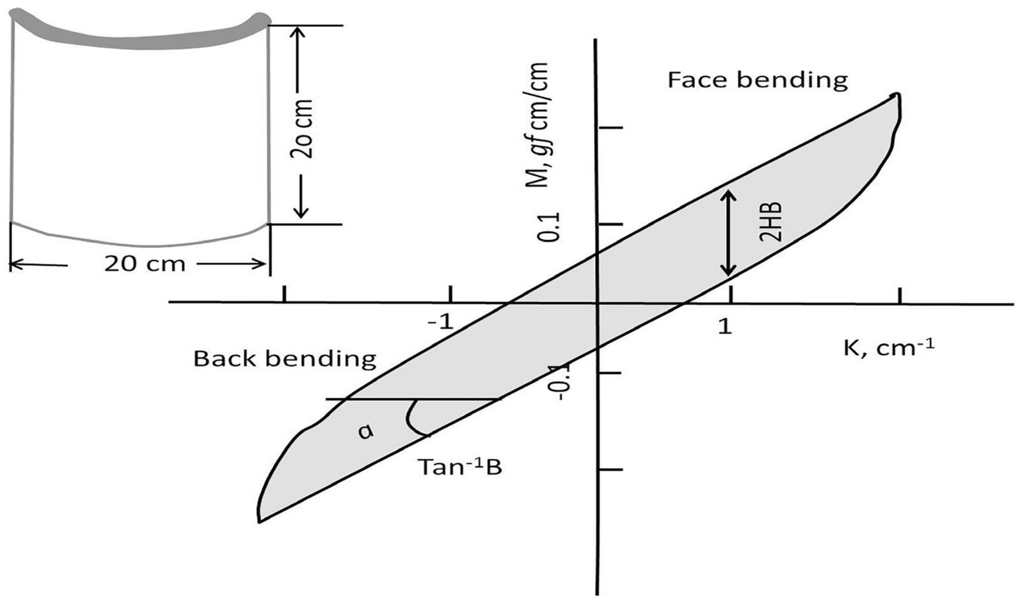


Figure 1.13 A typical bending curve for polyester fabric

The minimum-maximum curvature K for pure bending is between K =-2.5 and +2.5 (cm^{-1}) with a constant velocity of 0.5 cm^{-1}/s. The elementary bending properties which are measured using this norm is bending rigidity *B* [cm^2/cm] and movement of hysteresis per unit length 2HB [gf.cm/cm]. The measurements are engaged both in warp and weft directions of the fabric. The sample size is 20 x 20 cm where the effective dimensions of the specimen is 2.5 x 1 cm (Kawabata, 1980). Bending occurs when clothing materials worn under bowed body parts and has a direct relation to the handle of the product when worn next to the skin. Therefore, measuring the bending property is a very important step to determine the quality of the clothing materials in terms of tactile comfort.

1.5.2.4 Compression

Compression is the property of the fabric in the direction of thickness when a pressurized force acts upon it. Figure 1.15 describes the compressional property of the fabric where 2 cm^2 is an effective dimension and a maximum load of P 50 gf/cm^2 at a maximum fabric thickness (y_1) and measured using KES-FB3 (Kawabata, 1980).

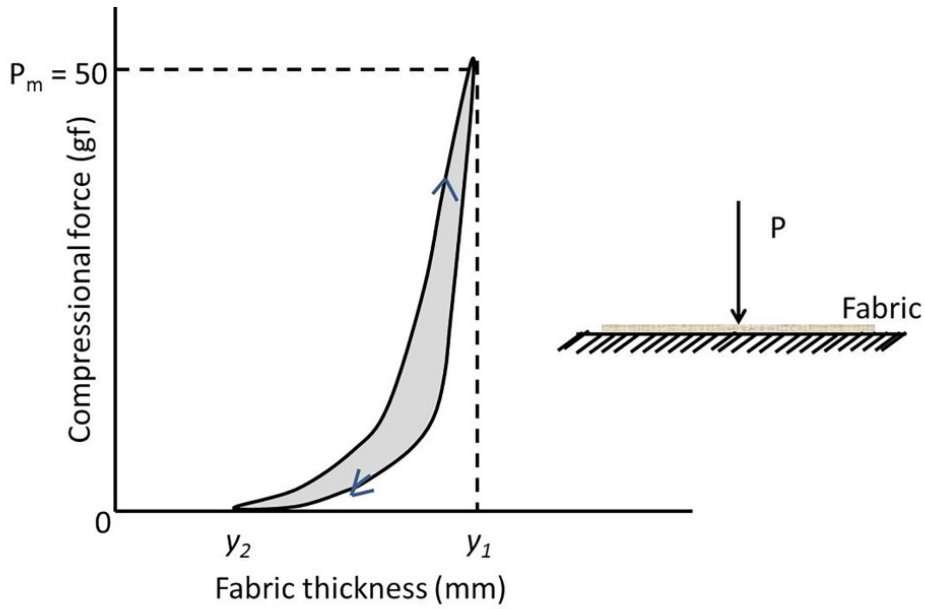


Figure 1.14 A typical compression curve for polyester fabric

The compressional properties measured are Linearity LC [no unit], compression energy WC [gf.cm/cm^2], and resilience RC [%] (Sun, 2017). In addition to the compressional properties, thickness T at the maximum pressure is measured laterally. Weight W is further articulated by the weight per unit area of the specimen. In addition to the compressional properties, the construction parameters (T and W) are very determinant factors in expressing the handle of the clothing materials.

Working out:

WC compression energy $WC = \int_{T_m}^{T_o} P.dT$ (1.4)

LC linearity $LC = \frac{WC}{P_{m.}(T_{m-}T_o)/2}$ (1.5)

RC compression resilience $RC = \frac{WC'}{WC} * 100$ (1.6)

Where WC': recovery energy

1.5.2.5 Surface and Frictional Properties

Surface and frictional characteristics of textile fabrics decide the smoothness and softness values of the fabrics which further influence the handle of the fabrics. Uses of chemicals and chemical finishing of the fabrics further decreases the handle of the fabric. Objectively, the surface properties of the textile fabric need to be measured using KES-FB4 (Kawabata, 1980). Figure 1.16 displays the surface roughness and surface friction properties measured using KES.

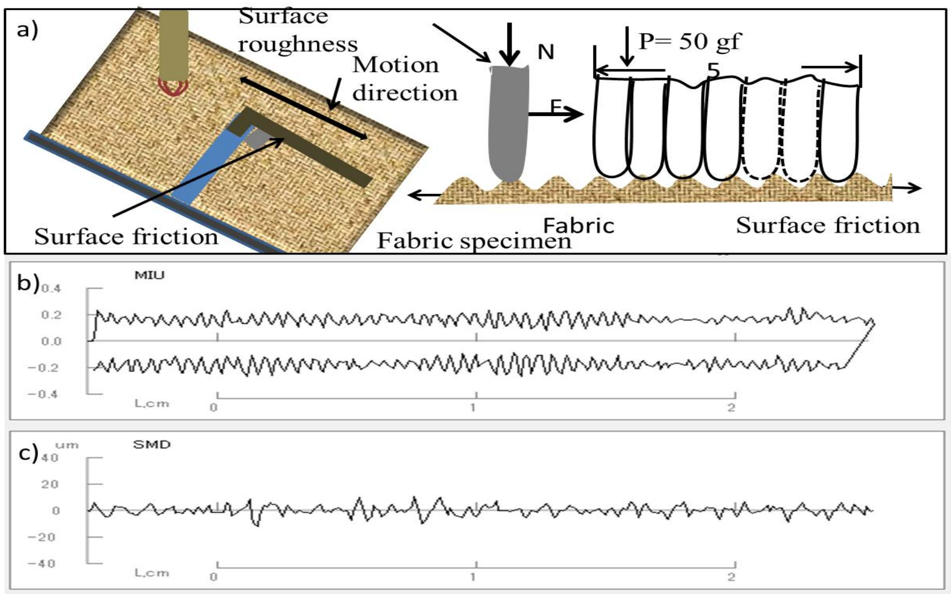


Figure 1.15 Surface roughness and friction properties a) illustrations of the surface friction measurement; b and c) the actual results of the frictional properties of polyester fabric by KES

The surface friction property of the fabrics is highly sensitive mechanical property which highly determines the handle of the fabrics. The frictional characteristics values measured using KES-FB4 are: mean value of the coefficient of friction MIU, mean deviation of the coefficient of friction MMD; and the roughness characteristics which is the deviation of surface roughness SMD (micron).

Working out:

- MIU mean value of coefficient of friction [-]: $MIU = \frac{1}{L} . \int_0^x \mu . dL$ (1.7)
- MMD mean deviation of coefficient of friction [-]: $MMD = \frac{1}{L} . \int_0^x |\mu - \bar{\mu}| \, dL$ (1.8)
- SMD mean deviation of surface roughness [μm]: $SMD = \frac{1}{L} . \int_0^x |T - \bar{T}| dL$ (1.9)

All these low-stress mechanical and surface frictional properties need to be measured and analyzed using KES-FB auto instrument. Over all, fabric mechanical properties are of great importance and decisive factors in determining the handle of the fabrics. This thesis presents the interpretation of the measured mechanical properties in relation to the tactile comfort properties of the functional fabrics.

1.6 Soft Computing in Sensory Evaluation

Once the subjective and the objective sensory evaluation data obtained, it is extremely important to realize a numerical modelling using an appropriate mathematical and intelligence approaches. This would help audiences to understand and interpret the data easily. Lots of efforts have been made to exploit the complex sensory data obtained using either the human experts and/or the instrumental measurements. Amongst the frequently employed used methods, multiple regression analysis and principal component analysis (PCA) (Cardello et al., 2003), multi-criteria group decision support system (Lu et al., 2009), fuzzy neural network (Luo et al., 2007), Steven power low (Elder et al., 1984), and various types of statistical and artificial intelligence modelling practices have been extensively employed. The hand evaluation techniques are very complex and have intricate relationships. Therefore, these soft computing methods enable to solve the non-linear relations amongst the input and outputs of the subjective and objective results. These methods are quite operative in demonstrating the intricate sensory examinations of textile-based materials. However, most recently the classical statistical methods are non-operational owing to some problems related to uncertainty, dataset nonlinearity, and imprecision are arising as claimed by Xue (Xue, 2012). These kinds of ineffectiveness are removed when intelligent and soft computing methods such as fuzzy logic and artificial neural networks employed. According to Xue, intelligent computational techniques have the following advantages when compared to the classical methods:

- Able to model and solve nonlinear problems and datasets;
- Able to made an analysis both in linguistic and numeric data;
- Able to model human perception;
- Able to compute small datasets; and
- No need of paraboilistic distributions that used in classical methods.

The results attained when intelligent techniques engaged are effortlessly interpretable and quantifiable. In our thesis, we employed these two types of soft computing methods.

1.6.1 Artificial Neural Network

Artificial neural network (ANN) is a soft computing scheme that is architectured to mimic the way the human brain investigates and processes information as claimed by Deb (Deb, 2010). Deb characterized ANN as an enormously analogous structure of the neurons with a high degree of connection, intricacy, and trainability as showed in Figure 1.17. Neural networks require being trained whereby the inputs and outputs are provided and a target output will be obtained by altering the weight. After training, the neural net configure in predict the output function. There are several architectures in the neural net and amongst this, feed-forward back-propagation and learning engine is frequently employed in fabric hand prediction as demanded by Karthikeyan and Sztandera (Karthikeyan and Sztandera, 2010). They applied ANN to predict the comfort of various textile fabrics such as woven, knitted, and non-woven or laminated and chemically finished fabrics using mechanical properties obtained by KES-F as an input parameter and the sensorial perception scores obtained by a human expert as an output parameter. They concluded that ANN can predict the comfort of numerous textile fabrics as the way the human expert perceives it.

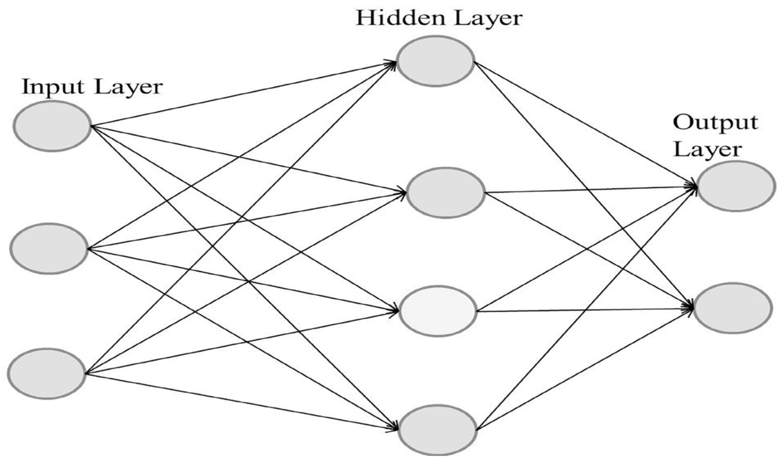


Figure 1.16 A simple architecture of ANN

Even though the fabric hand is a key property in terms of wearing comfort, it needs a sophisticated analysis due to its complexity. Because, fabric hand depends on many parameters such as fiber properties, yarn properties, fabric properties, and mechanical and chemical finishing process. In a similar manner, Park and his co-workers (Park et al., 2001) employed ANN to predict the hand values using low-stress mechanical properties obtained by KES-FB as input parameters and they found that the simulated results by ANN and the subjective evaluation results using the human expert has got a good agreement. Therefore, ANN can be used to predict the comfort of textile fabrics.

1.6.2 Fuzzy Logic

Fuzzy logic is a type of artificial intelligence based on the recognition that logical statements are not only true or false but also ranges from almost certain to a very doubtful which helps to pretend the human reasoning more thoroughly, so that decisions can be made with uncertain data (Deb, 2010) and this theory was proposed first by Zadeh in 1996 (Zadeh, 1996). Fuzzy logic is a perpetuation of crisp set theory. As Zadeh said, a fuzzy set A in X is defined by a membership function $f_A(x)$ which associates with each point in X a real number in the interval [0,1]. This means the degree of membership comprises real number ranges from 0 to 1 and denoted as:

$$\mu_A(x) \in [0,1] \qquad 1.1$$

The process of fuzzy reasoning is divided into what is called a fuzzy inference system (FIS) and comprises of fuzzification, rule evaluation, and defuzzification from appropriate input to output values. The first step is fuzzification where a crisp set is converted into fuzzy set input. In this thesis work, crisp sets are values obtained from the human panel perception on the hands of the functional and smart fabric evaluation. The second step in FIS is establishing the rules based on the hypothetical relations between the input and the output parameters. The most frequently used rules are those introduced by Mamdani (Kickert and Mamdani, 1978) called the IF-THEN fuzzy controller rules. More clearly can be explored as if x are A_i THEN y is B_i. Binary rules can be pooled using the conjunction AND or disjunction OR. And the third step in FIS is defuzzification where a fuzzy output is transposed back into a crisp output which can be easily interpreted according to the test performed. The most frequently used defuzzification method is the centroid method which finds the center point of the targeted fuzzy region by calculating the weighted mean of the output fuzzy region. It is illustrated in the following equation:

$$x = \frac{\sum_{i=1}^{n} x_i . \mu(x_i)}{\sum_{i=1}^{n} \mu(x_i)} \qquad (1.2)$$

Where xi; the sample element

μ(xi); the membership function, and

n; the number of samples.

The most common word definitions in fuzzy logic are:

- *The degree of membership DOM*: a value from 0 to 1 where a crisp value is adaptable to a membership function;
- *The membership function MF*: helps to map the crisp values from its domain to the sets associated DOM. MF can be the triangular; the trapezoidal or other types and the most frequently used membership functions are represented in Figure 1.18.
- *The universe of discourse*: range of all possible values in the system.

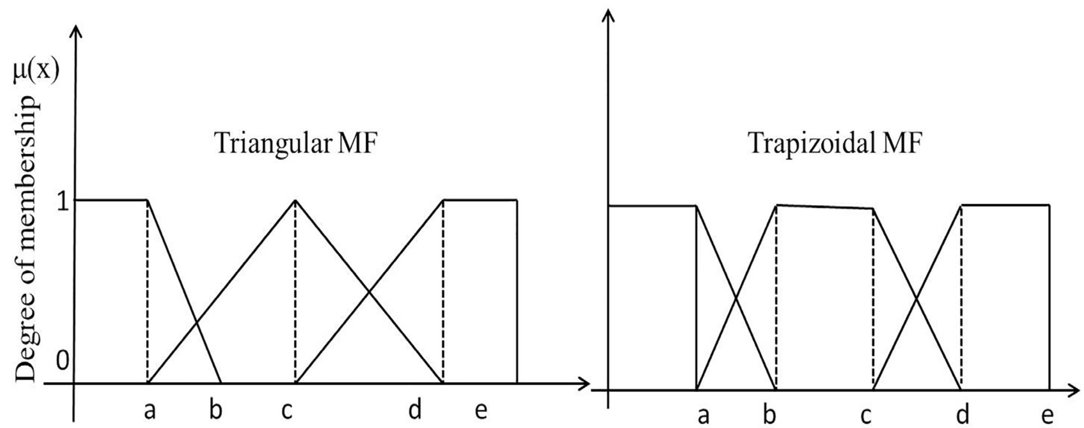


Figure 1.17 Membership functions in fuzzy logic

The fuzzy logic controller has been applied to predict the handle of the textile fabrics (Park et al., 2000). The authors used data obtained from the subjective evaluation of fabrics by a panel of experts and the objective data obtained using KES machine. They got a better agreement between the fuzzy logic prediction from subjective evaluation and the low-stress mechanical properties obtained from KES measurement. In our thesis, we applied the same principle.

In this thesis work, fuzzy logic modelling has been employed to predict two sensory perceptions of the functional and smart fabrics. On the one hand, fuzzy logic modelling has been used to estimate the hand values from the finishing parameters of the functional fabrics. On the other hand, fuzzy logic has been employed to predict the total hand values of our sample by using the subjective evaluation of the samples obtained from the panel of experts as an input parameter. We found the error of prediction is within the standard deviations of the population data. This is a good indication that fuzzy logic can be used to predict the handle of the serviceable fabrics.

RESEARCH OUTCOMES

Chapter 2 Development of Functional Fabrics

2.1 Effect of Liquid Immersion on Conductivity of PEDOT-PSS-Coated Fabric

This chapter is based on the publication:

> **Tadesse MG.** Loghin C, Chen Y, Wang L, Catalin D, Nierstrasz V, Effect of liquid immersion of PEDOT:PSS-coated polyester fabric on surface resistance and wettability, *Smart Materials and Structures* 2017; **26**(6):065016.

2.1.1 Introduction

Textile goods can be transformed into smart and intelligent materials by employing various techniques such as coating and printing employing different special function polymers as claimed by Mattila in 2006 (Mattila, 2006). The most outstanding and effective special polymers that most researchers frequently used is poly (3, 4-ethylenedioxythiophene)-poly (styrene sulfonate) (PEDOT-PSS).

The use of conducting-polymers has increased rapidly after the discovery of conducting polymers by Heeger and his co-workers in 1977 (Shirakawa et al., 1977). They found that the enhancement of the conductivity of the semi-conducting polymer, Trans polyacetylene (CH) *x* breakthrough that brought the dynamic change using conducting polymers instead of metallic conducting materials.

Recently, lots of researches have been performed to produce conductive textile fabrics using intrinsically conductive polymers (ICPs) (Cucchi et al., 2009; Dhawan et al., 2001; Ding et al., 2010). However, among these conductive polymers, PEDOT-PSS is now become acceptable due to its excellent electromechanical properties (Cairns and Crawford, 2005). The most important properties of the PEDOT-PSS dispersion is that it can be readily coated onto textile substrates with outstanding adhesion, electrical properties, and environmental resistance properties.

The electrical conductivity of PEDOT-PSS coated textile fabric has been measured by applying the Van Deer Pau surface resistance measurement (Banaszczyk et al., 2010). The measurement principle can be depicted as in Figure 2.1 below. The value is easily characterized by square values and measured in ohms per square which is denoted as R□ = P/t where P is the resistivity of the material and t is the thickness of the deposition. However, since the thickness of the textiles material is varied throughout its length, this formula may not be applied. Simply measured the surface resistance which is applied between the copper probes, where an electric current (I) flows between the two probes and voltage drop is flowing between the other two probes.

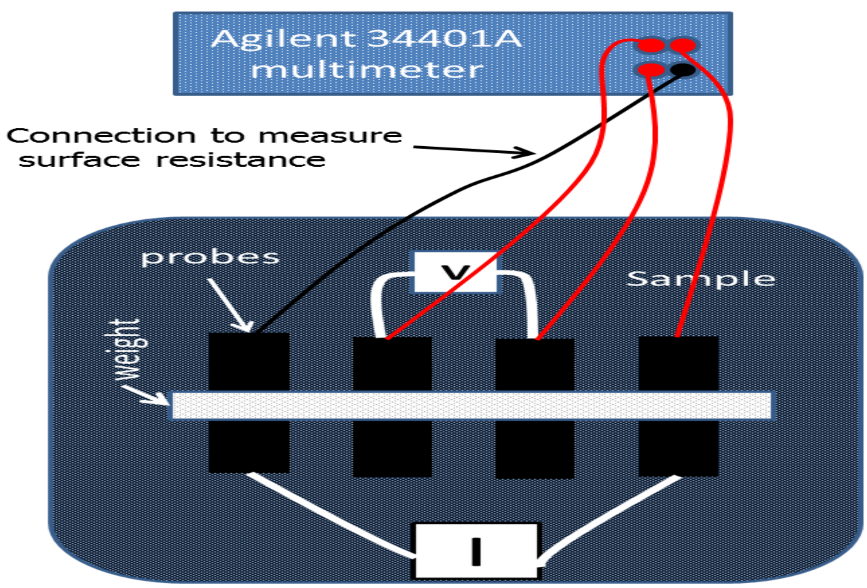


Figure 2.1 The Van Der Pauw method of measuring the surface resistance

Sometimes, the dead weight is very important as the textiles materials are anisotropic (Kazani et al., 2011); it helps to secure the contact between the fabric and the probes so that stable reading can be acheived. This method of electrical surface resistance measurement was applied with each mentioned chapter of this thesis.

The conductive textile fabrics can be produced using several means such as inkjet printing (Bidoki et al., 2005), screen printing (Kazani et al., 2012), and coating applications (Smith, 2010). Nevertheless, the coating process has been used frequently because it is as simple; do not require too much complex systems and time saving process. PEDOT-PSS can be simply deposited using coating applications and it is thermally stable and doesn't crack too many when the coated fabric is subjected to bending, shearing, and twisting actions during wearing and other mechanical actions in addition to the bowed shape of the human body that makes the wearable garment to bent, shear, tensions, and compressed (Okuzaki et al., 2009).

PEDOT-PSS is composed of two monomers: the first one is the hydrophilic (water loving) PSS that constitutes the polystyrene sulfonate with deprotonated behaviour and convey on a negative charge which acts as a counter ion for the compound. The second part is the hydrophobic (water hating) PEDOT which is a conjugated monomer and carries a positive charge (Groenendaal et al., 2000).

When the PEDOT mixed with the insulator PSS anion, the electrical conductivity of the dispersion will be lowered. However, this shortcoming could be overturned by enhancing the conductivity using organic liquids such as ethylene glycol (EG) (Lin et al., 2015) and dimethyl sulfoxide (Na et al., 2009). These conductive enhancers would to aid the PEDOT-PSS dispersion by increasing the conductivity of the film by partially get rid of the hydrophilic PSS that surrounds the conducting PEDOT film.

The purpose of this work is to coat polyester fabric with conductive polymers and characterize the surface properties of the textile fabric with PEDOT-PSS dispersion and immersing the coated fabric with various conductive enhancers. Simple, cost effective, and efficient immersion process was utilized to produce high electrically conducting textile fabric that can replace the stiff and heavy-weight metallic conductors. When the partial removal of the hydrophilic PSS occurred, the PEDOT will have different orientations with regards to crystallinity. This means the solution became hydrophobic. The hydrophobicity nature can also check by measuring the contact angles (Zhang et al., 2003). This phenomenon has been investigated in this work.

2.1.2 Experimental

Materials

In this experiment, plain woven polyester fabric with a weight of 158 g/m^2; 30 ends/cm; 22 picks /cm; scoured and heat-set by the provider (Almedahl-Kinna AB. Sweden) was met with a solution comprising PEDOT-PSS (Heraeus GmbH. Germany). The concentration of PEDOT-PSS is 1.3% by weight with a PSS to PEDOT ratio of 2:5. Methanol and ethylene glycol; both having 99.8% and a lab grade polyethylene glycol (PEG) with a molecular weight of 300 from Sigma Aldrich was helped as conductivity enhancers. HEUR (hydrophobically modified ethoxylated urethane) from Borchers GmbH with a solid content of 48 wt% was employed as a rheology modifier. Performax 1629G (Diazo Kemi, Sweden) was invoked as a binder. A DuPont Zonyl FSO-300 with solid content of 40 wt% was served as a surfactant. All the chemicals were used as received without any further modifications.

Methods

PEDOT-PSS ; ≈ 63.8%, binder; ≈ 28%, rheology modifier; ≈ 8% of and surfactant; 0.2% on weight were mixed using overhead mechanical agitator at an rpm of 500 for five minutes until the blend becomes consistent when observed with bare eye. Then, the coating on polyester fabric was accomplished with at a gap height of 200 μm by hand at a constant speed using coating applicator machine as shown in Figure 2.2. The samples were dried and cured at 50ºC and 90ºC, respectively for 30 min. After coating, immersing the coated fabric with the above mentioned conductive enhancers for two different times (5 and 15 min) with a liquor ratio of 1:10. Finally, the immersed samples were cured at 100ºC for 30 min under vacuum and air condition.

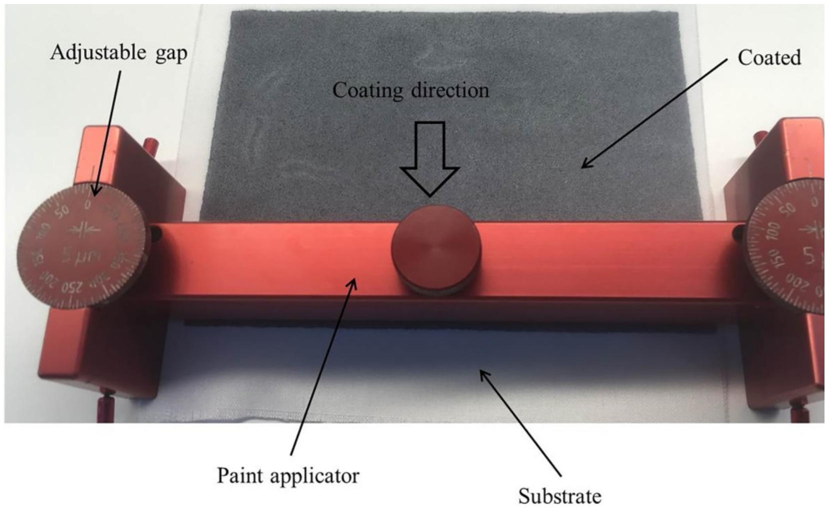


Figure 2.2 Coating applications

To investigate the sample's conductivity, Agilent 34401 multimeter was attached to a four-point probe resistance measurement principle to measure the surface resistance. Samples were put up for more than 18 hrs at standard room temperature (~22±5^{O}c; ~65±3 RH) before measurement. The measurement was taken both in the warp and in the weft directions. The average of the two was reported.

Nicolet iS10 FTIR spectrophotometer (Diamond ATR mode) was used to make an analysis of the spectra of the samples at a frequency range of 4000-500 cm^{-1} and a resolution of 4 cm^{-1}; the scanning was performed for 256 times. Two samples treated with EG using coating and immersion method were compared against the controlled sample.

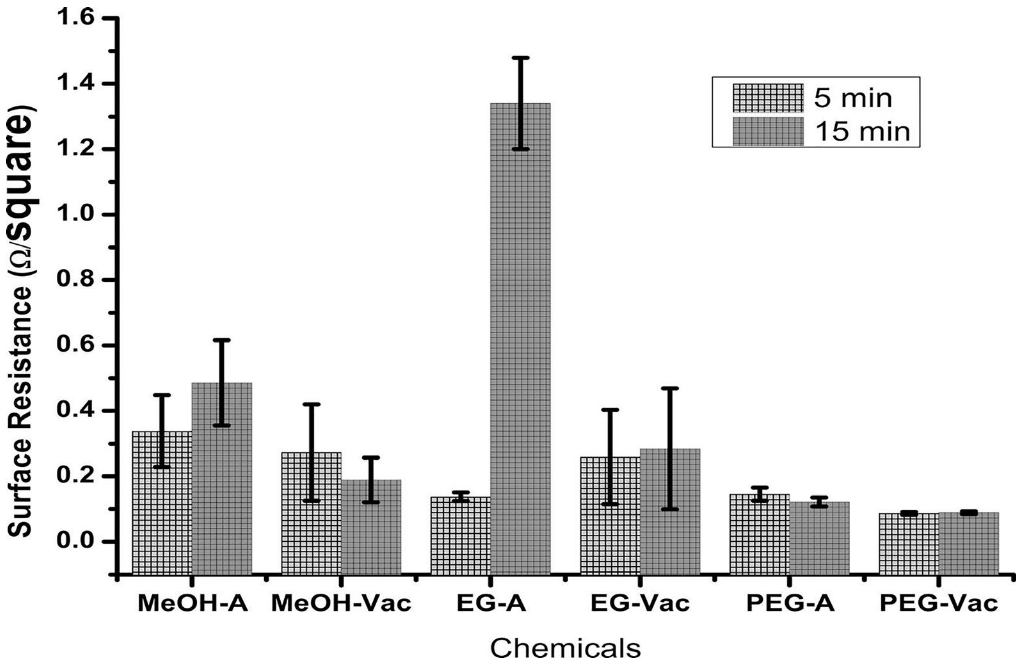
Sample images were taken using Leo Ultra 55 SEM armed with a field emission gun (LEO EMG, Germany) to perceive the PEDOT-PSS distribution at an acceleration voltage of 3 kV. Samples were cut by a razor blade after sputtered with gold.

The wettability study was performed utilizing Theta optical Tensiometer with a sessile drop technique. Contact angle measurement was determined at a drop size of 3000 μL and at 0.5 μL/s drop rate. Finally, environmental stability against washing was conducted with a domestic laundry washing and drying procedures of Type 3A (ISO 6330:2012). The test used 100% polyester ballast to washing.

2.1.3 Results and Discussion

Electrical properties: A simple EG, methanol, and PEG chemical treatment (immersion) was used to improve the conductive properties of the PEDOT-PSS-coated polyester fabrics. Electrical properties of the PEDOT-PSS-coated fabric treated with three various chemicals were analyzed by measurement of the surface resistance at room temperature under air and vacuum conditions.

Figure 2.1 displays the surface resistance of PEDOT-PSS-coated fabrics with variation of the treatment time, chemical type and treatment conditions. We chose ethylene glycol (EG), polyethylene glycol (PEG300) and methanol (MeOH) because they are the most widely used conductive enhancers and are environmentally friendly. The decrease in surface resistance of the PEDOT-PSS-treated fabric with EG, MeOH, and PEG might come from the reorientation of the PEDOT film which guide to better connection between the conducting PEDOT film chains. This interchain change causes the aggregation of PSS chains that itself reduces the active blocks between the PEDOT-PSS grains, and hence increases conductivity. The addition of conductive-enhancers brought the incomplete elimination of PSS anion and hence it encouraged to move to the outer surface of the PEDOT film. As a result the conductivity increases.



Note: Vac; refers vacuum, A; refers air

Figure 2.3 Surface resistance properties of fabric treated with various chemicals

As can be seen from the figure (Fig 2.3) The surface resistance values were decreased from 31.77 and 48.1 Ω/squares (values without conductive enhancers) to an average of 0.428 and 0.197 Ω/squares when the sample was treated under air and vacuum conditions, respectively with varying chemical type, treatment condition, and time. In addition, the surface resistance value reduced from an average of 1.34 to 0.138 Ω/squares with decreasing the treatment time when ethylene glycol was used as a conductivity enhancer at air conditions. This could be attributed to some experimental errors. Since the other conductivity enhancers did not show this much variation. Furthermore, the conductivity of the sample treated with PEG is much higher than ten orders of magnitude than that of methanol (MeOH) and EG. This could be ascribed to there is more number of hydroxyl ions in PEG than the other two conductive enhancers. As a result more number of hydrogen bonds might be formed between the PSS cation and hence high amount of PSS facilitated to move towards the surface of the PEDOT-PSS film. The surface resistance of the treated PEDOT-PSS-coated fabric is much lower than that of non-treated PEDOT-PSS-coated fabric due to the clear enhancement of the electrical conductivity of the chemically treated sample.

As was previously reported, treating PEDOT-PSS with organic liquids has brought increased in the conductivity of the polymer by partly eradicating the PSS ion from the surface of the film (Jikei et al., 2014). However, the treatment needs extra investment. To overcome this problem, we coated the fabric with PEDOT-PSS and then treated it with organic liquids with a very simple immersion technique.

***FTIR analysis*:** The sample treated with EG was selected randomly and analyzed with Fourier Transform Infrared (FTIR) under ambient conditions to observe the spectra of the samples. Figure 2.4 illustrates the difference in spectral formation when the PEDOT-PSS-coated fabric is immersed with EG, when EG is added before coating and the control fabric without EG.

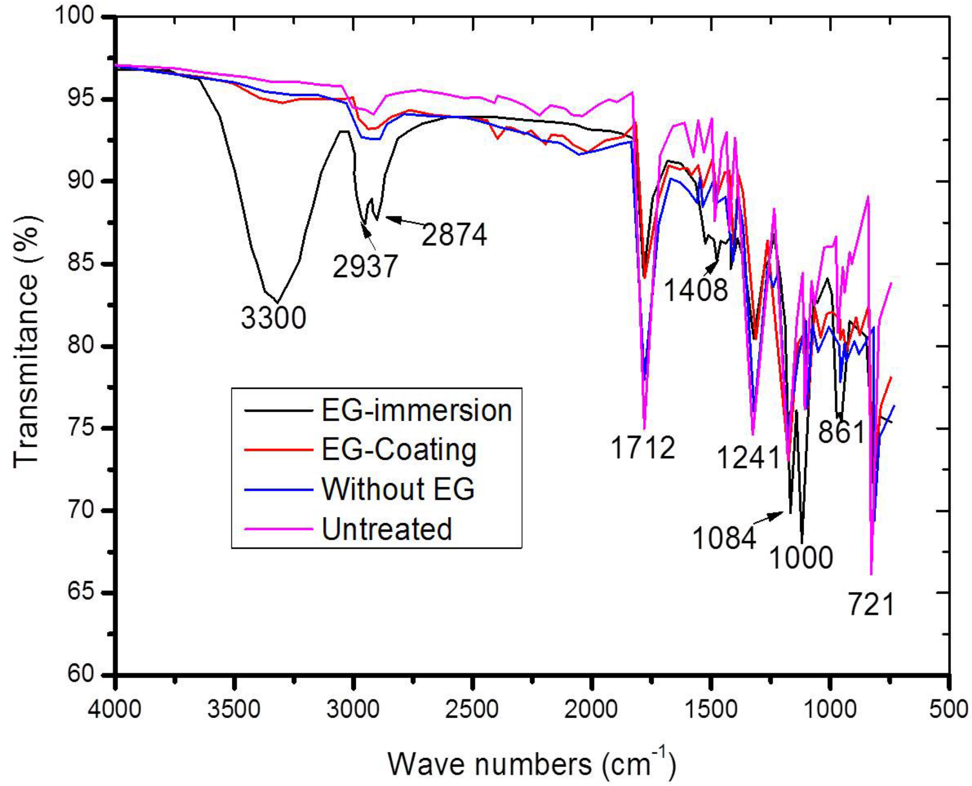


Figure 2.4 FTIR spectra of EG treated fabric (Tadesse et al., 2017)

Sharp peaks of 3300, 2937, 2874, and 1000 cm^{-1} were observed when the PEDOT-PSS-coated fabric was immersed with EG. Furthermore, decreasing in band intensity at 1712 cm^{-1} occurred. The extra bands created in the PEDOT-PSS and the decreased in band intensity of the polyester fabric occurred simultaneously. The reason for this could be that the addition of EG generated additional bands and the hydroxyl ion the EG produces a hydrogen bond along with the polystyrene sulfonic acid (PSSH) of the PEDOT-PSS so that partial reduction of PSS ion occurred. In addition, the OH ion in EG could form a hydrogen bond with the carbonyl group of the fabric so that band intensity reduced. FTIR spectra confirmed that the effectiveness of the immersion methods than that of the coating methods.

Surface morphology: Before SEM image observation, the specimen was sputtered with gold to protect the formation of surface charge in which the secondary electron information is unable to enter. Otherwise, the image view may be distorted both in signal level and image form. It is advisable to observe the differences in the surface morphology of the treated fabric using SEM.

Figure 2.5 ratify that the immersion methods produced more evenly distributed and uniform surface than the coating method. EG has inclined to reduce the surface tension of the PEDOT-PSS dispersion. This happened if we mix the EG before coating. This might resulted from the irregular distribution of the coating solution on the surface of the fabrics.

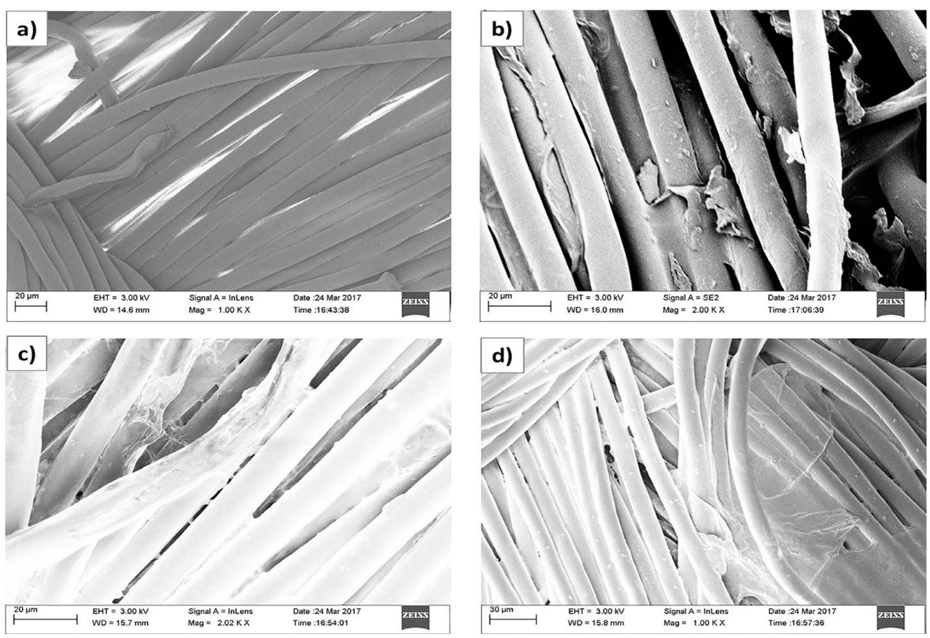


Figure 2.5 SEM images of the a) untreated b) coated and c-d) immersed with EG

The SEM image analysis shows that each individual yarn was coated with PEDOT-PSS in the situations when immersion method employed and coherently attached to the surface of the fabric. The PEDOT-PSS will remain attached to the fabric surface and can combat intensive washing. On the other hand, in the coated fabric, loosely attached PEDOT-PSS films were observed and these small particles might be voluntarily removed by washing from the coated fabric. It was noted that a smooth and evenly distributed embedding of the PEDOT-PSS could lead to an adequate performance of the conducting fabric materials. In the present study, comparison of coating and immersion with various additives was performed. As showed in the figure, the SEM images demonstrate that the immersion method produced uniform, smoother, continuous and denser than the coated samples. This could be ascribed to the strong interaction occurring between the textile materials and the PEDOT-PSS during immersion techniques.

Wettability study: Research in the area of coating indicates that wettability can be investigated by measuring the contact angles of the treated products (Farris et al., 2011). The ability of organic liquids to improve the surface wetting properties of the treated polyester fabric was studied by measuring the contact angles of the samples. The contact angle measurements resulted in is shown in Table 2.1. As showed in the table, the mean contact angle of the control fabric is ~50.98°. The contact angles of the treated samples are considered to be increased from the control fabric.

Table 2.1 Contact angle measurement results

Samples		Contact Angles			
		CA left [°]	CA right [°]	CA mean [°]	Volume [μl]
Control[1]	Mean	52.14	49.81	50.98	2.47
	Std	15.7	17.58	16.62	1.73
EG	Mean	81.42	81.44	81.43	1.44
	Std	15.32	15.49	15.38	0.49
PEG	Mean	83.04	82.73	82.90	1.99
	Std	6.97	6.37	6.34	0.38
MeOH	Mean	70.96	72.51	71.73	1.80
	Std	17.95	16.19	16.78	0.43

[1] Control fabric is PEDOT-PSS coated but not treated with organic liquids.

As showed in the table, the contact angles increased by 40.7, 59.7, and 62.6% when treated with methanol, ethylene glycol, and polyethylene glycol, respectively. This result confirmed that more hydrophobic surfaces of the fabric can be achieved when treated with conductive enhancers. Since, the hydrophilic part, PSS, was partially removed. Moreover, these results strengthens that the presence of more number of hydroxyl ions (in our case PEG has more number of hydroxyl ions), the more number of hydrogen bonds produced with PSS and hence more number of the hydrophilic PSS being detached from the surface. Since PSS is hydrophilic, as the hydrophilic part is removed the treated sample becomes more hydrophobic and hence contact angle becomes higher. In addition, PSS chain is partly removed from the surface of PEDOT-PSS film due to the presence of organic liquids, the coil structure has a tendency to change into a linear structure. Due to this reason, the increased interchain interaction occurred and hence became water resistant.

Washing stability studies: The washing stability of the treated fabric was studied at room temperature. From Figure 2.6 it is clear that the surface resistance of the untreated samples increases rapidly as the number washing cycle increased.

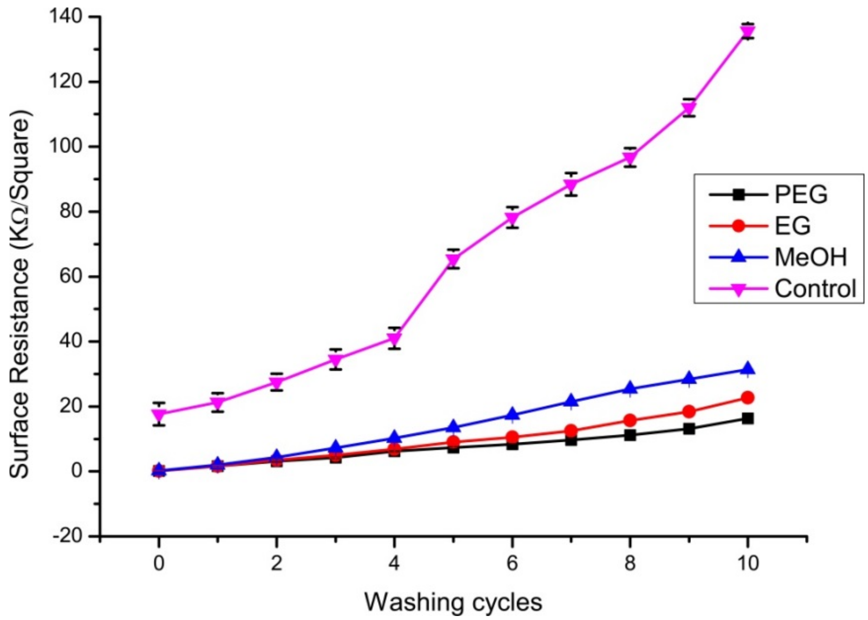


Figure 2.6 Washing stability of treated samples

Whereas, the increased in surface resistance in organic liquid treated samples showed only a little increase in the surface resistance value. The reason for this could be when the fabric is treated with organic liquids; the fabric became more hydrophobic as discussed above in wettability study section. Therefore, the penetration of water will be lowered. From this, we can conclude that when coated fabric was immersed with organic liquids, the washing stability can be improved.

Finally, the difference between coating and immersion techniques can be modelled as showed in Figure 2.7. As showed in the illustration, in the coating methods, the chemicals only appeared on one side of the fabric. On the immersion method, the chemicals are evenly distributed in both sides of the fabric as well on the inside structure of the fabric.

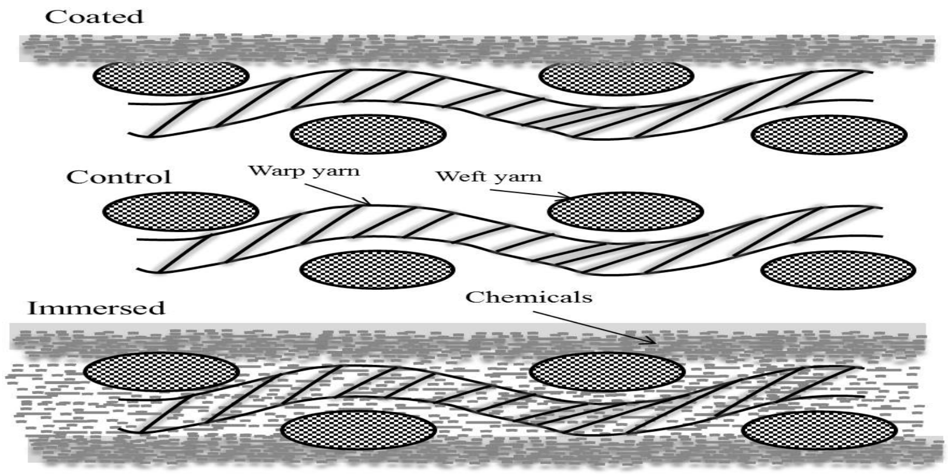


Figure 2.7 The illustrations showing the difference between coating and immersion

This indicates that immersion method is the excellent technique to diffuse the chemicals throughout the fabric structure. This enables the conductive fabric to withstand the environmental conditions such as stability against washing. This conductive sample can be served as sensors, actuators, connectors and other means to realize wireless smart and functional textiles. Simply put, smart and functional textile applications can be achieved by applying conductive polymers to textile substrates.

2.1.4 Conclusions

This chapter covers an interesting area in e-textiles, in which flexible and wearable e-textiles are developed apart from the traditional applications of e-textiles. The conductivity of PEDOT-PSS-coated polyester fabric is improved by the additions of conductivity enhancers. All characterization methods proved that it is possible to produce conductive e-textiles utilizing PEDOT-PSS conductive polymers using cost-effective coating methods. The conductivity of the PEDOT-PSS dispersion was highly enhanced by the addition of organic liquids. In addition several approaches used to confirm the attachment of the organic liquids in the PEDOT-PSS film such as FTIR. Furthermore, accompaniments of conductive enhancers like methanol, ethylene glycol, polyethylene glycol lead to the formation of more hydrophobic surfaces on the fabric, hence the wettability of the textile material reduced. Highly conductive fabric was acheived when PEG was applied and among the three conductive enhancers, PEG can be selected for the conductivity enhancing of PEDOT-PSS coated fabric. Washing stability of the PEDOT-PSS-coated fabrics indicates that this kind of conductive material can use for several applications even with wearable garments. In most commercially available smart and functional products, the role of conductive polymers is very predominant especially in diverse sensors, flexible displays, and other e-textiles. Therefore, addressing with such conductive polymers is permissible.

2.2 3D-Printing of Thermoplastic Polyurethane for Electroluminescence Applications

This chapter is based on the publication:

Tadesse MG, Dumitrescu D, Loghin C, Chen Y, Wang L, Nierstrasz V, 3D Printing of TPU Filament onto PEDOT: PSS-Coated Textile Fabrics for Electroluminescence Applications *Journal of Electronic Materials* 2018:47(3); 2082-2092.

2.2.1 Introduction

In recent times, researches are going on flexible e-textiles. Among these, electroluminescnce are one of them. Electroluminescence (EL) devices can be obtained using organic materials. This is because organic materials offer the opportunity to enable low-cost products (Sheats et al., 1996). However, most organic electroluminescence devices are not sufficiently flexible to incorporate into apparel products. The electroluminescence device can easily be integrated into textile products when the EL device is constructed from textile-based components.

Textile-based electroluminescence devices have been attracting a great attention in the past few decades due to their advantage of lightweight, mechanical flexibility, and ready to be integration with wearable textiles. This chapter is designed bring this idea to be a reliable prototype product.

In the present day, a wide-ranging materials have been examined for hopeful application in flexible and wearable electronics textiles such as polyaniline (Jin and Gong, 1996), polypyrrole (Sparavigna et al., 2010), and poly (3,4-ethylenedioxthythiophene)-poly(styrene sulfonate) PEDOT-PSS (Ding et al., 2010). Wearable electronics are subjected to various mechanical actions like bending, shearing, compression, and tension during wearing. This is because the arched shaped body parts (skin) and the clothing materials contact vigorously with during movement. Therefore, these mechanical loads should be taken into account when deigned for wearable applications. The rear electrode (anode) and the dielectric material are among the most significant constituents for the production of effective electroluminescence device to emit light. Organic polymers and indium-tin-oxide (ITO) (Akcelrud, 2003; Kido et al., 1995), and ceramics (barium titanate) (Perepichka and Perepichka, 2009) have been used widely for the making of cathode (rear electrode) and dielectric components of the electroluminescent device, respectively. However, ceramic materials and the ITO films are fragile and deteriorated when subjected to several mechanical actions and under tightness conditions. Presently, the stable and more flexible PEDOT-PSS has been studied for the possible replacement of the costly and brittle ITO film (Y.-H. Kim et al., 2006).

In this study, brittle and fragile ceramic materials were replaced by a more flexible material called TPU using 3D printing technology. We combined 3D-printing and the coating processes to produce an electroluminescence device which can easily integrate into wearable apparel. For this, TPU was printed on top of a PEDOT-PSS-coated polyester fabric using 3D printing technique which has been previously produced by coating applications. The PEDOT-PSS-coated fabric was invoked as rear electrode (anode). 3D-printed TPU served as a dielectric material, a 3D-printed BendLay filament used as translucent material on top to protect the short circuit. Copper fabric was sandwiched between the BendLay filament and emitter (phosphor blue paste) and served as the front electrode. A prototype electroluminescence device was then manufactured. The commercial name of the TPU used in this study was flexible NinjaFlex 3D printing filament.

2.2.2 Experimental

Materials: Plain woven polyester fabric (gsm: 159 g/m^2; average thickness: 0.3 mm; 30 ends/cm; 22 picks/cm) and cotton fabric (130 g/m^2; thickness: 0.29 mm; 30 ends/cm; 26 picks/cm) were used for a substrate for PEDOT-PSS coating. A PEDOT-PSS from Heraeus GmbH, Germany, 1.3% by weight) and a PSS to PEDOT ratio of 2:5 was used as a conducting polymer. The copper fabric plain knitted and having a dimeter of 0.1 mm and electrical resistivity of 2.5Ω/m was used as a front electrode. Gel L75N from Borchers GmbH, Germany, with solid amount of 48% was used as a rheology modifier. Ethylene glycol (EG) (Sigma Aldrich) with 99.8% concentration was invoked as a conductivity enhancer. All chemicals were used as received.

A flexible TPU from Creative Tools (diameter: 1.75 mm; specific gravity: 1.19 g/cc; elongation at break: 660%) was used for the production of dielectric material using a WANHAO 3D printer machine. ZEHNTNER ZUA 2000, a universal paint applicator, was utilized as an application of PEDOT-PSS and phosphor blue paste coating. Universal tensile testing machine and Shirley stiffness testing machine for analyzing the bending nature of the samples were used for the testing of adhesion and stiffness of the 3D-printed TPU filament on polyester and cotton fabric, respectively. Phosphor blue paste (Gwent Group with a viscosity of: 0.86-2.50 Pa.s at 25°C; 80-82.5% solid content at 150°C) was used as an emitter material.

Methods

Binder with 6%; a conductive enhancer with 5%; and PEDOT-PSS with a range of 0-90% concentrations was vigorously mixed using overhead mechanical stirrer at 600 rpm until the solution became homogenous with the naked eye. The concentration of the rheology modifier was adjusted to compensate for the concertation of the PEDOT-PSS when varied. Then, coating was made using a coating applicator at a gap depth of

200 μm with 10x10 cm; the samples were dried at 100°C for 30 min and cured for 150°C for 5 min. Electrical conductivity was measured using a four-probe surface resistance measurement principles using Van der Pauw method. A constant reading of surface resistance was acheived after using 2 Kg dead weight on top of the four probe instrument.

Before applying TPU as a dielectric material, it is necessary to observe the thermal stability of the materials. Thus, thermal stability obtained using thermobalance TGA (Q500-1763) ramp at 20-600°C at a rate of 20°C/min heated under nitrogen.

First, 3D scaffolds were designed using rhinoceros CAD software and then transferred using stereolithographic format (stl) and uploaded. Print parameters such as infill percentage (100%), printing speed (800 mm/min), printing temperature, and sample size were adjusted based on the properties of the filament. Finally, 3D printing of TPU was performed on top of the coated fabrics with 5 cm x 5 cm x 0.1 mm sample sizes. Printings were made at 230°C and 30°C extrusion and build plate temperatures, respectively.

After 3D printing of TPU, the phosphor blue paste was coated with a coating applicator machine manually at a gap height of 50 μm after it was mechanically stirred at an rpm of 600 for 5 hrs. Then, curing was performed at 130°C for 15 min.

BendLay filament was 3D-printed with the same procedure to that of TPU where a copper fabric sandwiched between BendLay filament and phosphor blue paste.

The bending ability of the 3D-printed TPU filament on top of the polyester and cotton fabric as well as the total electroluminescence device were obtained using Shirley stiffness bending length tester according to ASTM D1388-2007 and BSI BS 3356-1991(AMD 6337).

The adhesion strength of 3D-printed TPU with textile fabrics as well as the BendLay filament with the phosphor blue paste was obtained using a T-peel test machine according to SS-EN ISO 11339:2010 and a grab test (ASTM D5034) with a load cell of 5 kN.

Then, the electroluminescence device was fabricated with Rear electrode → Dielectric → Emitter → Front electrode sort order. Before testing the EL device, BendLay filament was 3D- printed top of the device to avoid short circuit and to safeguard sufficient interaction with the phosphor paste. Lastly, alternating current (AC) was applied using power supply (-S-350-12) of 12 V and 29 Ampere input at 50-60 Hz. The emission was observed at a dark environment to detect clearly the emitted light and to protect the backgrounding light.

2.2.3 Results and Discussion

The electrical conductivity and surface morphology of the PEDOT-PSS-coated fabric, the adhesion strength, the rigidity of the 3D-printed TPU and the thermal stability of TPU filament were measured to evaluate the performance of the EL components for the production of flexible electroluminescence device. The electroluminescent device was designed, developed, and demonstrated in dark environment. Permissible light emission observed during the demonstration of the device. The device enables to easily bend without running out of its properties.

Figure 2.8 presents the dependence of the electrical conductivity of the PEDOT-PSS-coated fabric on the concentration of PEDOT-PSS. As it is expected, the surface resistance shows a large variation up to 60% concentration of PEDOT-PSS and then nearly parallel value when the PEDOT-PSS concentration increasing. This could be ascribed to the increase in the conductive PEDOT dispersions.

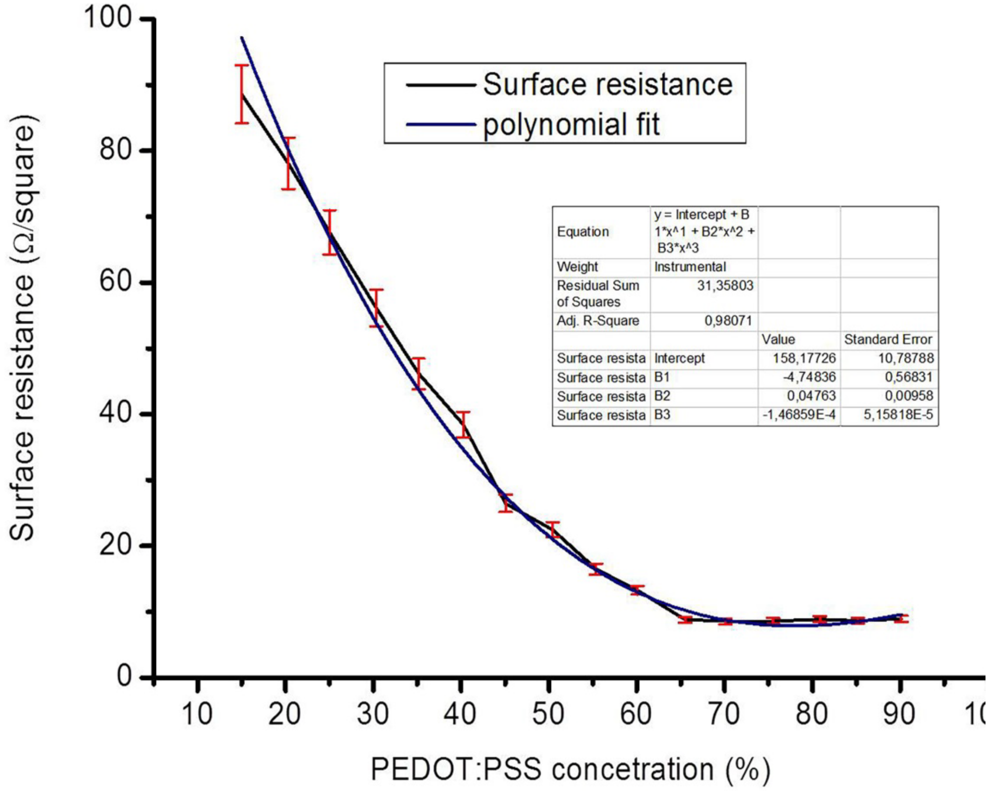


Figure 2.8 The surface resistance of PEDOT-PSS-coated fabric

Due to the dried weight of the dispersions, the weight of the fabric increased about ≈ 4.5%. Amongst the two fabrics, polyester and cotton, polyester fabric was chosen for the electroluminescence application. The reason for this selection is explained by the fact that polyester is more hydrophobic and hence the environmental resistance is higher than that of cotton fabric. The resulting coated fabric had an average surface resistance of 27.8 Ω/squares. This conductivity on the other hand enhanced was caused by the addition of ethylene glycol. Ethylene glycol leads to the partial reduction of the insulator PSS ion by forming a hydrogen bond with PEDOT cation. Furthermore, when PSS anion is moderately removed from The PDOT film, the film becomes parallel (the amorphous structure becomes crystal structure due to the addition of conductive enhancers) and hence the connectivity between the films improved. This also leads to further increase the conductivity of the coated fabric.

Thermogravimetric analysis (TGA) was carried out to investigate the thermal stability of the TPU filament where the mass of the filament was measured against the changes in temperature. During this temperature transition, the amount and rate of weight loss observed and hence primarily determine the composition of the filament and to predict the thermal stability at up to a certain temperature. Figure 2.7 illustrates the thermogravimetric analysis of polyurethane (TPU) filament.

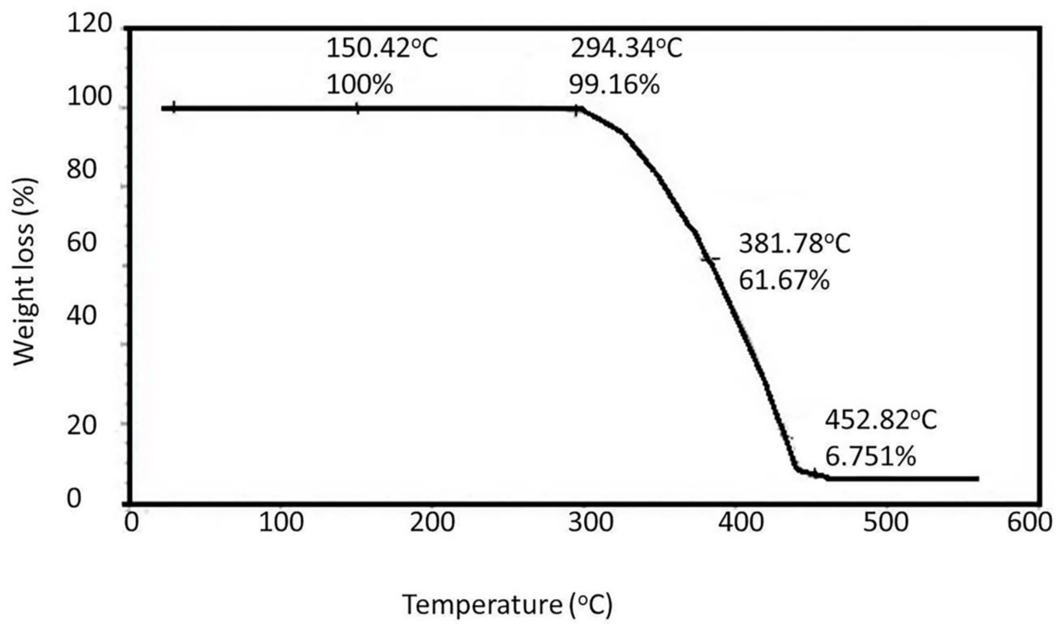


Figure 2.9 The thermogravimetric analysis of TPU filament

From this figure (Tadesse et al., 2018), we can point out that no weight loss observed up to 150°C. The initial weight loss occurred at 294°C is due to the start of decomposition and melting. The decomposing and the melting of the filament continue and a maximum weight loss noted at 452°C. Therefore, the onset of degradation of the TPU filament was at 382°C, where the loss in weight was ≈ 38.33%.

After 452ºC, no weight loss observed, this could be the weight of the final residue of the polymer like ashes. The result indicates that the TPU polymer can serve as dielectric material up to thermal stability up to 150ºC.

After executing the 3D-printing TPU on polyester and cotton fabrics, bending lengths of the samples were measured using Shirley stiffness bending tester equipment. The 3D printing was performed at 100% infill percentage and 800 mm/min printing speed; with variable thickness of 0.1, 0.2, and 0.3 mm; 5 cm width and 20 cm long samples were produced. In addition to the single 3D-printed TPU, the rigidity of the entire device including PEDOT-PSS-coated fabric, 3D-prinited TPU, phosphor paste, copper fabric and 3D-printed BendLay filament was tested. Figure 2.8 shows the bending length measurement results. The higher the bending length is, the higher the stiffness of the fabric. This indicates that the sample flexibility is low and the drapability could be affected. We compared with the original fabric sample to that of the 3D printed TPU and EL device.

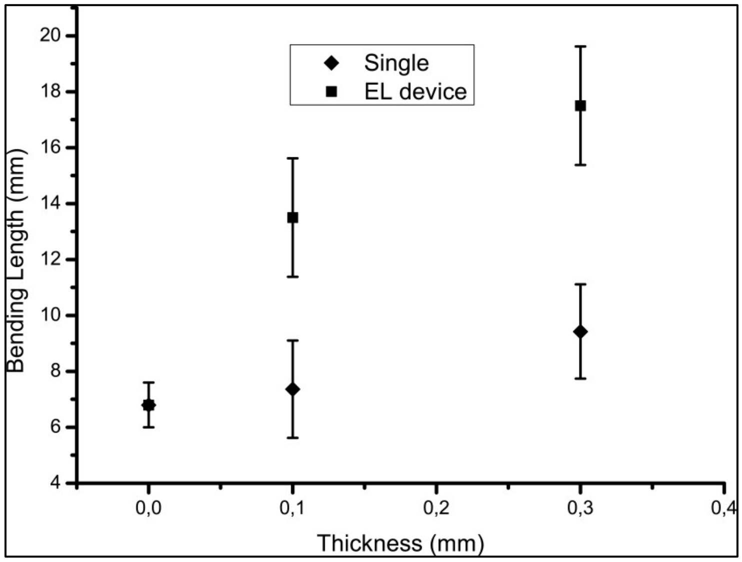


Figure 2.10 The bending length of the single TPU and the whole EL device

The flexibility of a wearable material is a very important character which restricts and decides its application in wearable clothing. Wearables with high bending length are stiffer; they lack good drape and flexibility. As can be seen from the above figure, the single TPU as well as the whole electroluminescence device is sufficiently flexible enough that it can be harmonized into the wearable apparel. This leads to the EL device can be used as decorating the fashionable dress during the night entertainment or any wearable garments.

Adhesion is of great important for the fabrication of the electroluminescence device at the point where 3D printing forms the attachment. Otherwise, the durability would put into questions. The durability and longevity of the 3D-printed film is largely dependent upon their adhesion to the substrate since this determines the ease of removal. The adhesion strength of the 3D-printed TPU was performed using T-peel test with the set up as illustrated in Figure 2.9.

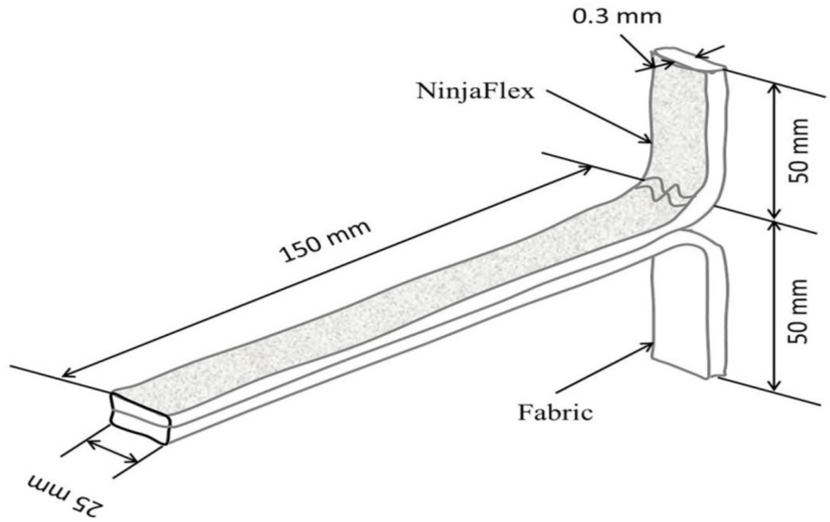


Figure 2.11 T-peel test of the 3D-printed thermoplastic polyurethane

The average maximum force (F) required to peel the TPU from polyester fabric was 13±4.4 N based on standard SS-EN ISO 11339-2010 at 0.3 mm 3D printing thickness of TPU. Polyester fabric was selected for the study due to its hydrophobic nature. This strength is quite sufficient for the fabrication of the electroluminescence device. So, for wearable devices the range could be acceptable since there no such strong forces that led to detach such kinds of strength.

The electroluminescence device was designed and developed as showed in Figure 2.10. An AC voltage of 12 V was supplied between the rear electrode (PEDOT-PSS-coated fabric) and the opposite electrode (copper fabric); a blue light emission observed during the dark environment.

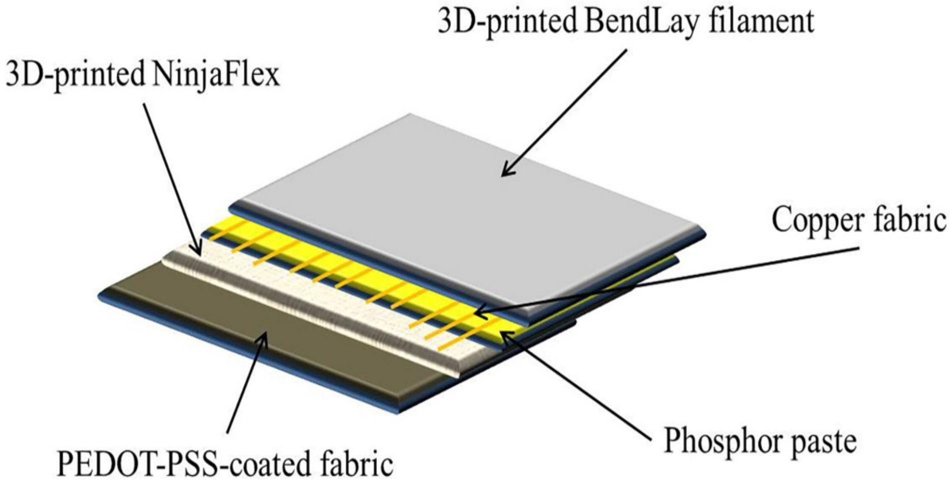


Figure 2.12 The electroluminescence device fabrication procedures

A simple bending test was carried out to see if it has an effect on light emission and if a cracking happens. The result confirmed that bending did not crack too much of the sample as well as has no effect on the blue light emission. Even though light emission achieved, the emitted light has a discontinuity and this should be improved in future research. This problem could be attributed to the minimal contact area between the phosphor paste and the copper fabric and the fabric should be tightly woven instead of knitted. Moreover, the insulator BendLay filament reduced the conductivity of the copper fabric. Other alternatives should be devised to replace the insulator BendLay filament. The actual prototype is shown in Figure 2.11.

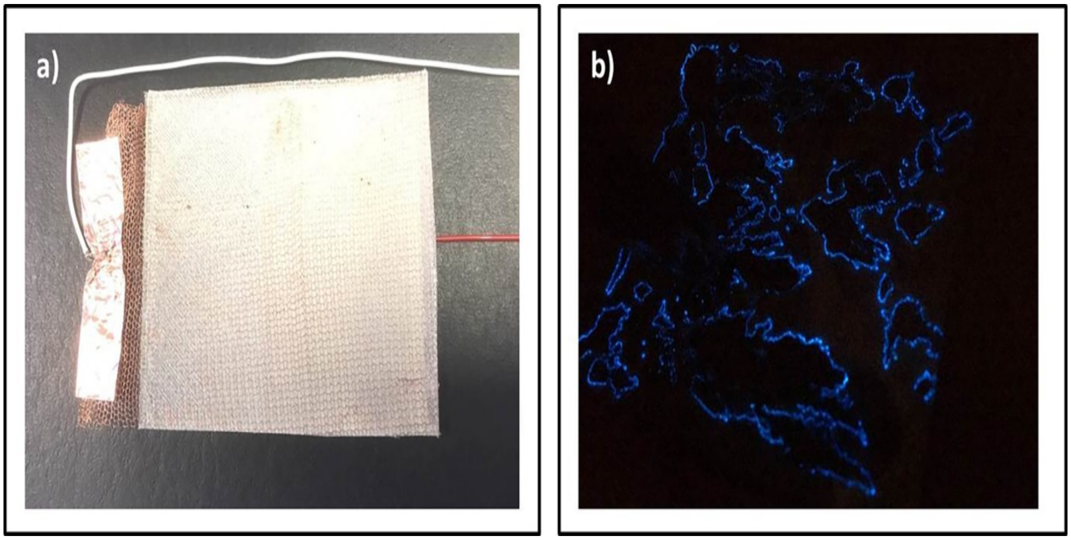


Figure 2.13 The EL device components a) prototype of EL device and b) EL emission

This work proposes a workable method of electroluminescence device design and fabrication with low cost and simple manufacturing principle. This will lead researchers to further investigate this kind of construction and improve the efficiency of the device. This electroluminescence device could provide a varied selection of claims such as in entertainment and nightlife industries or advertising; as decorative luminescence clothing and other light emitting devices.

2.2.4 Conclusions

Coating accompanying with 3D printing can be examined a promising approach for producing flexible-lightweight electroluminescence devices based on textile-based materials. Fabrications of the electroluminescence device resulted in an excellent with the maximum peeling force of 8.25 ±1.5 N. The bending test also confirmed that the sample exhibits the best flexibility when bent with relative bending length increases of 1.03 and 1.39 at 0.1 and 0.3 mm thickness of the 3D-printed TPU. The electroluminescence device emitted light at 12 V in the dark environment. This kind of construction can be taken to an alternative way of fabricating the simple and the cost-effective electroluminescence device.

To conclude, we reviewed the contemporary breakthrough of flexible and lightweight electroluminescence devices that provide cost-effective resolutions for the 3rd generation of flexible display applications. We applied the most operative way of assemblies of the electroluminescent devices that allow to use cost-effective and simple production methods with completely new materials and technologies compared that has been used recently. Our prototype with parameter optimization can provide an electroluminescent emission with straightforward techniques.

2.3 Characterization and Application of Conductive Knitted Fabrics

This chapter is based on the publication:
M. G. Tadesse, A. Desalegn, M. Christian, Y. Chen, L. Wang, V. Nierstrasz and C. Loghin,
Conductive elastic PA/Lycra knitted fabric treated with PEDOT-PSS for e-textiles (IOP Conf. Series: *Mater. Sci. Eng.*, 254 (2017) 072025 doi: 10, 1088/1757-899X/254/7/072025)

2.3.1 Introduction

E-textiles need to be flexible, comfortable, soft, lightweight, breathable, stretchable, robust, and washable (Tao, 2005). That is why the modern-day researchers have focused on making materials that have these above-mentioned properties for e-textile applications to fill all the different interests to build future e-textile scaffolds. For this, electromechanical property characterization could be one means.

The very quick development of the electronics industries, flexible and lightweight conducting wearable electronics are receiving widespread consideration. They play an important part in realizing flexible, durable, lightweight, and wearable e-textiles. Electro-mechanical properties have become progressively vital and extensively used in describing these wearable e-textiles. Applications such as flexible electronic displays (Cairns and Crawford, 2005) and conductive stretchable materials (Lipomi et al., 2012) necessity to have the malleable behavior. There are a lot of inherently conductive polymers (ICPs) that stretched fresh consideration on this context. Amongst these polymers poly (3, 4-ethylenedioxythiophene): poly (styrene-sulfonate) (PEDOT-PSS) is one of the best potential polymers due to its excellent electromechanical properties and mainly applied in many applications such as in chemical sensors and biosensors (Lange et al., 2008). These Properties must be completely understood for e-textile applications, such as sensing, transferring, and actuating data. From these electromechanical properties, stretchability and flexibility gain considerable attention in recent times in an e-textile application. Berendjchi et al. and Xue et al. have developed a flexible and conductive textile materials using polypyrrole polymer (Berendjchi et al., 2016; Xue and Tao, 2005). More efforts have been accomplished to create stretchable e-textiles such as interconnects using thin gold film on elastomeric membranes (Lacour et al., 2005), conductive PEDOT-PSS on stretchable poly-(dimethylsiloxane) (PDMS) substrate. However, the conductivity decreases hastily as the strain put on it. Silver-coated conductive yarn prepared into an e-textile using knitting operations and the resistance has been tested against stretching (Li et al., 2009) and obtained promising result.

Similarly, various struggles have been taken to advance strain sensitivity and flexibility of electronic materials. Among these, integrating textile materials with an electronic application such as coating nylon-lycra fabric with polypyrrole (PPy) for stretchable supercapacitor (Yue et al., 2012), wearable biomechanical sensors (Wu et al., 2005), flexible strain sensor (Li et al., 2005), and force, breath, and movement sensor (Guo and Berglin, 2009) applications. However, PPy has imperfect real-world claims due to absence of mechanical properties and poor processability (Xue and Tao, 2005). An attempt has been done to overcome these aforementioned difficulties using PEDOT-PSS. PEDOT-PSS has been used for various applications such as transport electrode, anti-static painting, solid state capacitors, and electrode buffer layer materials (Skotheim, 1997).

Wearable electronics demand systems that are worn on bowed human body that has many covered with highly extensible skin. Textile-based wearable e-textile systems hold great promise in this regard. In addition to the flexible nature of textile structures, flexibility can also be enhanced and/or maintained using various additives during the development of e-textiles. Among these methods using highly elastic polyurethane dispersions is part of them. Polyurethane dispersions have been shown to be used along with PEDOT-PSS for stress-strain responsive applications (Seyedin et al., 2014).

In the field of thermoelectrics, materials have complex nature, which is the substantial limitation of generated compounds that have manifold functions. Moreover, creating flexible, stretchable, and lightweight thermoelectric materials is not achieved yet as to our knowledge. For this reason, ICPs could offer a remarkably effective alternative provided their high electrical conductivity in doped/enhanced state, low thermal conductivity and Seebeck coefficient. Seebeck coefficient is a property of a material is a measure of the magnitude of an induced thermolectric voltage in response to temperature difference and vice versa (Iwanaga et al., 2011). Numerous electrical conducting polymers have tested as conceivably suitable materials for thermoelectric application. Among these polymers, PEDOT-PSS (Zhang et al., 2010), polyaniline(PANI) (Yakuphanoglu and Şenkal, 2007), polythiophene (PTH) (Ao et al., 2011), polypyrrole (PPY) (Maddison et al., 1988), and many others have been investigated and tested to produce lightweight and stretchy thermoelectric materials. More consideration has been given for PEDOT-PSS due to its electrical conductivity and stability. Moreover, a lot of efforts have been done to improve the thermoelectric property of PEDOT-PSS using various means and show a lot of possibilities such as polymer/inorganics bulk composites (Wei et al., 2015), treating it with N,N-Dimethylformamide (DMF) and zinc chloride ($ZnCl_2$) (Fan et al., 2016), treating PEDOT-PSS with ethylene glycol, polyethylene glycol, methanol and formic acid (Mengistie et al., 2014), post-treatment of PEDOT-PSS with dimethyl sulfoxide (DMSO) and ionic liquid (Luo et al., 2013), and treating PEDOT-PSS and tellurium-PEDOT-PSS hybrid composites with sulphuric acid and other organic and inorganic liquid pre- and post-treatments to enhance the conductivity.

A dimensionless figure of merit (ZT) is defined as a signal of the performance of thermoelectric materials, $ZT=S^2\sigma T/\kappa$, where S($V\ K^{-1}$) is Seebeck coefficient or thermopower, σ ($S\ m^{-1}$) is electrical conductivity, κ ($W\ m^{-1}\ K^{-1}$) is thermal conductivity and T is absolute temperature (Zhang et al., 2014). The challenging case here is when we increase the electrical conductivity, the thermal conductivity will increase according to the Wiedermann-Franz law (Hendricks and Choate, 2006). Therefore, for most thermoelectric materials higher electrical conductivity tend to have higher thermal conductivity. However, distinct from the inorganic thermoelectric materials, PEDOT-PSS has little effect on its thermal conductivity and Seebeck coefficient. Therefore, emphases can be given for improving the power factor ($PF=S^2\sigma$ in $Wm^{-1} K^{-2}$ (Zhang et al., 2014)) in order to enhance its thermoelectric efficiency. PEDOT-PSS was selected for our work due to its low thermal conductivity, good thermal and environmental stability, and other promising properties such as lightweight and flexible (Zhu et al., 2016).

In this study, we encompass the use of PEDOT-PSS polymer with polyamide-lycra knitted fabrics and using immersion and coating techniques, and studied the electrical properties and its sensitivity to strain and cyclic strain, washing stability and finally, tested as thermoelectric applications. To the best of our knowledge, there are no reports on thermoelectric applications of polyamide-lycra coated or immersed fabrics with PEDOT-PSS using polyurethane-based dispersions.

2.3.2 Experimental Section

Materials

Plain knitted nylon/lycra fabric with 78/44 Dtex; 0.41 mm thickness was used for immersing and coating using PEDOT-PSS with a concentration of 1.3% by weight from Heraeus, GmbH, Germany. Dimethyl sulfoxide (99.8%) (Sigma-Aldrich) and water-based polyurethane dispersions such as U3251 (20 - 200 mPas), U4101 (50 - 750 mPas), U2101 (600 – 1400 cps) (Alberdingk Boley), were used as conductive enhancer and binder, respectively. In order to improve the rheology, in the case of coating application, we hired Gel L75N (48% by weight); hydrophobically modified ethoxylated urethane as a rheology modifier (Borchers GmbH, Germany). All chemicals were utilized as received without further alterations.

Methods

Coating and immersion

The coating and the immersing nylon/lycra fabrics in an aqueous dispersion of PEDOT-PSS, water-based polyurethane dispersion binders, and rheology modifier (for coating only) followed by drying at 90°C for 30 min and proceeded by curing at 130°C for 5 min, conductive PEDOT:PSS-coated and immersed fabrics were prepared.

Surface resistance

The electrical surface resistance was investigated via an in-house designed four-point probe scheme linked to a multimeter (Agilent 3401A) using the Van der Pauw principle. The measurements were taken both in the wale and in the course directions for three times, and the averages were reported.

Electromechanical measurement

Tensile stretching to break and cyclic stretching at 100% stretching were conducted using an Instron Tensile Tester (model 5565A) equipped with a computer interface used for data acquisition in strain tests at a cross-head speed of 10 mm min^{-1}. The measurements were taken in the wale directions only (we chose to characterize only in the coating directions). The change in electrical resistance in every two minute was recognized by connecting the sample with KEYSIGHT U1233B digital multimeter. Furthermore, during the cyclic stretching using universal tensile testing machine, the change in electrical resistance was plotted by connecting into software called Handheld Meter Software. The substrate size was 20* 6* 0.41 mm (length x width x thickness).

SEM characterization

The sample images were taken with a Leo Ultra 55 SEM equipped with a field emission gun (LEO Electron Microscopy Group, Germany) and a secondary electron detector. The acceleration voltage was 3 kV. Specimens were cut by a blade and sputtered with gold.

Seebeck coefficient

PEDOT-PSS-immersed polyamide/lycra fabrics were cut into pieces before conducting the test. The Seebeck coefficient of films ~1.5 mm x 5 mm (mounted on the holder with silver paint) was measured at 300 K with an SB1000 instrument equipped with a K2000 temperature controller from MMR Technologies using low impedance 1000 gain board and a constantan wire as an internal reference. Each sample was measured five times and the average taken.

Washing stability

Home laundry washing and drying procedures of Type 3A situation washing for textile (ISO 6330:2012); these procedures were performed to observe the durability of the conductivity of immersed and coated samples to washing with 100% polyester ballast when exposed to washing procedure. Water supplying, washing, and repeated rinsing are predetermined on the wash machine.

2.3.3 Results and discussion

One of the most vigorous parameters in e-textiles is conductivity, which affect the performance of e-textiles. Since pristine PEDOT-PSS film has low conductivity, we used DMSO as a conductive enhancer in this work. We used polyurethane dispersion as a binder to enhance the performance of e-textiles under stress-strain conditions.

In order to decide the best way of introducing conductivity to the polyamide/lycra knitted fabric, first the physical appearance of the coating and immersion methods were taken by a professional camera and the result is illustrated in Figure 2.12.

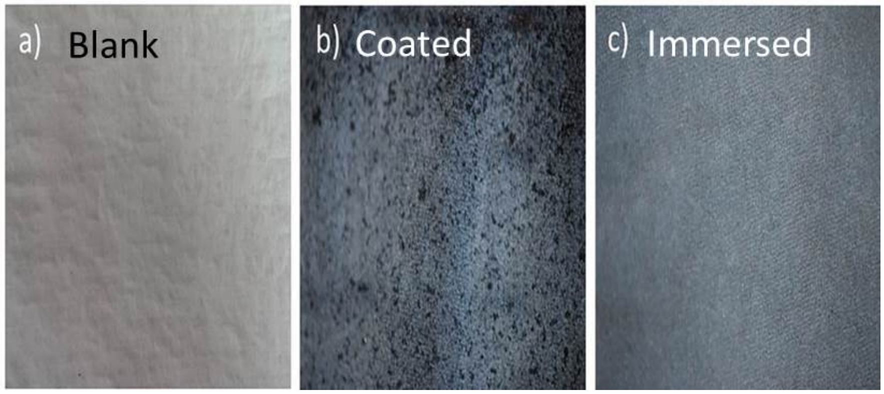


Figure 2.14 Simple surface appearances of samples

As showed in the figure, there is a clear difference between the two methods. In the case of coating method, the PEDOT-PSS dispersion is disproportionately distributed and hence might bring a conductivity disparity on the sample. We can see the back spots on the surface. The manual coating was not able to diffuse the coating solutions onto the surface of the fabric. Furthermore, the conductive film is not properly attached into the fabric structure even a rough surface is shown physically. This causes straightforwardly removal of the conducting material during vigorous washing. On the other hand, the immersion method produced a smooth surface appearance and consistently dispersed conducting material. PEDOT-PSS was successfully coated into each individual yarn and inside the fabric structure. The errors established in coating method eliminated during this method.

The surface characteristics of the sample fabrics were examined using scanning electron micrograph (SEM), and the SEM images exhibited that PEDOT-PSS is merged well into the structure in the immersion method whereas in the coating it mainly exists on the surface of the fabric in both longitudinal (Figure 2.13) and cross-sectional (Figure 2.16) views.

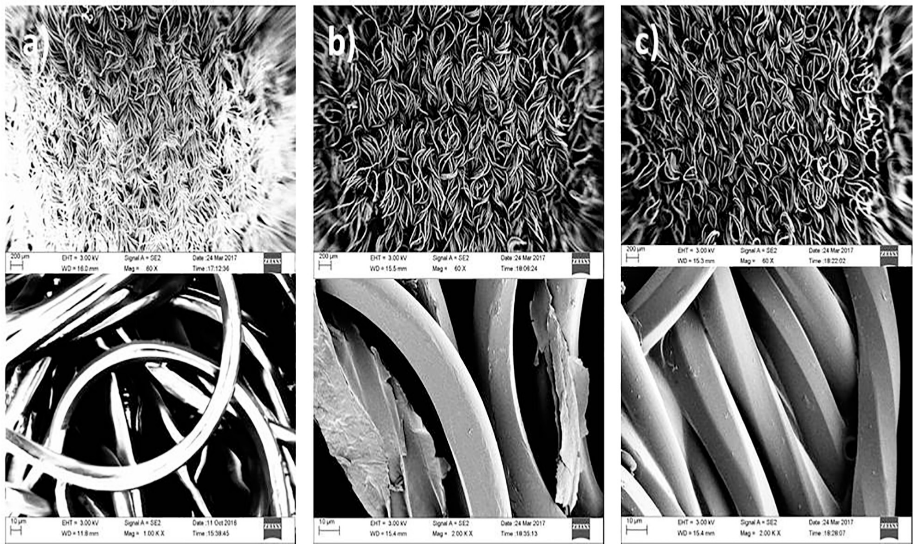


Figure 2.15 SEM images of a) unprocessed b) coated and c) immersed samples

The insecurely attached spots of dispersion in the coated sample are easily exposed to any mechanical action during use or can be readily removed during washing of the wearable e-textiles. From Fig.2.14, we can observe little spots on the cross sections on the surface of coated sample. While smooth appearance can seem on the immersed sample. In the immersed sample, we did not apply rheology modifier. This may be one of the reasons why spots are not observed.

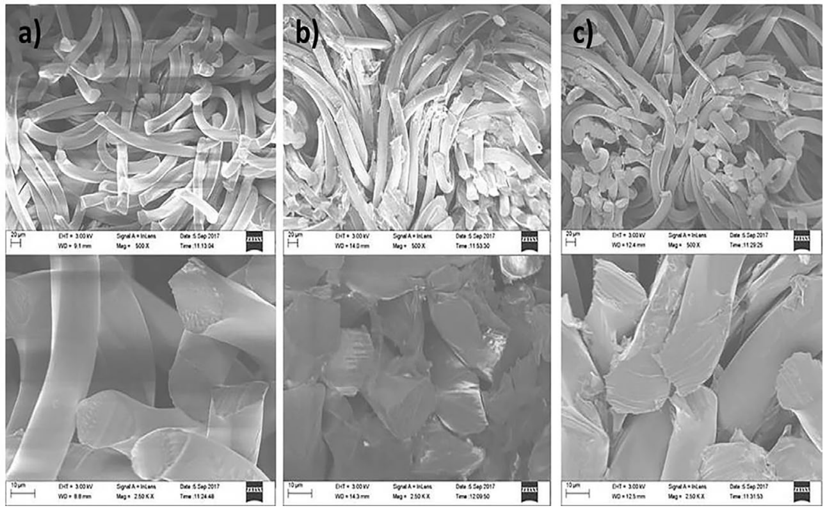


Figure 2.16 The SEM images of a) untreated b) coated and c) immersed samples

These crowds of PEDOT-PSS and PU dispersion into the fabric surface throughout immersion method to mark the conductive surface resistive to vigorous washing actions which indicate their robust binding to the PEDOT-PSS-coated layer. For this reason, low surface resistance was found in the immersed samples. The conceivable reason could be the conductivity requires an unceasing and an even and continue conductive network.

In order to evaluate the influence of the binder and the PEDOT-PSS concentration on the electrical conductivity, coating and immersion formulations were prepared with various concentrations of binder and PEDOT-PSS; the surface resistances of cured and conditioned coatings and immersions were measured. Coating and immersion formulations comprise of 0 wt% up to 90 wt% binders based on the solid weight of the binder and PEDOT-PSS. These formulations were utilized to apply both coatings and immersions. Furthermore, in coatings, additional rheology modifier was used only for thickening purpose. The surface resistance was measured directly on the immersed and coated samples with a four-probe surface resistance measurement principle in the most basic scheme called Van der Pauw method. The electrical property results obtained using coating and immersion methods are illustrated in Figure 2.17.

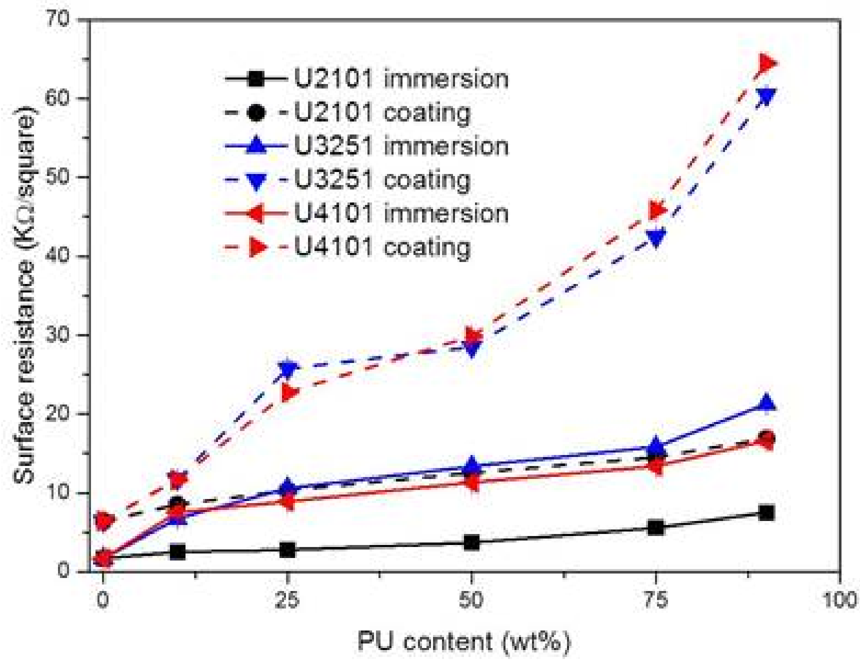


Figure 2.17 Surface resistance values at varied concentrations of polyurethane (PU).

As illustrated in the figure, it is clear that as the concentration of PU dispersion rises, the surface resistance values upturns in a similar way. It is primarily due to the insulator nature of the PU dispersions. The result clearly showed that immersion gave better results than the coating in terms of electrical conductivity. This may be caused by eventual distribution of chemicals towards the surface of the fabric during immersion. This means in the immersion cases, the PEDOT-PSS dispersions were absorbed and diffused into the yarn and in the inner structure of the fabric; giving a very highly even distribution of the conductive polymers hence lowering the surface resistance of the entire fabric.

From the figure, we can observe that the lowest surface resistance value was recorded when U2101 binder is used. Therefore, for the next experiments we study the effect of the U2101 binder on other properties of the treated fabric. The reason could be since U2101 is free of alkyl phenol ethoxylates (APEO) which is considered to be very toxic to aquatic life. On the other hand, samples treated with U2101 binder had excellent conductivity when compared to others (APEO is non-ionic surfactants with an emulsifying and dispersing action).

The durability against washing using numerous concentrations of PU dispersal in immersion procedures tested, and the result confirmed that the samples were still rationally conductive after 10 washing cycles and the result is depicted in Figure 2.18.

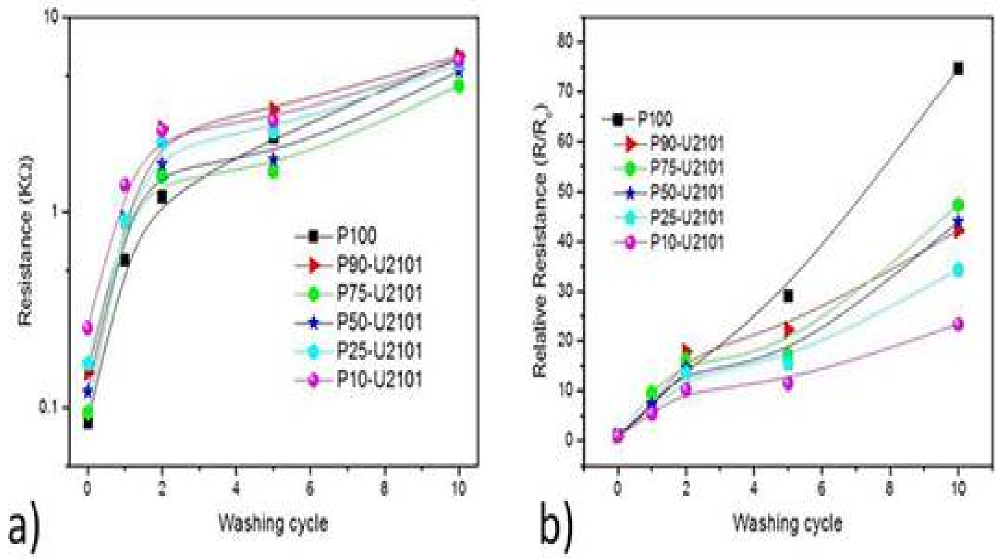


Figure 2.18 Washing stability of treated samples

In Figure 2.16a, it is shown that at zero binder concentration by weight %(P100), the resistance value is relatively higher at the beginning and alarmingly increases when washing cycle increases. This is very likely due to the absence of the binder. On the other hand, at the very high concentration of binder (P10), initially the resistance increase for the first three washing cycles and remains constant for the rest of the washing cycles.

In Figure 2.18b, relative resistance (R/Ro) at zero binder concentration (P100) rapidly increases as the washing cycle increases. However, at high binder concentration (P10), the increase in the relative resistance was trifling. The ostensible reason for this could be binder increased the stability of PEDOT-PSS on the fabric surface.

Fabric structure is always exposed to tension, compression, bending, and shearing actions during application. It is observable that during these actions there is always a ruin of conductive networks. Hence, conductivity deceases. Therefore, it is extremely important to recognize the effluence of these mechanical actions on the electrical conductivity of the samples. In addition, the difference of the two methods, coating and immersion, can be depicted. Figure 2.17 illustrates the influence of cyclic stretching on the electrical resistance of the coated and immersed samples for 10 stretching cycles at 100% stretching. After the first stretching cycle, the increase in resistance values while stretching was insignificant (Figure 2.19). The fabric showed hysteresis of about 17% strain after the first stretching cycle which remained stable thereafter. However at P100 coating in the increase in relative resistance (resistance at the end of each cycle divided by the initial resistance-R/Ro) is still high. This could be attributed to the high content of binder cracked easily. The ability of the binder to diffuse into the fabric structure is less than that of the PEDOT-PSS polymer.

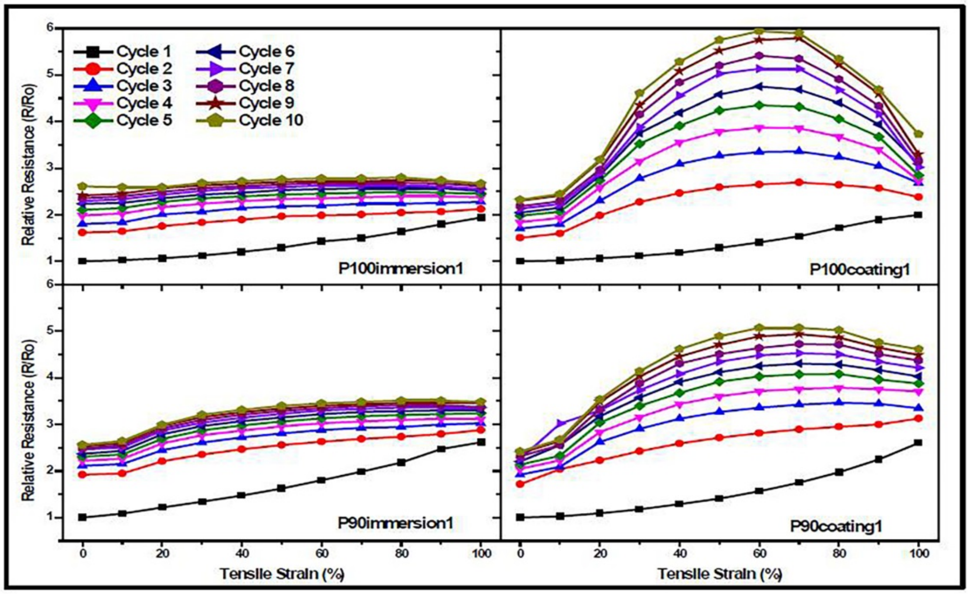


Figure 2.19 Cyclic stretching of treated samples

As noted in the figure, the relative resistance increases more rapidly after the first cycle of stretching. This could be ascribed to the cracking of the conductive materials due to stretching and hence electrical discontinuity occurred. However, the increase in the relative resistance in the situation of the immersion method is fewer, because the conductive material is highly embedded inside the structure of the fabric. In spite of the increase in the relative resistance after the first cycle, the increase did not continue as such as depicted without (P100) and (P90) binder. This may be explained the elasticity behaviour of the polyurethane dispersion brought the resistance to further cracking of the conductive materials. In both cases, the immersion methods had a very good stability against stretching when compared.

Electrical resistance of nylon/lycra fabric was investigated at 100% stretching and plotted using software connected to the digital multimeter and is illustrated Figure 2.20.

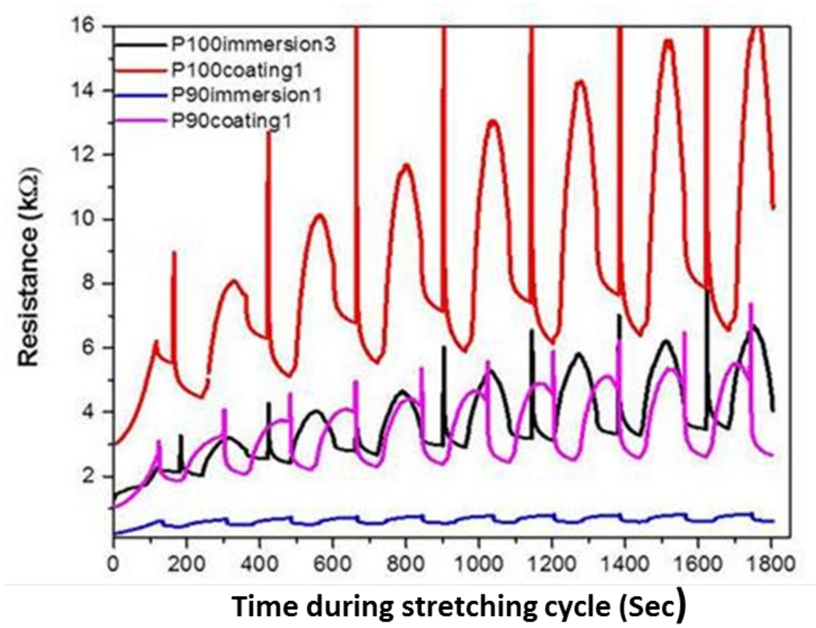


Figure 2.20 The cyclic stretching results

As noted in Figure 2.20, cyclic resistance changes were detected during the elongation-recovering process. The recovering time was one minute and is displayed in the lower pick. The upper peak is the maximum electrical resistance recorded during consecutive cycles. The electrical resistance is slightly increased during the first stretching cycles and became stable after that. This may be attributed to during the first cycle cracking of the conductive materials occurred and then became stable due to the stitching nature of the polyurethane dispersion.

Measuring the Seebeck coefficient is a well-known method to determine the thermoelectric behaviour of the substance. The measurements in the Seebeck coefficient were recorded between 16-20 μV/K. The obtained Seebeck coefficient at various concentrations of PEDOT-PSS is shown in Figure 2.21.

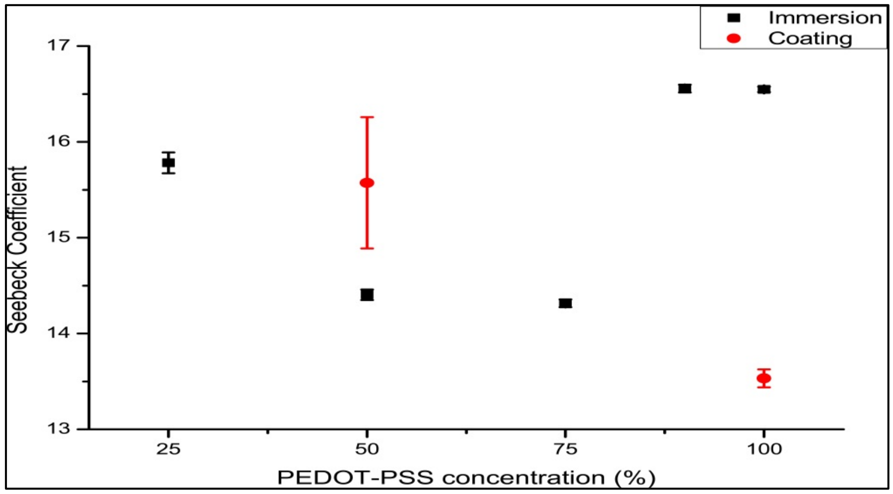


Figure 2.21 The Seebeck coefficient measurement results

This result confirmed that our samples can be used as thermoelectric materials with further investigations by enhancing the Seebeck effect. The conductive fabric sample with high electrical conductivity and stretchability can be an option for this application.

2.3.4 Conclusions

The electrical surface resistance of the conductive fabric was investigated with an elongation percentage of 100% used at a speed rate of 10 mm/min at the wale direction. Cyclic resistance changes were noted during the mechanical elongation-relaxation process. Surface resistance was soundly reversed to its initial value after one minute slackening time after stretching at surface resistance became increased. The electrical surface resistance increased during the elongation process and decreased during the relaxation process with 100% extension. The resistance increases only by insignificant amount when samples were stretched cyclically by stretching 100%. Generally, samples prepared by the immersion method maintained better conductivity while stretching than those by the coating method.

Chapter 3 Subjective Evaluations of Functional Fabrics

This chapter is based on the publication:

M G Tadesse. R Harpa. Y Chen. L Wang, V Nierstrasz and C Loghin, Assessing the comfort of functional fabrics for smart clothing using subjective evaluation, *Journal of industrial textiles*; 2018, DOI :10,1177/15280883764906.

1.1 Introduction

Subjective evaluations of the tactile comfort of the smart and functional textiles may include evaluation and inspection that consist of various tests such as touching great number of parts so that the psychological and physiological perception of the human could be elaborated and affected. Smart and functional developers usually attentive on the functionality and durability feature only (Slater, 1997) even though comfort is one of the instant demand for the consumers (Li, 2001). Functional textile quality in terms of tactile quality should be evaluated and inspected on a regular basis during development and production to ensure that a homogeneous product is produced till it meets the customer requirement and hence quality product standards.

A number of various current e-textile materials for irregular usage are extensively discovered. For this reason, it is very valuable to judge the e-textile material regarding quality in terms of tactile comfort before any developing and manufacturing process. The tactile comfort of e-textiles can be subjectively assessed similar to the ordinary fabric (Kandzhikova and Germanova-Krasteva, 2016). In the subjective evaluation of the functional fabric, the fabric is touched with both hands so that the fabrics characteristics (fabric hand) like smoothness, roughness, itchiness, and others can be assessed with a finger. This is because the largest mechanoreceptors found in the fingers (Militký, 2005). Fabric hand is therefore, is not actually a property by itself;

rather it is a very intricate combination of various physical properties of textile materials which can be assessed by the human expert. The difficulty of fabric hand assessment arises due to the fact that human subjects use their intuitive/instinct knowledge to judge the comfort of the fabric. Since every individual has very distinct intuitive knowledge, the discrepancy is well. To overcome such challenges, large numbers of data were collected using different compositions of human subjects. The difference can be with age, sex, geographical location, background knowledge, and other distinctive feature disparities.

The subjective evaluation of the e-textiles may be influenced by many factors such the differences in age, gender, geographical location, experience, and culture of the panel of experts. Furthermore, training of the panel of experts has a pronounced influence on the reproducibility and reliability of the data (Naima et al., 2013a). Training the panel of experts could be taken into account before conducting the actual evaluation procedure with specific protocols.

Numerous mechanical and chemical finishings can bring a change in the handle properties of the fabric (Song, 2011). Therefore, the change occurred during these treatments can be assessed using subjective evaluation techniques. In addition, this study provides the sensory profile data for functional textile manufacturers so that it can be used as a definite standard for similar fabric production methods.

The purpose of this sub-chapter is to conduct the detail panel selection, panel training, and finally to perform the subjective evaluation using blind and visual subjective scenarios of assessing the functional fabrics. The obtained subjective data have been analyzed using different statistical softwares statistical software to observe the consensus between the panels and to check the reliability and reproducibility of the methods applied.

1.2 Experimental Section

Materials: Various state of the art technologies such as 3D-printing, inkjet printing, coating, screen printing, and knitting were utilized to produce functional textile fabrics for the subjective evaluation methods. The samples have various functionalities such as photochromic, conductive, insulator, and thermochromic properties. See Table 3.1

Table 3.1 Samples and the representations

No	Description	Numeric representation	Alphabetic representation
1	Photochromic (inkjet printed)	1	A
2	Conductive (3D-printed)	2	B
3	Dielectric (3D-printed)	3	C
4	Conductive (inkjet-printed)	4	D
5	Conductive (Coated)	5	E
6	Conductive (Screen-printed)	6	F
7	Conductive (Knitted-Cotton/steel)	7	G
8	Conductive (Knitted-PET/copper	8	H
9	Thermochromic (Screen-printed)	9	I

Methods

Panel selection and training: Sufficient panel training is very significant for the reliability and reproducibility of the subjective evaluation of the functional textile fabrics. Four male and six female experts having textile background aged between 23 and 54 years were recruited and trained. During the training the following issues were focused:

- Definition of the fabric handle;
- Concept of linguistic variables and their definitions;

- Methods of assessment (Blind and visual subjective evaluation);
- The grading scale being used;
- The timing usage; and
- Demonstrating how to handle the sample during the evaluation
- Practical sessions were also conducted to observe the reliability; the results obtained during the training were interpreted and the reliability and the agreement between the panels were tested and evaluated.

The experts were then seated in a group and discussed to generate some tactile sensory terms. They also provided with surveys which further help them to list down some sensory linguistic variables. Lastly, the list of bipolar phonological variables were selected by merging terms which are most nominated by the experts and a full explanation of each bipolar descriptors were provided for full thoughtful.

Subjective evaluation: The subjective assessment of the functional textile fabrics was accomplished based on an eleven-point scale as showed Table 3.2. The subjective evaluation was achieved based on two techniques namely blind subjective evaluation (BSE) and visual subjective evaluation (VSE). In the case of BSE, panels were not allowed to see the sample (a box with two holes was provided for ease of use) and only they were able to touch and sense with their hands only. On the other hand, panels can see and touch the sample simultaneously while assessing the handle of the sample in the case of VSE.

Table 3.2 Linguistic variables and their rating scales

Var*	Attributes	0	1 2 3 4	5	6 7 8 9	10	Attributes
WC	Warm	Extremely warm		medium		Extremely cold	Cold
IS	Itchy	.		.		.	Silky
SS	Sticky	.		.		.	Slippery
RS	Rough	.		.		.	Smooth
HS	Hard						Soft
TT	Thick						Thin
NCC	Non-compressible						Compressible
NSS	Non-stretchable						Stretchable
HL	Heavy						Light
SF	Stiff	Extremely stiff		medium		Extremely flexible	Flexible

*var-Variables

The total hand value evaluation on the other hand, was performed with a five-point rating scale as shown in Table 3.3.

Table 3.3 Rating scales for total hand values

Fabric Code--	Subjective evaluation for total comfortability (Total handle value) The functional fabric is used for smart applications				
	1	2	3	4	5
Evaluators	The most uncomfortable	Uncomfortable	Medium	Comfortable	Most comfortable
E1					
E2					

In the case of BSE method, a box was afforded to conceal the specimens from the expert's vision and two hand holes in the box were prepared during the evaluation taking into account the comfort of the assessor. Appearances of sample fabrics worn next-to-skin were assessed. The experts were first asked to distinguish the sample between the two linguistic variables and then allow to give the rating based their first decision. Each expert spent between 15-20 min in the controlled room before evaluation. The assessment was achieved based on the AATCC 5-2011 practice.

1.3 Results and Discussion

Subjective evaluation of the functional textile fabrics were assessed by carefully following five steps namely:

- Selecting the judges taking into consideration their expertise, age, gender and cultural background;
- Choosing the linguistic descriptors and criteria of judgment (blind and visual);
- Training the experts;
- The method of ranking; and
- The conditions of the experiment (standards followed).

Having this in mind, the resultant data were analyzed by statistical sensory analysis software called XLSTAT (is a statistical tool in excel designed for sensory analysis).

In order to observe the agreement level of each judge on the tactile perceptions of the functional fabrics, every set of samples was given to ten human experts. Every expert conducted both blind subjective evaluation and visual subjective evaluation. Figure 3.1 illustrates the tactile perception similarity and differences between the panels of experts during blind subjective evaluation.

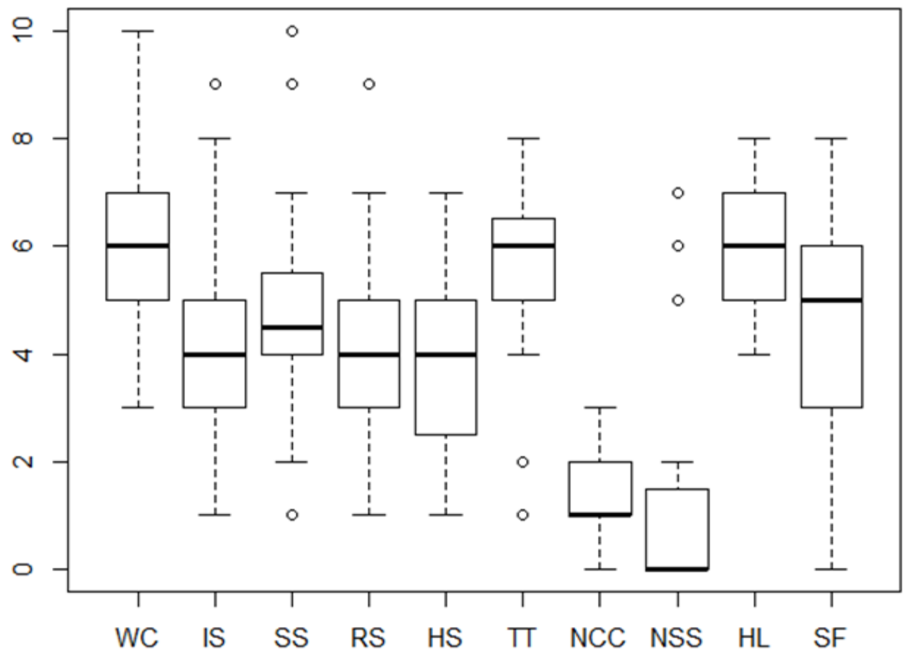


Figure 3.1 The box plot showing the perception difference between experts in BSE

As can be noted from the figure, the maximum perception difference occurred at bipolar descriptors IS, SS, TT and NSS. Some values are within the upper whiskers. This indicates that the agreement between the experts on the above mentioned bipolar attributes is somehow beyond the box plot.

In a similar way, in bipolar attributes WC and NSS, some datasets are within the upper whiskers; indicating that the agreement level for the panels for these bipolar attributes is less. The results are shown in Figure 3.2. In order to have a good consensus, all that should be within the box plot.

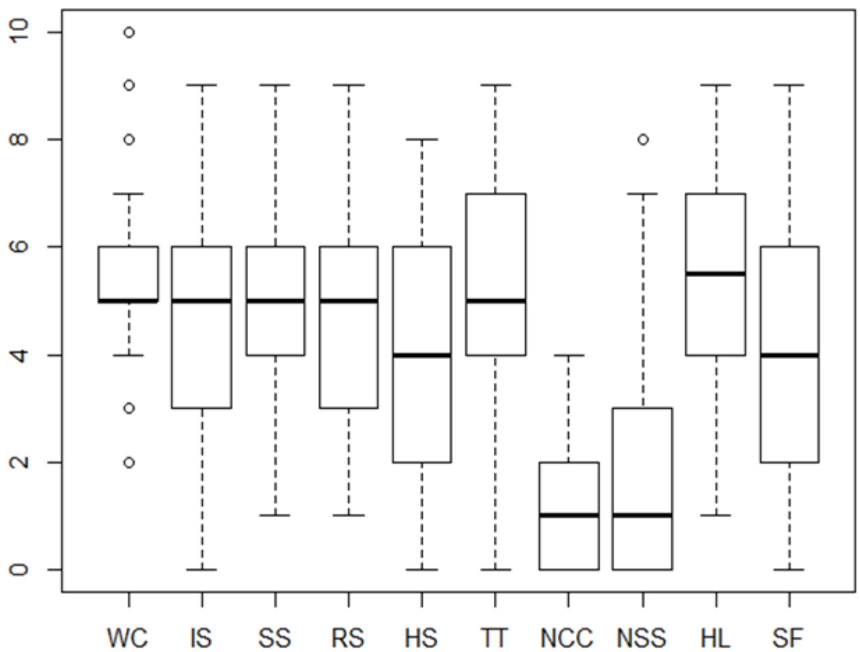


Figure 3.2 The box plot showing the distribution of the datasets in VSE

All these results verify that NSS is the most difficult bipolar attributes for handle assessment. By far VSE is better than BSE for the subjective evaluation of functional fabrics; less number of datasets is with in the upper whiskers in the case of VSE.

In order to observe the association between bipolar attributes and to see the most appropriate attributes that can influence the total hand values of the functional fabrics; the Pearson correlation coefficients were established. The correlation in the blind subjective evaluation is presented in Table 3.4. As showed in the table, top three correlation coefficients observed were between rough/smooth and itchy/silky; between hard/soft and rough/smooth; and between hard/soft and itchy/silky, with the values of 0.99, 0.87, and 0.85, respectively. On the other hand, the top three correlation coefficients amongst the total hand value and the bipolar attributes were 0.78 (with stiff/flexible), 0.73 (with non-compressible/compressible), and 0.68 (with thick/thin). This indicates that the compression and bending properties of the functional fabrics have the capability to influence the comfort of these fabrics when compared. The negative correlation indicates that the total hand value depends on the first bipolar attribute while a positive correlation means the total hand value depends on the second bipolar attribute of the two mentioned. The maximum correlation coefficient (0.99) occurred between rough-smooth (RS) and itchy-silky (IS) bipolar attributes; these bipolar attributes are both surface and friction properties that is why they get maximum correlation.

Table 3.4 The correlation coefficient between the average ratings of the 10 experts for total hand value and 10 bipolar attributes for BSE evaluation

	WC	IS	SS	RS	HS	TT	NCC	NSS	HL	SF	THV
WC											
IS	0.19										
SS	0.26	-0.01									
RS	0.20	0.99	0.10								
HS	0.06	0.85	-0.09	0.87							
TT	-0.54	0.23	-0.47	0.21	0.37						
NCC	-0.57	0.01	-0.09	0.06	0.40	0.59					
NSS	-0.47	-0.71	-0.37	-0.73	-0.44	0.36	0.30				
HL	-0.33	0.43	-0.66	0.39	0.64	0.83	0.46	0.27			
SF	-0.19	0.26	-0.41	0.23	0.48	0.75	0.58	0.40	0.83		
THV	-0.27	0.21	-0.33	0.19	0.35	0.68	0.73	0.20	0.55	0.78	

In a similar way, the correlation coefficients between the average score of the ten experts on the total hand values and the bipolar attributes were recognized and illustrated in Table 3.5.

Table 3.5 The correlation between the average ratings of the 10 experts for THV and 10 bipolar attributes for VSE evaluation

	WC	IS	SS	RS	HS	TT	NCC	NSS	HL	SF	THV
WC											
IS	-0.41										
SS	-0.39	0.29									
RS	-0.56	0.91	0.13								
HS	-0.37	0.58	-0.21	0.69							
TT	-0.47	0.27	-0.39	0.61	0.69						
NCC	-0.34	0.09	-0.24	0.12	0.69	0.32					
NSS	-0.23	-0.72	-0.18	-0.52	-0.22	0.17	0.29				
HL	-0.57	0.05	-0.16	0.17	0.10	0.40	0.37	0.53			
SF	-0.50	0.54	-0.10	0.64	0.84	0.71	0.66	0.03	0.50		
THV	-0.54	0.36	-0.35	0.56	0.71	0.73	0.69	0.17	0.62	0.74	

The maximum correlation coefficients were amongst rough/smooth and itchy/silky (r=0.91) (VSE), amongst stiff/flexible and hard/soft (r=0.84); between non-stretchable/stretchable and itchy/silky (r = -0.72). The negative correlation in the later bipolar attributes specifies that the more the stretchable the fabric is, the more the itchiness. While the positive correlation indicates the bipolar attributes influenced each other proportionally. On the other hand, bipolar descriptors such as stiff/flexible with r ~0.74; thick-thin with r ~0.73; and hard-soft with r ~0.71 have the potential to influence more to that of the total hand value. In associated with that of the blind subjective evaluation, the influence of hard-soft replaces in place of non-compressible-

compressible characteristics. This could be accredited the hard/soft bipolar attribute got consideration to the experts when saw due to the different patterns seen on the fabric surface. Based on the correlation studies blind subjective evaluation recorded the highest correlation coefficient between the bipolar descriptors. The reason could be during visual subjective evaluation the panels may be in dilemma to believe their sense of touch or sense of vision as there are some agglomerations on the surface which looks rough (example) when seeing and smooth (example) when touching due to applied finishing chemicals. The decisive sense organ now became to; the average of the two will be reported for some panels or on the other hand some panels may decide at the instant of vision of touching.

In order to see the relationship between blind subjective evaluation (BSE) and visual subjective evaluation (VSE), correlation check amongst the two variables were established by taking the average score results for each bipolar attribute and the results are showed in Figure 3.3. As shown in the table, the R value is high and is found to be ~0.721. This indicates that the observations of the individual experts on bipolar attributes of each sample were found to be comparable.

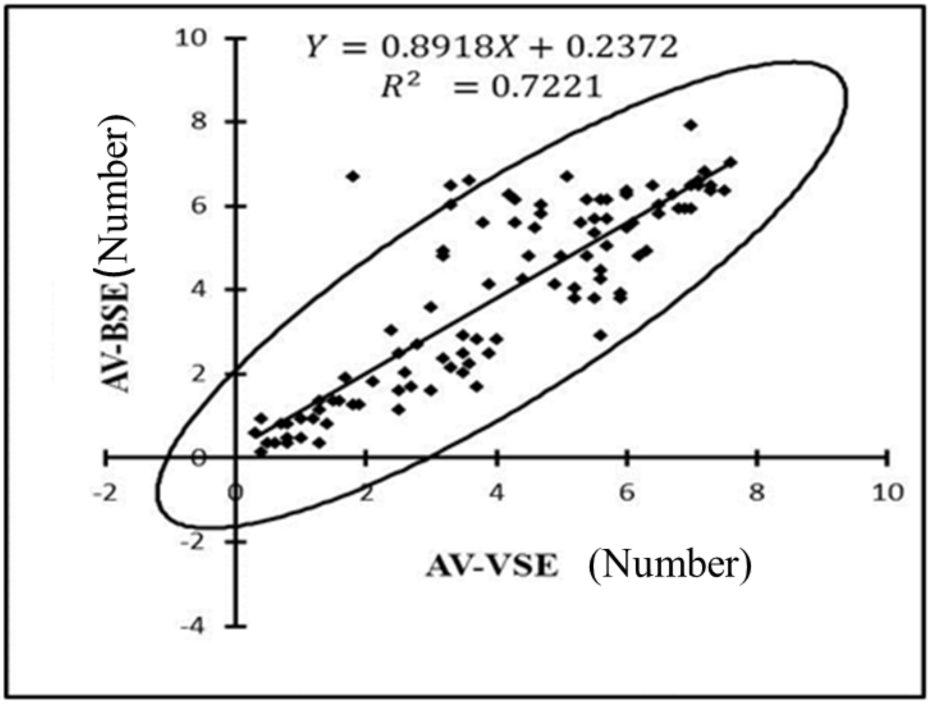


Figure 3.3 Correlation between BSE and VSE (average results)

All values were within the oval shape except a few rating results. This designates that all the rating scales provided by individual experts were in a tolerable range and showed that there are analogues sensorial perceptions amongst the experts. R values can also indicate that ~72.21% of the blind subjective evaluation can be explained by changes in the visual subjective evaluation. The remaining ~27.79% of the variation may be happened due to the test circumstances and other humanity variables. Overall, there found to be a good agreement of the sensory perceptions of the functional fabrics between the individual experts and this could be an approval that subjective evaluation could be applied for the sensory evaluation and inspection of the functional fabrics.

Finally, to establish the better understanding of the category of each product, a sensory profile was plotted using product characterization methods (XLSTAT).

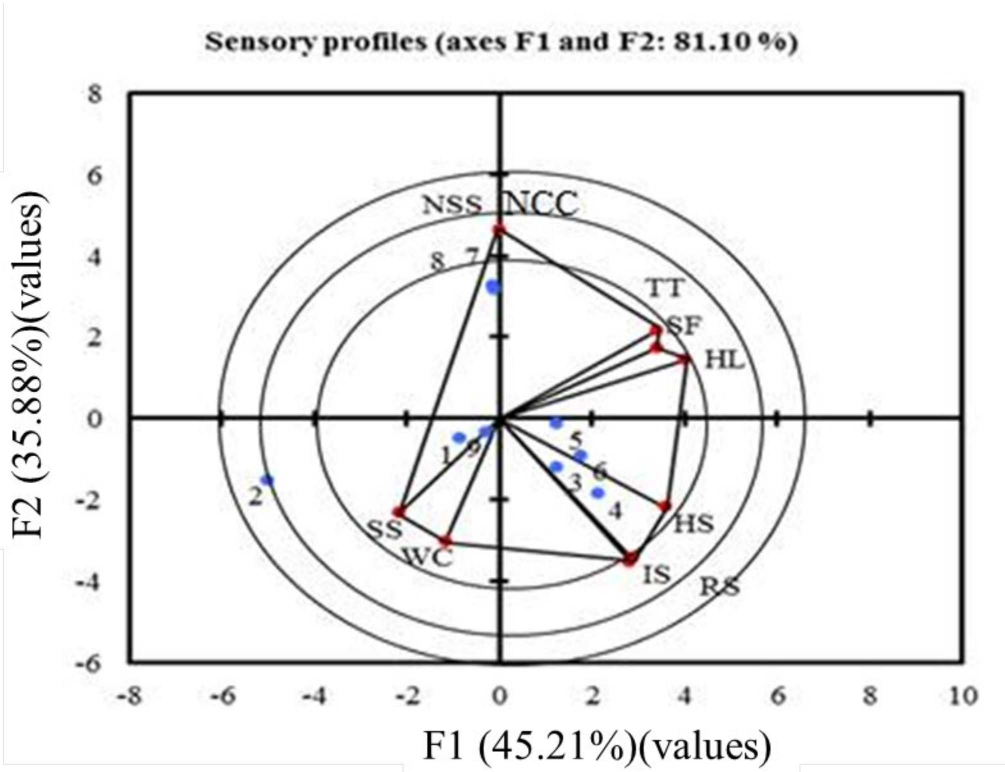


Figure 3.4 Sensory profile data obtained using BSE

The sensory profile data obtained using BSE (Figure 3.4) could be used to categorize each functional fabric with respective bipolar descriptors. For instance, for product 2 and for the bipolar descriptors SS and WC, it has coefficients that have a significant positive value, while large negative coefficient is associated with the bipolar descriptors of TT, SF and HL. Positive coefficients are related with the second bipolar descriptors, while negative coefficients are associated with the first bipolar descriptors. Based on these results, product 2 found to be slippery, cool, thick, stiff, and heavy. On the other hand, product 2 can be taken as negligible in the non-stretchable (as NSS bipolar descriptor is near to product 2).

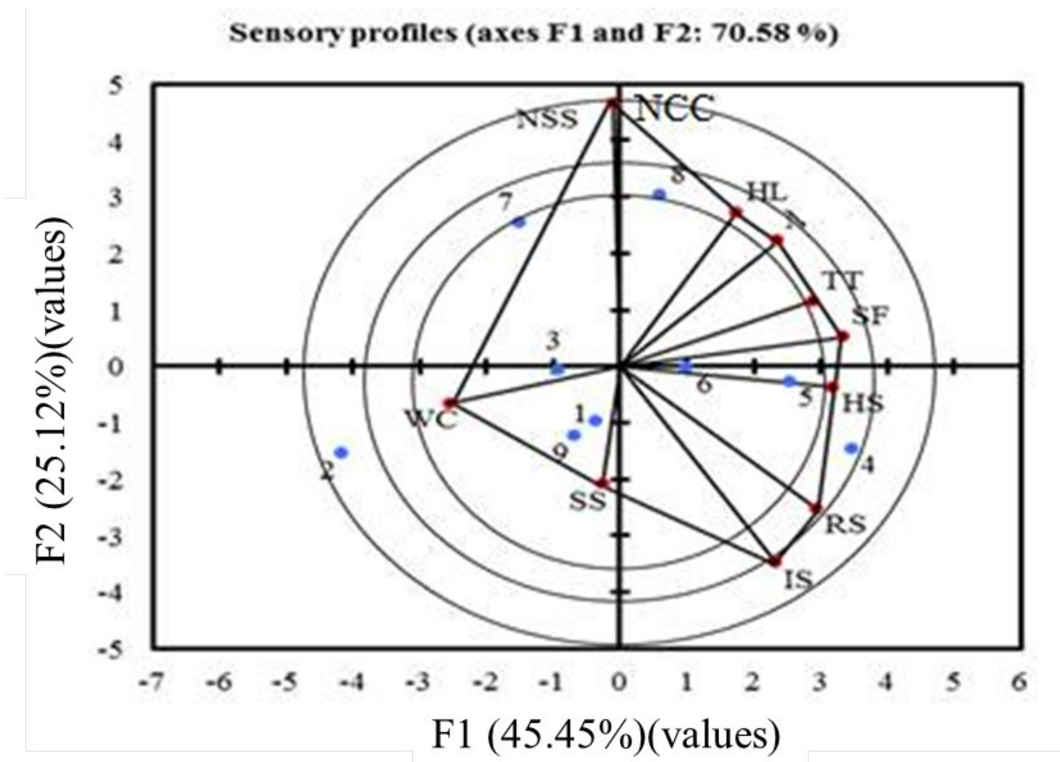


Figure 3.5 Sensory profile data obtained using VSE

A similar description can be conferred in the case of visual subjective evaluation (Figure 3.5). However, the sample is relatively warm as equated with the results in the case of BSE. The bipolar descriptors in the case of VSE relatively deviated from that of the BSE result for product 2. The only basic change between the sensory analyses of the functional fabric using the two methods is product 3. Product 3 is made of a very delicate TPU using 3D printing, and the pattern created during this 3D printing process could be the reason that this sample has basic differences when perceived. These sensory profile statistics could help functional and smart textile manufacturers and developers in decision making during developing, finishing, manufacturing, and design of the functional fabrics. However, the geographical location should be taken into account as the study was conducted within the specific geographical area.

1.4 Conclusions

Based on the subjective evaluation of the functional fabrics, physical properties of the textile-based materials such as warmness, coolness, roughness, thickness, compressibility, flexibility, stiffness, stretchability, stickiness, slipperiness, itchiness, smoothness, softness, weight, and other physical properties can be assessed using the panel of experts. Among the said samples, inkjet printed conductive samples provides the best product in terms of the subjective handle. The obtained results indicates that there is an excellent perception agreement between panelist members and from this the sensory profile data of the functional textile fabrics can be drawn; the sensory profile data can be further used as an inspection and the quality check of the smart and the functional textiles before proceeding to manufacture. Consumers are always accustomed to check the handle of the garment before buying the product. Therefore, the sensory profile data can be used to solve this kind of issue and hence the internet marketing can be boomed. Those bipolar attributes which can be descried by the same surface properties recorded high correlation coefficients between them.

Chapter 4 Objective Testing of Functional Fabrics Using Kawabata System

1.1 Introduction

Mechanical and surface properties of fabrics such as tensile, bending, compression, shearing, surface friction, and other constructional properties such as weight and thickness are challenging to measure subjectively. These all properties are linked to fabric handle. Therefore, it requires the objective measurement technique to enumerate the fabric handle using some other means. Objective evaluation uses several types of equipments to assess the tactile comfort of the textile product instead of irregular human factors. Such kinds of fabric quality are indispensable in the functional and smart textile manufacturing industry, particularly for the quality control and inspection of the textile-based product.

Tactile comfort has a strong association with the mechanical properties of clothing goods measured under low-region conditions (Dhingra et al., 1989). In addition, the subjectively measured, quality index assessed by human experts, and the objectively measured mechanical properties have been applied to optimize the fabric properties as mentioned in (Mahar and Postle, 1989). Linen fabrics subjected to various finishing as well as blended with other fibers have been investigated for its ease using KES-F (Behera, 2007). However, standard fabrics touch the whole body parts while functional fabrics may or may not touch the whole body parts. That is why this paper intended to find if there is mandatory or is there any difference between the standard and functional fabrics comfortable property prediction when applying the same equations.

The KES is the primary system that does not only foresee the human sensory perception but also figuring out the sensitivity of the tactile properties of the fabrics. In the 1980s, Kawabata and his co-workers (Kawabatra, 1980) established the Kawabata's evaluation system (KES-F), a sophisticated and reliable tool to measure the low-stress mechanical properties of (tensile, shearing, bending, compression, thickness, weight, surface, and frictional) various kinds of fabrics. The KES system that was initially designed for the objective evaluation of textile-based goods under low-load regions enables a precise measurement which is sufficient for the quality inspection of textile-based materials and further used to the quality assurance and design development purpose.

Other equipments such as fabric assurance by simple testing (FAST) (Giorgio Minazio, 1995) from CSIRO Australia and fabric touch tester (FTT) from SDLATLAS (Textile Testing solutions) have been used to measure the mechanical properties without the physical damaging of the sample. However, still most researchers follow the KES even though costly when matched with other methods. Because this method has its own chart that can carry on to briefly explain and observe the tailoring control process of the sample; fabric application category based on total hand value (THV); and finally can provide seventeen physical parameters which could help to analyze the handle of the fabric very easily.

In this chapter, we extend the use of the Kawabata evaluation system (KES) for the tactile evaluation of smart and functional textile fabrics. The objective results of the functional fabrics could be associated with the sensory evaluation of the same product to make sure that the evaluation is a reliable index of quality of the textile product in terms of tactile comfort.

1.2 Experimental

Materials: Seven different functional fabrics produced using inkjet printing; coating, screen printing, 3D printing, and incorporation of smart fibers during knitting were used for the unbiased measurement techniques. The substrate used for producing functional fabrics except the knitting product was polyester fabric with a gsm of 159.

The same kinds of sample fabrics were employed as that of the previous chapter (Chapter 3)

Methods: Low-stress mechanical properties of the functional textile fabrics were measured using KES-FB-Auto (KATO TECH Co... LTD). The KES system makes up of four automatic test instruments for conducting: tensile, shearing, bending, compression, surface, and friction tests. These are:

1. ***KES-FB1*** (Tensile): is destined to measure the tensile properties of the fabric (velocity: 0.2 mm/s; clamp interval: 5 cm; maximum load: 500 gf/cm);
2. ***KES-FB1*** (Shear): intended to measure the shearing behaviour of the fabric (shear tension: 10 gf/cm; clamp interval: 5 cm; maximum shear angle: ±8);
3. ***KES-FB2***: aimed to measure the bending property of the fabric (clamp interval: 1cm; maximum curvature K: ± 2.5 cm^{-1});
4. ***KES-FB3***: designed to measure the compressible property of the fabric (velocity: 50 s/mm; compression area: 2 cm^2; maximum load: 50 gf/cm^2); and
5. ***KES-FB4***: measure the surface and the frictional properties of the fabric (velocity: 1 mm/s; initial tensioning: 20gf/cm).

All samples have sizes of 20 x 20 cm long and measurement taken place in both in the warp and weft directions excluding the compressional quantity where the direction only cross sectional.

1.3 Results and Discussion

The seventeen physical parameters were obtained using Kawabata's evaluations system. Table 4.1 shows the details of the mechanical properties to be measured using KES-FB.

Table 4.1 Low-load mechanical properties obtained using KES

Property	Symbol	Parameters measured	Unit
Tensile (KES-F-1)	EMT	Extensibility; the strain at 500 gf/cm	%
	LT	Linearity of tensile load-extension curve	-
	WT	Tensile energy per unit area	$gf.cm/cm^2$
	RT	Tensile resilience; the ability of recovering from tensile deformation	%
Bending (KES-F-2)	B	Bending rigidity; the average slope of the linear regions of the bending hysteresis curve to ± 1.5 cm^{-1} curvature	$gf.cm^2/cm$
	2HB	Bending hysteresis; the average width of the bending hysteresis loop at ± 0.5 cm-1 curvature	gf.cm/cm
Shear (KES-F-1)	G	Shear rigidity; the average slope of the linear regions of the shear hysteresis curve to ± 2.5°	gf/cm.deg
	2HG	Shearing hysteresis; the average widths of the shear hysteresis loop at ± 0.5° shear angle	gf/cm
	2HG5	Shearing hysteresis; the average widths of the shear hysteresis loop at ± 5° shear angle	gf/cm
Surface (KES-F-4)	MIU	Coefficient of fabric surface friction	-
	MMD	Mean deviation of MIU	-
	SMD	Geometrical roughness	μm
Compression (KES-F-3)	LC	Linearity of compression-thickness curve	-
	WC	Compressional energy per unit area	$gf.cm/cm^2$
	RC	Compressional resilience; the ability of the recovering from compressional deformation	%
	T	Fabric thickness at 50 N/m^2	mm
	W	Fabric weight per unit area	mg/cm^2

The KES is originally industrialized for the measurement of low-stress mechanical property of the conventional/traditional fabrics. However, it possible to utilized KES measurement for other textile-based materials which can serve for human being (Kawabata and Niwa, 1996). Therefore, in this chapter, we applied the methods developed by Kawabata et al. named as the Hand Evaluation and Standardization Committee (HESC) (Kawabatra, 1980). The obtained results from KES measurement will be exploited for the quality control and inspection of the functional and smart textile fabric production and development.

Tensile properties: Figure 4.1a) shows a typical load-elongation curve of the samples during loading-unloading conditions where the tensile behaviour of the samples is thoroughly dependent on the finishing effect. For instance, to extend sample 1 (thermochromic), it required a load of ~300 N/m while it required ~100 N/m forces to extend sample 7 (substrate) at 1% elongation in the extension way. This could be attributed to the use of different chemical reagents, application methods, and the drying-curing process of the sample. The conductive inkjet solution (sample 4) constitutes PEDOT-PSS, glycerol, water, and surfactant required around 50 N/m which is better than the substrate sample. The inkjet-printed sample was considered to be more extensible than the substrate fabric. This may be due to wet effect due to an addition of water and glycerol on the functional fabric make more extensible. Fabric extensibility in the initial loading range was extreme; this provides the fabric more comfortable in wearing the functional fabric.

Figure 4.1b) represents the tensile properties of the functional fabrics are shown in Table 4.2. EMT (strain) (X/50 mm) where X is extensibility is an indication of low-stress extensibility and related to crimp removal through the tensile loading. Seam slippage and tailorability mainly be contingent on this strain property. The higher the value of the EMT is, the excelling the wearing comfort. However, this in turn generates problems process such as stitching. From the result, it is observed that sample 4 found to have a good result with an EMT value of 1.47 and 3.75% for the warp and weft directions, respectively (this is where the same substrate of polyester fabric used). Based on this result, sample 4 has got very comfortable when equated with others. But this sample is different from the rest samples and can be not compared. In the case of linearity, LT, as the value approaches to 1, the sample becomes harder. LT relates to wearing comfort such that the lower the LT values, the better the wearing comfort is.

It is observed that sample 4 have a lower LT values, indicates that sample 4 is comfortable when compared to other samples with the same substrate fabric.

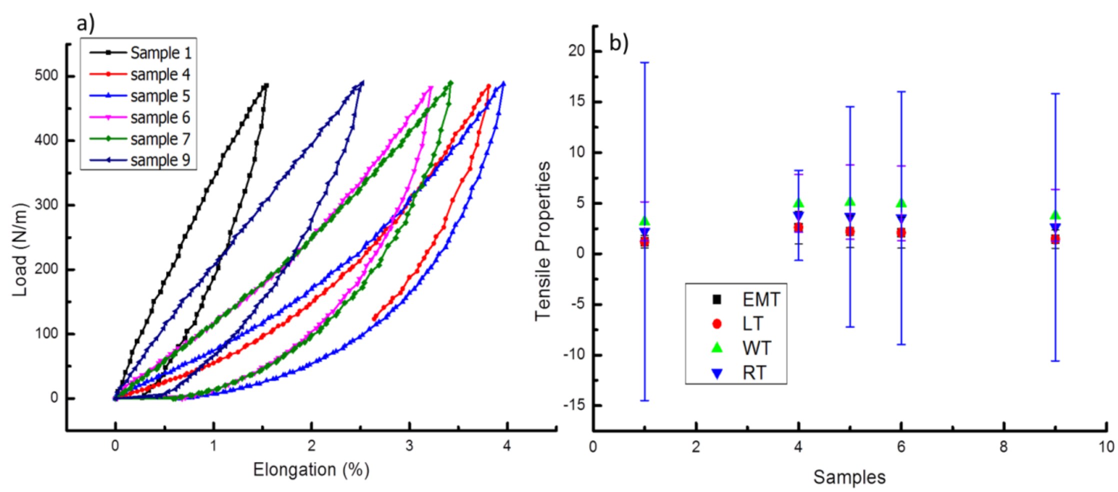


Figure 4.1 a) load-elongation curve in the weft direction and b) tensile property results

When we comply with the tensile energy, WT, as the value develops larger, the sample becomes easier to stretch. In tensile resilience, RT, as the value approaches to 100, the sample becomes more resilience. Higher RT values were observed for photochromic (sample 1) and thermochromic samples (sample 9). This could be ascribed to the nature of the finishing chemicals.

Bending properties: Figure 4.2 shows the amount of load required to bend the fabrics at different bending rates. The bending behaviour of these samples follows possibly the same tendency towards the bending actions. For example, at the bending rate of 1 cm^{-1}, the amount of load required bending the control (sample 7), the photochromic (sample 1), and the inkjet printed samples (sample 4) were ~0.1, ~0.5, and ~0.1 m/m, respectively. This demonstrates that the bending resistance increased more than 5 fold when the fabric is treated with thermochromic dyes. Bending is linked to the stiffness of the fabric hence the drapability of the clothing produced from the photochromic and thermochromic fabric may be altered. Hence, comfort slightly influenced when thermochromic employed. This could be attributed to the types of chemical and treatment types during functional fabric finishing. Therefore, we can conclude that inkjet printed sample produces exactly the same behavior to that of the control sample.

The rigidity of the yarn and the flexibility of the warp and weft yarns in the fabric structure determine the bending rigidity (B). Then bending properties of the fabrics can be influenced by the finishing treatments. Therefore, functional fabric produced using inkjet printing gives a lower rigidity (Figure 4.2b) with a value of 0.16 and 0.10 in the warp and weft directions, respectively. In addition, the lower the bending rigidity is, the better the tailorability of the fabric. The hysteresis of the bending moment is represented by 2HB, which is a measure of recovery after bending.

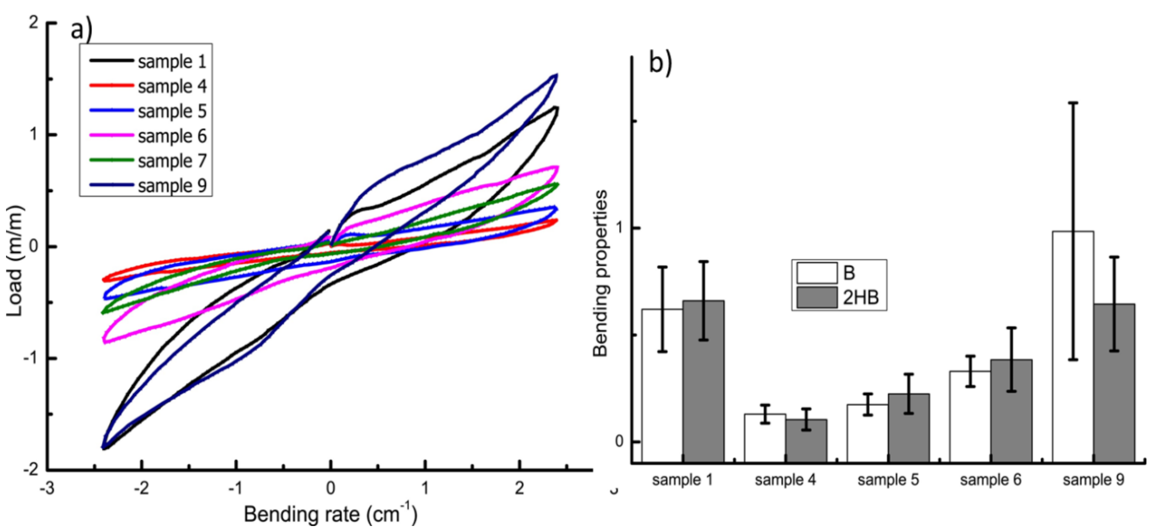


Figure 4.2 a) load versus bending rate for weft direction and b) bending properties

The bending rigidity on the other hand is related to the softness of the fabric. The lower the bending rigidity, the softer the fabric is. Therefore, fabric sample 4 with an average bending rigidity of 0.13 found to be feeling softer and comfortable when wearing.

Shearing properties: is a mechanical property occurred due to strain force when the internal fabric surface slides past each other. Shearing also influences the tailoring property of the fabric. Figure 4.2a) represents the shearing behaviour of the samples at different angles for the weft direction only. The figure clearly revealed that the kinds of functional treatment greatly influenced the stress required at each shear angle. The maximum shear angle applied was 8 degrees. As showed in figure 4a, for the control sample, the maximum load counts ~25 N/m at ~8 degree shear angle. The conductive sample prepared by inkjet printing showed a distinct trend in load-shear angle relationships. At 8 degree shear angle for sample 4 counts around 20 N/m; and sample 1 recorded ~60 N/m at 8 degree shear angle. The result tells that inkjet sample produces the best sample with respect to the tactile comfort, it requires less amount of force to be sheared at the same shear angle.

The higher the shear rigidity (G) is, the more problem set up in the tailoring process. Furthermore, fabric with higher shear rigidity brings discomfort during wearing. From Figure 4.3b it is observed that sample 4 has low shear rigidity implies this sample feels comfortable when compared to others.

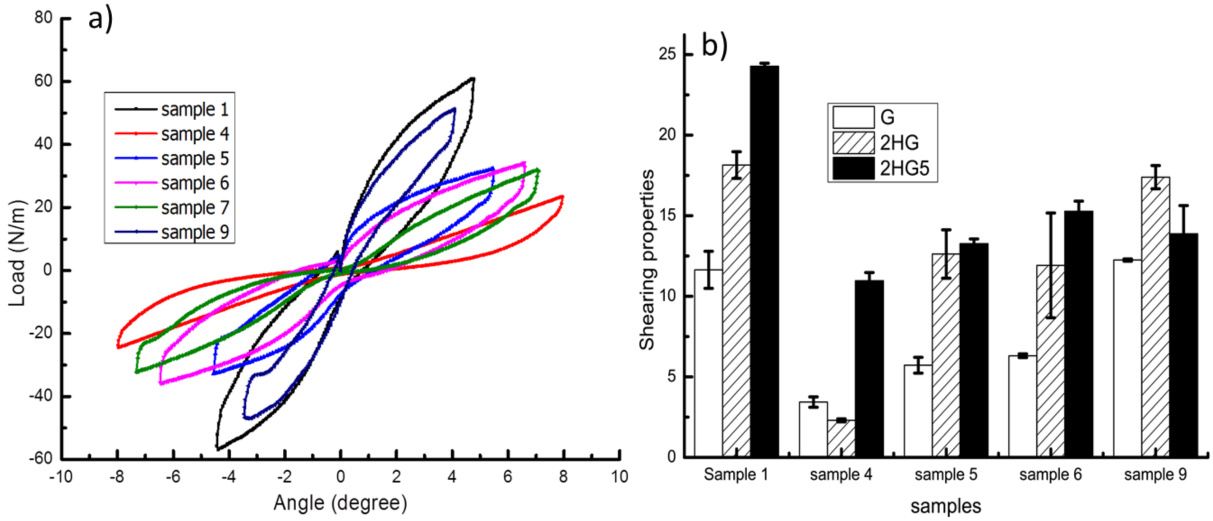


Figure 4.3 a) the forward-back ward shearing and b) the bending properties

The hysteresis of shear at 0.5° and 5° were represented by 2HG and 2HG5, respectively. Similarly, it was observed that, the lower the shear hysteresis, the better the hand feel of the fabric. Hence, as the lower shear hysteresis, the better the resiliency and hence the better the hand feel (comfort) of the fabric.

Surface properties: the surface and frictional properties of the functional fabrics are showed in Figure 4.4. It is seen that the coefficient of friction (MIU) is higher for sample 4. This suggested that sample 4 is still showed a good comfortable property. This could be attributed to the smooth surface structure of the functional fabrics has a larger contact area. On the other hand, the MIU is related with the slipperiness feel of the fabric when touched. The bigger the MIU value is, the less slippery it is. Therefore, fabric with larger MIU feels comfortable when touched.

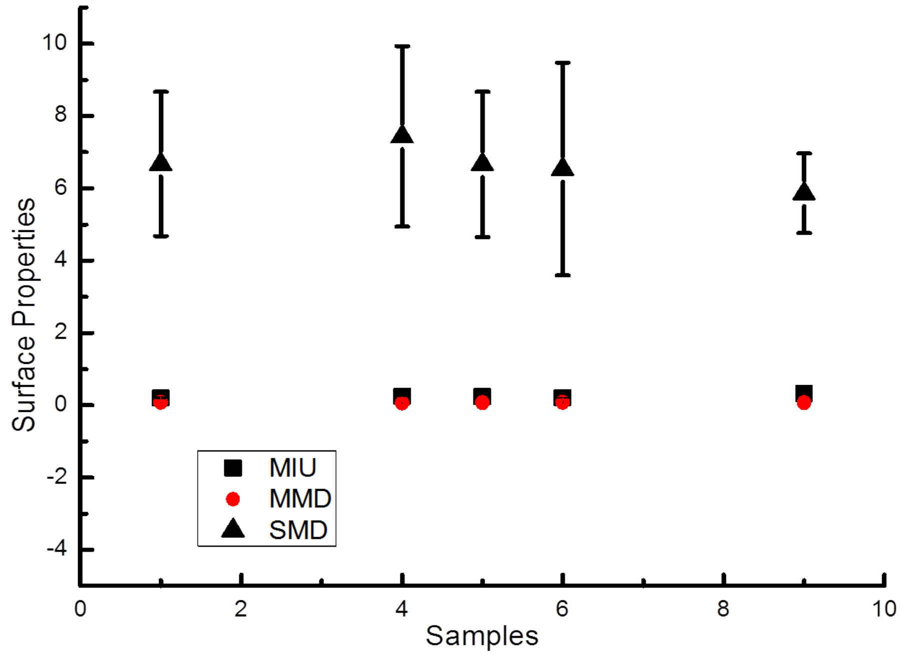


Figure 4.4 Surface and frictional properties under low-load conditions

However, the mean deviation, MMD, of the fabric is related to the smoothness and roughness that we feel when we rub the surface of the fabric. The larger the MMD value, the rougher the fabric surface of the fabric. It is seen that sample 4 with lower MMD is comfortable fabric when compared. SMD indicates the physical roughness.

Compression, thickness and weight properties: The compressional properties were measured by applying a pressure against its thickness. The results are presented in Table 4.2. Therefore, the fabric thickness determines the linearity of compression (LC). From the table, it has been observed that the LC is larger for inkjet printed sample (sample 4). Furthermore, the compressional energy (WC) follows the same pattern to that of LC; indicates that WC depends on LC. Compressional resilience (RC) also mainly depends on the fabric thickness. It has been observed values for the fabric thickness and the weight is prohibitive for inkjet fabric sample (sample 4).

Table 4.2 Compression, thickness and weight of functional fabrics

Sample code	LC	WC	RC	T	W
1	0.31	0.23	54.85	0.62	18.2
4	0.40	0.43	42.42	0.75	18.8
5	0.39	0.42	42.48	0.73	17.8
6	0.37	0.23	49.64	0.56	18.6
9	0.34	0.32	52.75	0.70	24.5

Compression resilience (RC) mainly determines the comfort properties of the fabrics. As it is can be seen in the table, sample 4 has got relatively low resilience value, when compared to other samples. This could be a good indication of the lower the RC is, the better comfort of the fabric and compression properties of the fabric could be used as measure of the handle of the fabrics. Functional and smart textiles are produced for special applications and their productions consume many chemicals and are costly. It therefore, very much paramount that the manufacturers of the smart and functional textile fabrics should be aware of the quality parameters of their product and should be cost-effective. Hence the data obtained by measuring of the low-stress mechanical properties could be one kind of approach to use as a sensory profile data. It could help the smart and functional textile fabric producers to manufacture consistent product that can satisfy the tactile comfort needs of the consumer.

1.4 Conclusions

In this chapter, the practical investigations of the unprejudiced evaluations of textile-based materials are presented objectively. Fabric hand is an essential property of wearable textiles and it significantly affects the final quality of the product. Fabric hand depends on low-stress mechanical properties of the textile-based materials. It is a complex property which is related to many low-stress mechanical properties such as tensile, shearing, bending, compression, and surface and frictional characteristics of the given fabric. Therefore, a complete study of these low-stress mechanical properties and surface frictional properties is one step ahead to study the fabric hand especially the tactile comfort of the product observed when in contact with the human skin. The Kawabata's evaluation system (KES) is part of the instruments that used to predict the fabric hand in a similar manner that feels when the fabric touched with the finger of the human being. Investigations grounded on KES also predict the total hand values of each product. Based on the KES investigations, the functional fabric produced using inkjet printing recorded best fabric hand value in all low-stress and surface friction properties. The results obtained using KES could also be used for further quality inspection and evaluation of the functional fabric produced using the same processes.

Chapter 5 Comparison between Subjective and Objective Tactile Evaluation of Functional Fabrics for Tactile Comfort Evaluation

5.1 Introduction

Most recently, tactile comfort of fabric is measured by combining both subjective and objective evaluation techniques; the demands of the customer towards the tactile comfort led these types of effort. It can be assessed by either by an established subjective evaluation (Kandzhikova and Germanova-Krasteva, 2016) or indirectly by measuring the low-stress mechanical properties (objective evaluation) by KES-F and SiroFAST systems (Bajzík, 2015), or employing FTT method (Hu, 2006).

Objective evaluation was started by Pierce in 1930 (Peirce, 1930), where he claimed that fabric handle is related to physical properties of fabrics such as bending properties, thickness, compression, surface friction, and extensibility measured by regular equipment. In modern days, the most detailed objective evaluation has been performed by Kawabata (Kawabata and Niwa, 1989) where low-stress mechanical properties such as tensile, bending, shearing, surface friction, and compression are measured systematically. The subjective evaluation mainly depend on many factors such as sensitivity and experience (Singh and Verma, 2016) of the expert that carries out the subjective evaluation are very crucial and they determine the reproducibility, reliability, and acceptability of the testing method. On the other hand, the interaction of the human being to the textile materials is increasing (Slater, 1997), because comfort related properties have greatly affected due to the introduction of new fibers types or the use of various finishes applied on the textile-based materials. These various finishing methods have greatly affected the comfort of the textile fabrics (Zouhaier et al., 2013).

In order to have a common language between smart fabric developers, manufactures, sellers, and consumers, it is very important to predict the comfort of the smart and functional fabric using low-stress mechanical properties. The low-stress mechanical properties are very crucial properties and determine the quality of the smart and functional fabric properties (Singh and Verma, 2016). Predicting comfort quality of the apparel fabrics has been started before three decades ago by Kawabata and his co-workers (Kawabatra, 1980). However, there are not yet such equations developed for smart and functional fabrics. In spite of the fact that there are no such equations to predict the handle of smart and functional fabrics, in this chapter, we applied the equations developed for the men's winter suit developed by Kawabata and his co-workers as it is applicable for diverse application can be extended for human interactive materials (Kawabata, 2002).

Establishing a logical relationship between fabric subjective evaluation and low-stress mechanical measurement results appears to be an acceptable modelling means in the history of assessing fabric tactile comfort. In this regard, the most obvious ways of comparing subjective and objective measurement result are calculating the Pearson correlation coefficients between them. Therefore, in our thesis, we applied the Pearson correlation coefficient between the subjective and objective measurement results to observe the association between them. Furthermore, we used objective data obtained by KES to predict the hand and the total hand values of the samples.

Calculation of hand value (HV)

As per the Kawabata and Niwa equations since developed in 1980 (Kawabatra, 1980), we selected the equations developed for men's winter suit equation KN-101 and the hand values calculated are KOSHI (stiffness-related to bending), NUMERI (smoothness and softness), and FUKURAMI (fullness and softness). The equation (KN-101) has the form;

$$Y_k = C_o + \sum_{i=1}^{16} C_i \frac{X_{i\,-}\ \ddot{X}_i}{\sigma_i} \tag{6.1}$$

Where Y_k; hand values (k = 1, 2, 3): (1; Koshi, 2; Numeri, and 3; Fukurami);

X_i; the i^{th} low-stress mechanical properties or its logarithmic values (i = 1, 2, 3……16);

$\ddot{X}_i$ and σ_i are the mean and standard deviations of the i^{th} low-stress mechanical properties; and C_o and C_i, are constant coefficients (see table for men's winter suit) in our case sample 1. This means, we used the same coefficients (C_o and C_i) that have been used to calculate the hand and the total hand values of men's winter suiting fabrics developed by Kawabata. We only swapped the mean and the standard deviations of functional fabrics found using Kawabata's evaluation systems. This approach is based on the men's winter suit and the functional fabrics that we developed have similar tactile perception.

Calculation of total hand value (THV)

The total hand value (quality index of fabric's comfort) of the fabric is the total sensations perceived by experts when touched or squeezed by the human hand. Three hand values calculated in KN-101 were employed to calculate the total hand values. The total hand value is calculated from the primary hand values and can be equated (KN-301) as:

$$THV = C_o + \sum_{i=1}^{k} Z_i \tag{6.2}$$

Where $Z_i = \left(\frac{Y_{i-M_{i1}}}{\sigma_{i1}}\right) + C_{i2}\left(\frac{Y_i^2 - M_{i2}}{\sigma_{i2}}\right)$ (6.3)

Y_i; primary hand values (i = 1, 2, 3)

M_{i1}, M_{i2}, σ_{i1}, σ_{i2}; mean values of Y and Y^2, standard deviations of Y and Y^2, respectively

C_{i1}, C_{i2}; constant parameters and are shown in Table 6.1 The three primary hand values (KOSHI, NUMERI, and FUKURAMI) calculated in the equation KN-101 were used to calculate the total hand values. The second translation equation, KN-301-WINTER-THV (Kawabatra, 1980), were also applied in our thesis work to observe the relations between the subjective total hand and the calculated total hand values associations and to see if this equation is favorable to the functional fabrics quality evaluation.

In a similar way, we employed the same constants (C_{i1} and C_{i2}) that have been used to calculate the total hand values of the men's winter suit. Only the mean and standard deviations are to be varied according to the results obtained in equation KN-101.

In the scope of chapter 6, functional fabric samples were evaluated subjectively using bipolar descriptors for the fabric's warm-cool, itchy-silky, sticky-slippery, rough-smooth, hard-soft, thick-thin, noncompressible-compressible, nonstretchable-stretchable, heavy-light, and stiff-flexible as well as the sixteen objective data were obtained using KES-F. The obtained subjective and objective data were compared by calculating the correlations between them as well as the objective data were used to predict the hand and the total hand value by the most appropriate equations (men's winter KN-101 and KN-301); equations developed by Kawabata and Niwa.

Even though there is a basic difference between the nature of the conventional and the functional textile fabrics, the sensory comfort scenario when touched with the human skin is basically similar as well as architecturally they are the same. This is the reason we applied the same equations and tools to characterize the tactile sensory properties of the functional fabrics to that of the conventional fabrics. Furthermore, the substrate for the functional fabric is woven polyester fabric. Therefore, the equations established for winter suit fabric was openly employed to compute the hand value and the total hand values of the functional fabrics; the Kawabata's evaluation system used for computing the mechanical parameters on low-load region was employed to measure the same parameters for the functional fabrics.

5.2 Experimental

Materials: The materials used in the subjective and objective evaluation methods are shown in Table 3.1 (chapter 3). However, only sample 1 (photochromic), sample 4 (conductively-inkjet-printed), sample 5 (conductively-coated), sample 6 (conductively-screen-printed), and sample 9 (thermochromic) were selected for the comparison study. This is because the above mentioned samples were undergone Kawabata evaluation system (KES) due to sample incompatibility to the KES system.

Methods:

Subjective evaluation: The subjective evaluations were performed using blind subjective and visual subjective evaluation techniques. Six functional textile fabrics were evaluated using ten experts and an eleven point scale for hand value and a five-point scale (most uncomfortable, uncomfortable, medium, comfortable, and most comfortable) for total hand values. Ten-tactile based skin-body contact related bipolar attributes for hand values were employed. A box with two holes was made to the experts to hide the samples from seeing. Training was provided before evaluation to increase the chance of having a similar perception.

Objective evaluation: Objective evaluation was undertaken at Technical University of Liberec using KES-FB evaluation method. Three samples from each fabric were prepared according to KES standards. Tensile, shear, bending, compression, surface, and friction properties of the functional textile fabrics were measured using tensile and shear tester (KES-FB1), bending tester (KES-FB2), compression tester (KES-FB3), surface and friction tester (KES-FB4) with KES FB-Auto (KATO TECH CO.,LTD). All low stress-mechanical properties were needed to be measured in both the warp and the weft directions except the compression property; the averages of the two were reported. Seventeen low-stress mechanical properties were needed to be measured and reported. The predictions of the hand and total hand values of the samples were carried out according to Figure 5.1

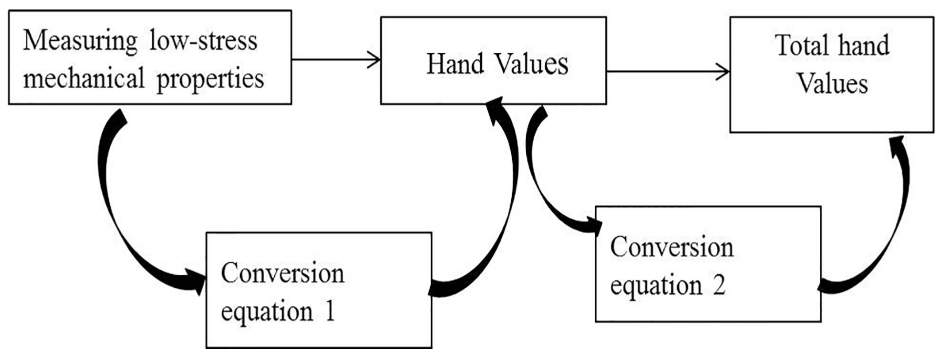


Figure 5.1 The objective hand predictions

5.3 Results and Discussion

Comparison between subjective and objective measurement results: in order to observe the relation between subjective assessment results and the data obtained by KES-F, we established the Pearson correlation coefficient between the two values. Then we defined the range of the correlation coefficient as follows:

1. $| r (p) | = 0$: no linear correlation;
2. $| r (p) | \leq 0.4$: low linear correlations;
3. $0.4 \leq | r (p)| \leq 0.7$: significant linear correlations; and
4. $0.7 \leq | r (p) | < 1.0$: high linear correlations.
5. $| r (p) | = 1.0$: perfect linear correlations

Table 5.1 shows the Pearson correlation between the blind subjective assessment of the hand value and total hand value of the fabric and the low-stress mechanical measurement results for the functional fabric. This table indicates high correlations between subjective HV, THV and the mechanical parameters measured by Kawabata's evaluation system. This is an indication of both the subjective evaluation and objective measurements can be applied for the quality evaluation and inspection of functional and smart textile fabrics.

Table 5.1 Correlation between subjective (BSE-Chap 3) and objective (Chap 4)

	WC	*IS*	*SS*	*RS*	*HS*	*TT*	*NCC*	*NSS*	*HL*	*SF*	THV
LT	0.41	0.50	-0.14	0.38	0.01	-0.35	-0.84	-0.85	-0.58	-0.55	-0.33
WT	-0.79	-0.81	-0.16	-0.74	-0.47	0.24	0.61	1.00	0.19	0.24	0.18
RT	0.77	0.73	0.19	0.66	0.36	-0.27	-0.69	-0.96	-0.33	-0.40	-0.33
EMT	-0.78	-0.82	-0.16	-0.74	-0.46	0.23	0.61	1.00	0.19	0.23	0.17
G	0.13	0.09	-0.19	-0.01	-0.37	-0.43	-0.92	-0.54	-0.86	-0.88	-0.61
2HG	0.03	0.09	-0.41	-0.05	-0.40	-0.41	-0.85	-0.54	-0.83	-0.75	-0.38
2HG5	0.39	0.26	-0.37	0.15	0.09	-0.81	-0.79	-0.69	-0.55	-0.68	-0.52
B	-0.63	-0.64	-0.12	-0.66	-0.87	-0.06	-0.40	0.42	-0.69	-0.69	-0.55
2HB	-0.29	-0.28	-0.29	-0.37	-0.64	-0.49	-0.85	-0.14	-0.87	-0.92	-0.73
LC	0.84	0.92	0.29	0.89	0.67	0.11	-0.22	-0.91	0.17	0.21	0.21
WC	-0.04	-0.28	0.09	-0.18	0.02	0.66	0.91	0.51	0.39	0.57	0.68
RC	-0.88	-0.89	-0.30	-0.88	-0.74	-0.15	0.05	0.83	-0.28	-0.32	-0.32
T	-0.69	-0.81	-0.13	-0.73	-0.46	0.32	0.69	0.98	0.17	0.24	0.25
W	-0.64	-0.57	0.22	-0.52	-0.73	0.42	0.01	0.62	-0.29	-0.24	-0.24
MIU	0.02	0.04	0.42	0.07	-0.37	0.66	-0.10	-0.04	-0.32	-0.16	0.00
MMD	0.08	0.30	-0.05	0.21	0.10	-0.73	-0.84	-0.48	-0.26	-0.50	-0.71
SMD	-0.71	-0.79	-0.15	-0.71	-0.38	0.19	0.66	0.98	0.25	0.26	0.18

The top three tough relationship happened amongst the total hand value and the low stress-mechanical properties are; with mean deviation, MMD of MIU ($r \approx -0.75$), hysteresis, 2HB ($r \approx -0.73$), and with compressional energy, WC ($r \approx 0.68$). This indicates that the total hand values of the functional fabric are mainly depending on the bending (2HB) , shearing, and surface friction (MMD) properties while has low correlation with the tensile and compression properties. This indicates that bending, shearing and surface properties are viable to subjective evaluation while tensile and compression properties are highly liable for objective measurements. On the other hand, we can observe that the hand values of the functional fabrics are highly correlated to that of the physical measurement results obtained by Kawabata's evaluation system where most of the correlations are within the significant relation and higher correlations as per our definition of Pearson correlations above.

In a similar situation, the correlations between the visual subjective evaluation and the KES-F measurement results are established and are illustrated in Table 5.2

Table 5.2 Correlation between subjective (VSE-Chap 3) and objective (Chap 4)

	WC	*IS*	*SS*	*RS*	*HS*	*TT*	*NCC*	*NSS*	*HL*	*SF*	THV
LT	0.10	0.54	0.11	0.36	-0.33	-0.81	-0.53	-0.87	-0.40	-0.66	-0.30
WT	0.37	-0.87	-0.51	-0.73	-0.11	0.61	0.22	1.00	0.62	0.30	0.21
RT	-0.33	0.79	0.55	0.71	-0.04	-0.54	-0.39	-0.99	-0.71	-0.44	-0.33
EMT	0.36	-0.87	-0.51	-0.72	-0.11	0.62	0.21	0.99	0.61	0.29	0.20
G	0.36	0.13	-0.04	0.09	-0.72	-0.60	-0.88	-0.63	-0.40	-0.94	-0.53
2HG	0.46	0.14	-0.26	0.00	-0.64	-0.76	-0.70	-0.59	-0.17	-0.86	-0.31
2HG5	0.18	0.39	-0.08	0.27	-0.35	-0.60	-0.48	-0.70	-0.53	-0.66	-0.54
B	0.71	-0.73	-0.39	-0.61	-0.92	-0.02	-0.82	0.30	0.18	-0.71	-0.41
2HB	0.71	-0.31	-0.38	-0.35	-0.95	-0.51	-0.93	-0.24	-0.10	-0.96	-0.63
LC	-0.65	0.98	0.65	0.83	0.50	-0.42	0.19	-0.86	-0.47	0.13	0.16
WC	-0.51	-0.14	0.22	0.15	0.55	0.83	0.56	0.54	0.12	0.61	0.70
RC	0.77	-0.98	-0.69	-0.89	-0.65	0.26	-0.33	0.77	0.49	-0.27	-0.25
T	0.23	-0.81	-0.39	-0.59	-0.04	0.73	0.23	0.97	0.51	0.31	0.29
W	0.43	-0.74	-0.15	-0.57	-0.58	0.27	-0.49	0.52	0.35	-0.27	-0.11
MIU	-0.14	-0.01	0.42	0.16	-0.24	0.08	-0.44	-0.14	-0.09	-0.27	0.14
MMD	0.45	0.15	-0.19	-0.13	-0.47	-0.75	-0.46	-0.50	-0.15	-0.50	-0.75
SMD	0.29	-0.83	-0.46	-0.66	-0.03	0.68	0.27	0.99	0.54	0.35	0.19

The top three strong correlation between the total hand values and the low-stress mechanical properties are found to -0.75, 0.70, and -0.63 with mean deviation of coefficient of friction MMD, compressional energy WC, and hysteresis 2HB, respectively. While most of the associations between the low-stress mechanical properties of the sample and hand values are with significant correlations and higher correlations. However, there are some correlations results whose result are within the range of low correlations (the highlighted values), as per the definitions of the correlation r (P) above.

The results obtained in both BSE and VSE scenarios confirmed that the consistency of the subjective evaluation and its reproducibility because in both cases we found the highest three correlations with the total hand values with the same mechanical properties. In both cases, sticky/slippery has got fewer correlations with Kawabata's evaluation system results. The total hand value has got high correlations with the surface friction properties in both BSE and VSE cases. This shows that we the human being given more focus on the tactile comfort related to surface friction.

Applying Kawabata translation equations for primary and total hand values calculations

Even though the apparel fabric hand equations were produced in the early 1980s by Kawabata (Kawabatra, 1980), they are not yet developed for functional and smart fabrics. For this thesis work, we applied the hand equations developed for men's winter suit as it is possible and applicable for many apparel products (Kawabata et al., 1994; Yokura and Niwa, 2003). Based on these previously developed equations, the mean and standard deviations of the functional fabrics were substituted in the equations while the same constant coefficients to that of equation KN-101 series were applied. We applied this equation to the calculation of the hand of the functional fabrics because the tactile sensory of both fabrics like good feeling and a bad feeling when the fabric touches the fabric. The perception is based on the physiological and psychological perception of both fabrics.

The low-stress mechanical properties of the functional textile fabrics were measured under the conditions of woven fabric based on Kawabata's evaluation system. On the other hand, the subjective evaluations were performed under standard temperature and pressure condition following the standards used in the AATCC 5-2011. Brainstorming kinds of training with demonstrations were performed before going to the actual total hand evaluation and hand evaluations of the functional fabrics.

Based on the above assumptions, we applied KN-101 equation series to calculate the primary hand and the total and values of the functional fabrics. We performed a series of calculations to arrive at the final destination. Table 5.3 demonstrates the 16^{th} mechanical parameters and logarithmic values of the five functional fabrics having the same substrate materials.

Table 5.3 The i^{th} parameters of the samples (X_1, X_2……X_{16})

Mechanical parameters		Fabric samples				
		1	4	5	6	9
Tensile	LT	1.036	0.783	0.944	0.954	1.033
	logWT	0.508	0.699	0.710	0.698	0.581
	RT	68.54	63.97	58.85	58.92	70.81
Bending	logB	-0.193	-0.883	-0.749	-0.483	-0.007
	log2HB	-0.181	-0.973	-0.641	-0.413	-0.188
Shearing	LogG	1.066	0.537	0.758	0.800	1.088
	log2HG	1.259	0.362	1.101	1.076	1.240
	log2HG5	1.385	1.040	1.123	1.184	1.142
Compression	LC	0.312	0.398	0.402	0.367	0.343
	logWC	-0.631	-0.366	-0.378	-0.640	-0.499
	RC	54.85	42.62	43.44	49.64	52.75
Surface	MIU	0.198	0.243	0.239	0.205	0.315

Friction	logMMD	-1.121	-1.167	-1.175	-1.119	-1.151
	logSMD	0.824	0.871	0.823	0.815	0.779
Thickness	logT	-0.211	-0.123	-0.135	-0.249	-0.157
Weight	logW	1.260	1.271	1.246	1.269	1.388

These values are used to derive the primary hand values (KOSHI, NUMERI, and FUKURAMI) according to equation KN-101. Before calculating the primary hand values, the correlation coefficients between the sixteen mechanical parameters and the subjective total hand values (THV-SB) were calculated and the results are displayed in Table 5.4 In addition, since the population parameters are used to calculate the primary hand values, the results are shown in the same table below.

Table 5.4 Population parameters of the samples (n=5) ($\ddot{X}_i$ and σ_i)

Mechanical parameter		Correlation with THV-SB	Mean Value $\ddot{X}_i$	Standard deviation σ_i
Tensile	LT	-0.35	0.950	0.103
	logWT	0.73	0.639	0.090
	RT	-0.69	64.218	5.456
Bending	logB	-0.53	-0.463	0.367
	log2HB	-0.18	-0.479	0.335
Shearing	logG	-0.57	0.850	0.231
	log2HG	-0.67	1.008	0.370
	log2HG5	-0.56	1.175	0.129
Compression	LC	0.83	0.364	0.038
	logWC	0.71	-0.503	0.132
	RC	-0.79	48.660	5.471
Surface friction	MIU	0.53	0.240	0.046
	logMMD	-0.37	-1.147	0.026
	log SMD	0.07	0.822	0.033
Thickness	logT	-0.75	-0.175	0.054
Weight	logW	0.19	1.287	0.058

As shown in the table, the correlations were strong enough that were obtained between the subjective hand values and the low-stress mechanical properties measured by KEF-F. This indicates that there is a better agreement between the low-stress mechanical properties and the human perception of tactile comfort. Both can be validated to control and inspect the quality of smart and functional textile fabrics.

Table 5.5 shows the calculated primary hand values according to equation KN-101. The result confirmed that the equation developed for woven fabrics can be applied to calculate the hand values of the functional fabrics. This can be further proved by calculating the correlation coefficients between the calculated hand values to that of the subjective total hand values evaluated by human experts and will be discussed in the next session.

Table 5.5 Calculated hand values for functional fabrics

Y_i	Fabric samples					Mean	SD
Hand factors	1	4	5	6	9	M_{i1}	σ_{i1}
KOSHI	7.49	3.59	3.85	6.65	7.35	5.36	1.97
NUMERI	2.96	5.67	6.37	3.81	4.86	5.18	1.59
FUKURAMI	3.67	5.98	6.37	3.90	4.87	5.28	1.39

People nowadays are becoming much aware of the tactile comfort of the textile-based materials as it brings discomfort when wearing. The three most important low-stress mechanical properties namely tensile, shearing, bending; compressional and surface friction properties were used to predict the handle and the total handle values of the samples. The prominent quality properties of the functional and smart fabrics are highly viable and influenced by the use of various chemicals, finishing techniques and production methods. That is why we tried to investigate the engineering quality characteristics of the functional and smart fabric using Kawabata's evaluation system.

The reason for this is because Kawabata's evaluation system is the most widely accepted and viable method of evaluating, inspecting and investigating the quality of textile-based materials.

After calculating the primary hand values of the fabrics, mean, standard deviations, and the squared values are calculated to be further used as input for equation KN-301 and the results are illustrated in Table 5.6 and Table 5.7.

Table 5.6 Calculated inputs for equation KN-301

Y_i	Fabric samples					Mean	SD
Hand factors	1	4	5	6	9	M_{i1}	σ_{i1}
KOSHI	7.49	3.59	3.85	6.65	7.35	5.36	1.97
NUMERI	2.96	5.67	6.37	3.81	4.86	5.18	1.59
FUKURAMI	3.67	5.98	6.37	3.90	4.87	5.28	1.39
THV-Cal	3.564	3.339	3.674	2.796	3.091	3.293	0.357

Table 5.7 Inputs for conversion equation 2 (KN-301)

Y_i^2	Fabric samples					Mean	SD
Hand factors	1	4	5	6	9	M_{i2}	σ_{i2}
KOSHI	56.10	12.89	14.82	44.22	54.02	31.49	21.53
NUMERI	8.76	32.15	40.58	14.52	23.62	27.72	14.87
FUKURAMI	13.47	35.76	40.58	15.21	23.72	28.82	13.92

The constants that are used to calculate the total hand value are shown in Table 5.8.

Table 5.8 THV equation (KN-301) parameters and constants

i	Y_i	C_{i1}	C_{i2}	M_{i1}	M_{i2}	σ_{i1}	σ_{i2}
1	KOSHI	0.6750	-0.5341	5.36	31.49	1.97	21.53
2	NUMERI	-0.1887	0.8041	5.18	27.72	1.59	14.87
3	FUKURAMI	0.9312	-0.7703	5.28	28.82	1.39	13.92

Following the calculated results of the primary hands and driving the input to calculate KN-301, the total hand values were calculated for each sample and the correlation coefficients between the calculated hand factors and the subjective total hand values were recognized. The results are given in Table 5.9. Tabulated hand factors show a strong correlation with the subjective total hand values given by the panel of experts.

Table 5.9 Correlations between calculated hand factors and subjective THV

	KOSHI	*NUMERI*	*FUKURAMI*	*THV-Cal*	*THV-SB*
KOSHI	1				
NUMERI	-0.840	1			
FUKURAMI	-0.890	0.982	1		
THV-Cal	-0.411	0.316	0.453	1	
THV-SB	-0.779	0.852	0.822	0.401	1

This data affirmed that subjective evaluation and objective measurement of the mechanical properties can be concurrently practiced equally the comfort evaluation of the functional fabrics. In order to explore more the relationship between the calculated hand factors and the mechanical properties measured by Kawabata's evaluation, the correlation coefficients were calculated and the results are shown in Table 5.10.

Table 5.10 Relation b/n calculated hand factors & mechanical parameters

Mechanical parameter	KOSHI	NUMERI	FUKURAMI	THV
LT	0.836	-0.552	-0.608	-0.037
log WT	-0.769	0.690	0.626	-0.181
RT	0.575	-0.365	-0.318	0.053
log B	0.936	-0.626	-0.677	-0.262
l2HB	0.943	-0.695	-0.751	-0.200
log G	0.886	-0.592	-0.626	-0.043
log 2HG	0.737	-0.458	-0.529	-0.013
log 2HG5	0.722	-0.843	-0.787	0.180
LC	-0.919	0.866	0.842	0.087
log WC	-0.864	0.947	0.983	0.460
RC	0.982	-0.849	-0.868	-0.244
MIU	0.982	-0.849	-0.868	-0.244
log MMD	0.812	-0.966	-0.986	-0.480
log SMD	-0.714	0.249	0.380	0.328
log T	-0.706	0.846	0.903	0.539
log W	0.480	-0.015	-0.106	-0.429

The table shows correlation coefficients were strong enough to say that there existed good relationships between the calculated hand factors and the mechanical parameters measured at low-load regions. This is a pure suggestion of the prediction performance of the equations of KN-series for the functional fabric hand value and total hand value is in satisfactory range.

Furthermore, to evaluate the prediction performance of the mechanical parameters to the hand factor of the functional fabrics, mean square error was calculated. We calculated the predictive mean square error (MSE) between the subjective total hand value and the calculated THV by equation KN-301 previously developed for men's suiting fabric using the following equation:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{y}_i)^2 \qquad (6.4)$$

Where Y_i; the actual values given by the panel of experts; and

$\bar{y}_{i;}$ the predicted hand value using equations KN-101 and KN-301

n; the number of samples taken

The calculated mean square errors are within the standard deviations of each product. Furthermore, the commonly employed measure of the alterations amongst the hand factors foretold by the mechanical parameters and subjective total hand values given by the experts could be superiorly explained by the root mean square error (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{y}_i)^2} \qquad (6.5)$$

Table 5.11 Calculated hand factors and subjective THV

Samples	KOSHI	NUMERI	FUKURAMI	THV-Cal	THV-SB
1	7.49	2.96	3.67	3.564	2.25
4	3.59	5.67	5.98	3.339	3.15
5	3.85	6.37	6.37	3.674	4.5
6	6.65	3.81	3.9	2.796	2.9
9	7.35	4.86	4.87	3.091	2.7
Mean	5.786	4.734	4.958	3.293	3.100
SD	1.915	1.376	1.207	0.357	0.849

The formulated standard deviation of the differences between the predicted and the total hand values of the fabrics is ~0.788 and the root mean square error amongst the predicted and the evaluated total hand values found to be ~0.808. This designates that the root mean square error is within the standard deviation values. This result confirmed that the prediction performance of the KN-301 equation on the total hand values of the functional fabric using the mechanical parameters obtained by the Kawabata's evaluation system is an excellent one and acceptable.

5.4 Conclusions

This chapter intended to compare the subjective and objective results using correlation analysis and to apply the already established Kawabata and Niwa equations (men's winter suit) for the functional fabrics. Ten-skin contact tactile sensations were used for the subjective evaluation and sixteen low-stress mechanical properties were obtained by KES-F. The results confirmed that the subjective evaluations of the fabrics are the foundation for the quality inspection and evaluation of the functional fabrics. The results will be complete if it can be supported by objective measurements results. The correlation analysis also confirmed that there existed a good association between the subjective evaluation result obtained by human perceptions and the objective results obtained by measuring the low-stress mechanical properties of the functional fabric.

The perdition capability of the KES-F to the hand value and the total hand value was in a satisfactory value as the root mean square error fall within the standard deviation of the changes amongst the predicted total hand value and the total hand value given by human experts with the scale of 1-5.

The correlation between the predicted hand and total hand values to the measured low-stress mechanical properties of the functional fabric confirmed found to be strong. This is an indication of both the objective and the subjective evaluation of the functional fabrics can be used to evaluate and inspect the quality of the smart and the functional fabrics.

Chapter 6 Predicting the Comfort of Functional Fabrics Using Intelligent Systems

6.1 Introduction

Some research works has shown that the soft computing methods such fuzzy logic and neural network have been applied to predict the handle of textile products using different input and output parameters (Jeguirim et al., 2011; Zeng et al., 2004). It is also important to predict the effect of functional finishing on fabric hand as the functional finishes brought special functions to the textile fabrics (Lam et al., 2011). Therefore, the effect of these functional finishing methods brought change on the tactile comfort of the functional fabric can be predicted using intelligent systems such as fuzzy logic and artificial neural-network (ANN) using the subjective perception results as input parameters.

A linear regression model was introduced by Kawabata and his co-workers in 1982 (Kawabata, 1982) to predict the total hand values of the fabrics. Although it was a great start, the results are far from the actual value. This explained by the fact that the non-linear relationships and the complexity of the hand insight. After a while, lots of researchers used other intelligent methods to predict the handle of the textile-based materials such as adaptive neuro-fuzzy inference systems (ANFIS) (Ju and Ryu, 2006), fuzzy logic and neural net-works (Jeguirim et al., 2011). These two methods are very convenient in the prediction of the hand of textile-based materials and are promising tools in this area. They can simulate the non-linear relationships between tactile comfort parameters.

6.2 Experimental Part

Different functional fabrics produced utilizing specific manufacturing procedures were used for the prediction of the hand value (HV) and total hand value (THV) of the fabrics. The details of the samples are shown in Table 3.1 (chapter 3).

Fuzzy logic: A fuzzy logic system used to extend the crisp set into a fuzzy system. It takes care of ambiguous systems and its use of phonological variables. The vague and imprecise data are changed into significant data that can be easily interpreted by the user. Figure 6.1 indicates the decision making schematic flow of fuzzy decision methods.

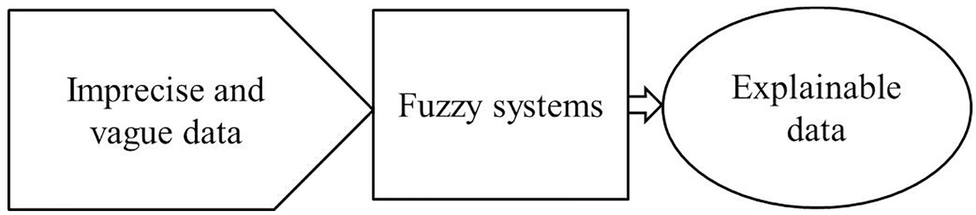


Figure 6.1 The fuzzy decision system

In order to apply the fuzzy decision rules, the following rules are carefully followed:

- *Fuzzy rules should be established*: The majorly rules used are the if-then rules (Kickert and Mamdani, 1978); for example, if "factor 1 is big" then "the output is medium" etc.
- *Degree of membership (DOF) should be assigned*: that used to transform the non-fuzzy input into a value of 0 to 1.
- *A membership functions (MFs) should be selected*: Like trapezoidal, triangular etc. See Figure 6.2.

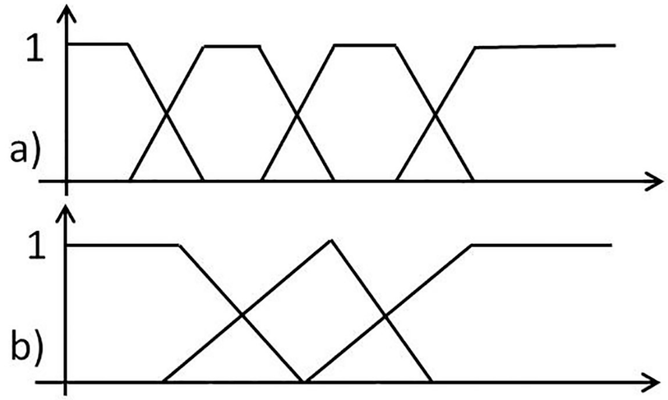


Figure 6.2 MFs of type a) trapezoidal and b) triangular

- *Fuzzy rules should be established:* a conditional statement in the form if "x is A" then "y is B" where x and y are linguistic variables used in the system;
- *Fuzzification:* Conversion of a crisp set (scalar value) into a fuzzy value [0, 1] using various fuzzifiers (membership functions); and finally
- *Defuzzification:* re-conversion of fuzzy set into crisp set (scalar value).

The overall process that utilized to convert the subjective data into quantitative data is shown in Figure 6.3.

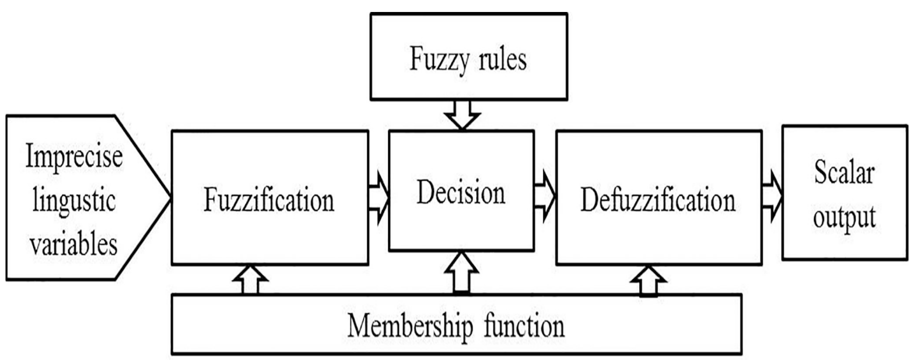


Figure 6.3 Fuzzification and defuzzification processes

Artificial neural net-work (ANN): Is a computer replication inspired by biological neurons and can achieve certain complex tasks. It imitates the human brain where an input signal is transferred to the brain from diverse communication channels (nerve endings). ANN has been applied to predict the total hand value of the textile-based materials with Feed-forward backpropagation learning algorithm (Wong et al., 2003). Mean square error (MSE) has been realized to review the prediction performance of the ANN. For our work, Gradient descent with momentum and adaptive learning rate with 1000 epochs was applied. A max-fail for 1000 was implemented. Subjective rating of the linguistic variables evaluated by a panel of expert was used as input variables (hand value) while the total hand value (THV) given by the same panel of experts was used as an output value for the ANN architecture.

Subjective evaluation and selecting relevant HV for the prediction of THV: The functional fabrics mentioned in Table 3.1 (chapter 3) were subjectively judged by a trained panel of experts using the bipolar verbal variables. The bipolar variables were described in Chapter 3 of the thesis. The samples were then evaluated for the total hand value using a five point scales (very uncomfortable; uncomfortable; medium; comfortable and very comfortable; values from 1 to 5 were given, respectively). More detail subjective evaluation methods can be found in Chapter 3.

Then, Pearson correlation analysis was performed between the hand value and the total hand value to determine the most determining factor for the hand value that mainly affects the total hand value. Then after, based on the correlation coefficient result, the most eminent three hand values (absolute value) were selected and employed to predict the total hand value of each fabric and the selected HV are illustrated in Table 6.1 with their order of importance. The descriptions of the bipolar attributes can be found in chapter 3 of this thesis at Table 3.2.

Table 6.1 Selected HV for THV prediction

Fabric code	Selected hand values	Correlations
1	WC; HL; HS	-0.61; -0.51; -0.41
2	HL; RS; IS	0.77; 0.70; 0.61
3	NSS; HS; WC	0.54; 0.43; -0.32
4	HL; SF; RS	0.76; 0.67; 0.65
5	SS; HS; IS	0.70; 0.61; -0.52
6	SF; HL; SS	0.72; 0.51; 0.38
7	IS; WC; RS	0.61; 0.51; 0.44
8	HS; SS; NSS	0.56; -0.42; 0.34
9	SF; IS; TT	-0.50; 0.45; 0.41

6.3 Results and Discussion

Prediction of the hand value from finishing parameters: In order to perceive the effect of functional finishing on the tactile comfort of the functional fabrics, the finishing types (coating, inkjet printing, screen printing, 3D printing, and knitting) were taken into consideration and served as an input variable to predict the hand value of these fabrics. Thus, a trapezoidal membership function with Mamdani IF THEN rules were precisely defined based on the hypothetical background of each characteristic value against the comfort of textile-based materials. Optmized input values obtained by principal component analysis (PCA) were converted into: small, medium, and big; the fuzzy subsets are scaled between -1 and +1 ((Jeguirim et al., 2011). PCA results for the hand value are displayed in Table 6.2.

Table 6.2 PCA results for HV and THV of subjective evaluation (Input values)

Var	WC		IS		SS		RS		HS		TT	
Fabric	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2
1	-0.21	-0.58	0.31	-0.39	-0.24	0.31	0.45	-0.01	-0.24	-0.43	-0.20	0.46
2	0.08	-0.70	-0.24	-0.28	0.10	-0.58	-0.22	0.52	-0.11	-0.45	0.38	0.07
3	-0.33	-0.24	0.14	-0.47	0.14	0.5	0.06	-0.56	-0.1	-0.36	0.27	0.45
4	-0.45	0.06	0.44	0.22	0.42	0.04	0.29	0.48	0.23	-0.24	0.15	0.47
5	-0.46	0.02	0.39	0.18	-0.32	0.25	0.42	0.23	0.31	-0.44	0.43	0.33
6	0.38	-0.04	0.39	-0.18	0.42	0.24	0.34	0.13	0.48	-0.21	-0.21	0.42
7	-0.35	-0.01	0.02	-0.62	0.36	-0.3	0.37	-0.31	-0.32	0.31	-0.41	0.15
8	-0.28	0.01	0.36	-0.23	0.53	0.31	0.30	0.1	-0.45	-0.20	-0.29	0.14
9	-0.28	0.34	0.45	-0.12	0.21	-0.12	0.40	-0.1	-0.48	-0.23	0.49	-0.17

	NCC		NSS		HL		SF		THV	
	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2
1	-0.08	0.39	0.39	0.23	-0.09	0.47	-0.37	0.18	0.01	0.55
2	0.11	0.53	0.42	0.14	0.27	-0.55	-0.34	-0.09	-0.37	0.37
3	0.25	0.46	0.35	-0.19	-0.34	-0.08	-0.4	-0.26	-0.19	0.05
4	0.45	-0.15	0.33	0.08	-0.17	-0.33	-0.34	-0.28	-0.42	-0.06
5	0.42	0.03	0.38	-0.37	-0.34	0.02	-0.41	-0.23	-0.45	-0.07
6	0.44	-0.18	0.35	-0.06	-0.5	-0.1	-0.45	0.05	-0.27	0.28
7	0.22	0.48	0.14	0.53	0.18	0.52	-0.08	0.61	-0.25	-0.51
8	0.44	-0.06	-0.14	0.66	0.47	0.14	-0.22	0.27	-0.34	-0.44
9	0.32	-0.28	0.36	0.21	-0.41	0.25	-0.23	0.55	-0.46	0.16

While output hand values scaled from 0 to 10 was transformed into five fuzzy subsets namely: very small, small, medium, big, and very big and some results are shown in Figure 6.5.

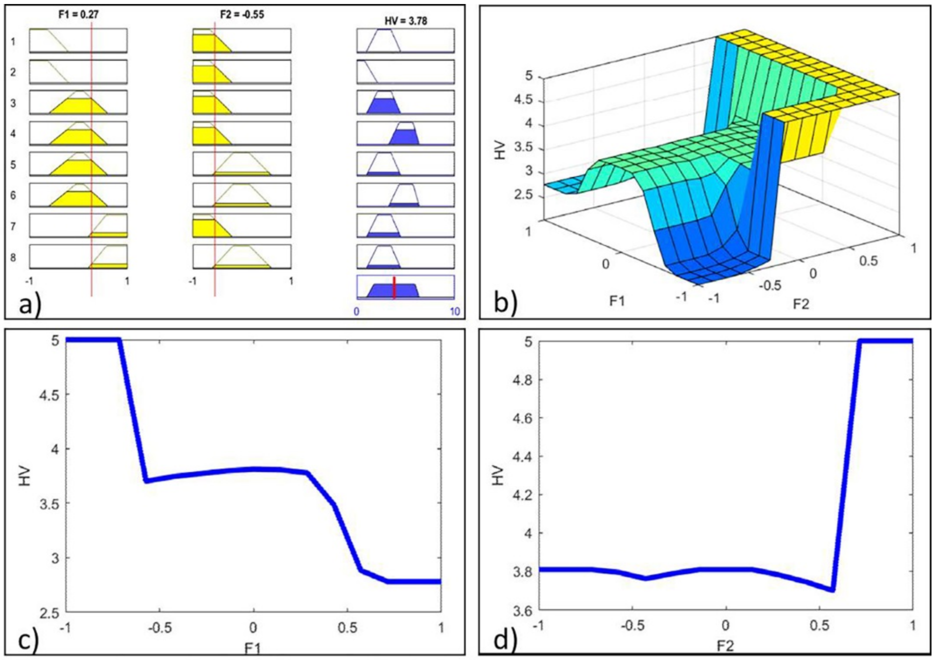


Figure 6.4 a) fuzzy rules and (b-c) fuzzy surfaces for fabric 2 (HL)

Fuzzy rules:

1. If (F1 is Small) and (F2 is Small) then (HV is Small)
2. If (F1 is Small) and (F2 is Small) then (HV is Very Small)
3. If (F1 is Medium) and (F2 is Small) then (HV is Small)
4. If (F1 is Medium) and (F2 is Small) then (HV is Medium)
5. If (F1 is Medium) and (F2 is Medium) then (HV is Small)
6. If (F1 is Medium) and (F2 is Medium) then (HV is Medium)
7. If (F1 is Big) and (F2 is Small) then (HV is Small)
8. If (F1 is Big) and (F2 is Medium) then (HV is Small)

From this result (Figure 5.4 (b-c), it is easy to detect that, the lower the value of F1 is, the higher the value of the hand value. On the other hand, the HV became constant until the value of F2 became higher than 0.5; after this value, the HV value increases rapidly until F2 became 1. The rules are constructed be taken into account this reality.

By applying the fuzzy rules for each fabric sample and for each bipolar variable, the following (Table 6.3) results are found. As showed in the 2D surface plot, the THV have various minimums and maximums. This indicates that the relation between the hand value (HV) and total hand values (THV) are complex and non-linear. That is why we applied the fuzzy logic instead of the linear regression to model the relations between the HV and THV of the functional fabrics.

Table 6.3 Hand value prediction using fuzzy logic from finishing parameter

FC	*WC*		*IS*		*SS*		*RS*		*HS*		*TT*		*NCC*		*NSS*		*HL*		*SF*	
	y	p	y	p	y	p	y	p	y	p	y	p	y	p	y	p	y	p	y	p
A	5.7	5.4	5.2	5.1	3.9	3.7	5.5	5.7	3.0	2.9	5.6	5.8	0.7	0.8	0.5	0.8	5.3	5.7	2.7	2.8
B	7.6	7.3	3.7	3.7	7.0	6.9	2.6	2.7	1.0	0.9	1.7	2.0	0.6	0.8	0.4	0.8	3.5	3.8	0.8	0.9
C	7.5	7.6	3.3	3.4	2.4	2.5	3.8	3.8	5.2	5.3	5.5	5.5	1.2	1.4	0.8	0.9	3.3	3.1	3.2	3.2
D	3.6	3.8	6.8	6.5	7.3	7.3	7.1	7.3	6.5	6.2	6.9	6.5	1.5	1.7	0.8	0.9	5.1	4.9	7.2	7.4
E	4.7	4.9	6.3	6.2	4.4	4.5	6.2	6.1	5.9	6.0	5.7	5.8	1.6	1.8	1.3	0.9	6.5	6.6	6.0	6.1
F	5.7	5.7	5.6	5.6	4.3	4.1	4.7	4.8	4.5	4.4	4.6	4.8	1.3	1.0	1.0	0.9	7.0	7.2	6.0	6.1
G	4.3	3.9	1.8	2.0	5.6	5.5	2.5	2.4	2.1	2.1	4.2	4.0	1.4	1.6	6.7	6.8	6.4	6.2	1.8	2.0
H	5.9	6	2.5	2.1	3.2	3.1	3.6	3.8	3.9	3.8	7.0	7.2	1.3	1.7	7.1	7.2	7.3	7.4	6.1	6.1
I	5.5	5.7	5.0	4.9	5.5	5.9	5.4	5.9	2.5	2.5	5.5	5.5	0.4	0.8	0.3	0.8	6.0	6.1	2.8	2.7

*Where **FC**: fabric code; **WC**: Warm-Cool; **IS**: Itchy-Silky; **SS**: Sticky-Slippery; **RS**: Rough-Smooth; **HS**: Hard-Soft; **TT**: Thick-Thin; **NCC**: Non-Compressible-Compressible; **NSS**: Non-Stretchable-Stretchable; **HL**: Heavy-Light; **SF**: Stiff-flexible; **y**: actual value given by experts; and **p**: predicted value using fuzzy logic.*

Moreover, the prediction performances of the fuzzy logic was evaluated by calculating standard deviation (STDV), root mean square error (RMSE), and relative mean percentage error (RMPE) according to (Jeguirim et al., 2011), using the following equations:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(y-p)^2} \tag{5.1}$$

$$RMPE = \left|\sum_{i=1}^{n}\frac{y-p}{y}\right| * \frac{100\%}{N} \tag{5.2}$$

Where *y*: the actual score given by experts; *p*: the predicted score using fuzzy logic; and *N*: the number of times where an attribute was estimated. Based on these and STDV calculations, the following results are obtained (Table 6.4). Standard deviation indicated that the variations of the experimental results while the error values indicate how the predicted results are deviated from the actual hand perception consequences as evaluated by the human subjects.

Table 6.4 Summary of the HV prediction results using FLM

Bipolar descriptors	RMSE	RMPE	STDV
Warm-cool	0.23	0.23	0.24
Itchy-silky	0.06	1.31	0.19
Sticky-slippery	0.19	0.27	0.19
Rough-smooth	0.21	2.40	0.19
Hard-soft	0.13	2.12	0.12
Thick-thin	0.22	2.18	0.22
Non-compressible-compressible	0.26	**23.6**	0.20
Non-stretchable-stretchable	0.28	**33.5**	0.27
Heavy-light	0.21	0.84	0.21
Stiff-flexible	0.12	3.32	0.10

The calculated error (RMSE) is inside the series of the SD of the samples for most of the linguistic variables. However, the prediction performance of the fuzzy model based on finishing parameters on the linguistic variables of non-compressible/compressible and non-stretchable/stretchable was poor; the RMPE is higher than 10% (23.6 and 33.5%). When we observe the history of these bipolar descriptors, their value is on the lowest extreme on the rating scale. The lower prediction performance of the fuzzy logic on these linguistic variables could be attributed to lower rating scales of the same linguistic variable. In general, the prediction performance of the fuzzy logic for most of the phonological variables was effective and could be used to predict the comfort of the functional fabrics from finishing parameters.

Prediction of THV from HV using fuzzy logic: The fuzzy logic also applied to predict the total hand values of the functional fabrics. The prediction was performed based on the selection made and displayed on Table 5.2. The fuzzy logic rule was established and depicted in Figure 6.5 (as an example for sample 6). Now, the input parameters are the three most influential hand values based on correlation analysis while the output is the sum total hand value. The total hand value represents the overall quality index of the textile product in terms of the tactile comfort.

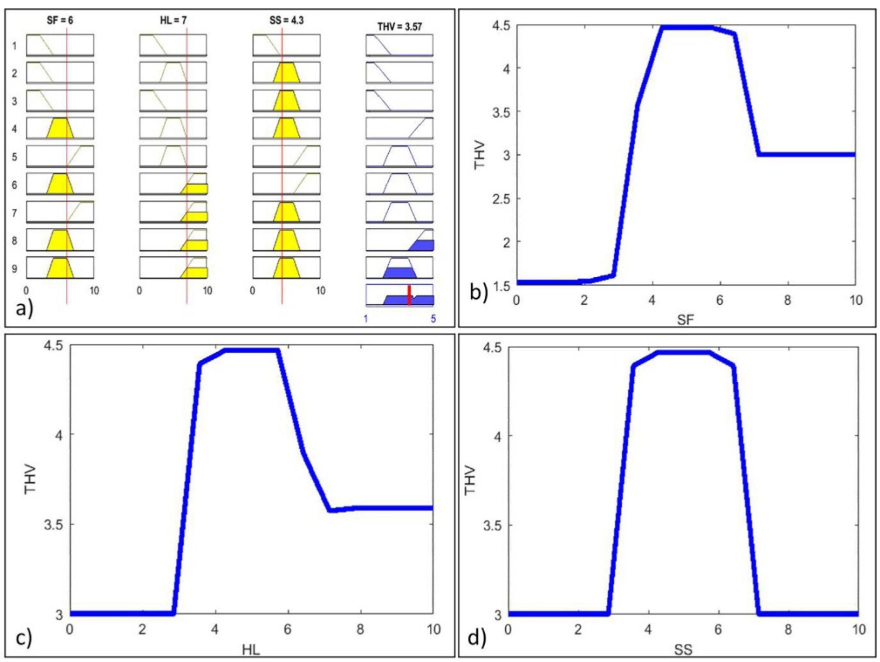


Figure 6.5 Fuzzy logic rules for the prediction of THV using HV

Fuzzy rules

1. If (SF is stiff) and (HL is heavy) and (SS is sticky) then (THV is non-comfortable)
2. If (SF is stiff) and (HL is medium) and (SS is medium) then (THV is non-comfortable)
3. If (SF is stiff) and (HL is heavy) and (SS is medium) then (THV is non-comfortable)
4. If (SF is medium) and (HL is medium) and (SS is medium) then (THV is comfortable)

5. If (SF is flexible) and (HL is medium) and (SS is slippery) then (THV is comfortable)
6. If (SF is medium) and (HL is light) and (SS is slippery) then (THV is medium)
7. If (SF is flexible) and (HL is light) and (SS is medium) then (THV is medium)
8. If (SF is medium) and (HL is light) and (SS is medium) then (THV is comfortable)
9. If (SF is medium) and (HL is light) and (SS is medium) then (THV is medium)

The surface plot of total hand values was drawn against heavy-light, stiff-flexible, and sticky-slippery hand values in a 2D surface plot. The non-linear relationships between the absolute hand values and the hand values are clearly indicated in the 2D graph. This is explained by the fact that; the total hand value has more than two local minimum and local maximum values. For, linear relations, only one local value should be revealed. As a result, comfort related dimensions are related non-linearly. The non-linear relations could only be solved using intelligent systems. Intelligent systems like the fuzzy logic can solve the problems eventhoguh the relationships are non-linear. This is the advantage of using artificial intelligence predicting models.

Thus, the dependency of the total hand value on each hand value can be clearly seen in the figure. For example, the total hand value of the sample is consistent between 0 and 2.5 and again between 7 and 10 in the case of sticky/slippery bipolar attribute. This means total hand value will have comfortable property when the sample is neither sticky nor slippery. This is definitely having similar theoretical observations of the attributes. In a similar way, for other attributes the total hand value had comfortable nature when the bipolar attributes fall on the intermediate situations except few deviations.

In order to assess the prediction performance of the fuzzy logic on the estimation of the total hand value of the functional fabrics. RMSE, RMPE, and STDEV are computed and are shown in Table 6.5.

Table 6.5 THV prediction from HV using fuzzy logic (FL) (p_1) and ANN (p_2) models

Fabric	A	B	C	D	E	F	G	H	I	RMPE	RMSE	STDV
y	3	1.9	3.3	3.7	4.9	3.5	3.2	4.0	3.5	-	-	-
p_1	3	1.7	3.0	3.6	4.5	3.6	3.0	4.2	3.6	2.89	0.21	0.20
p_2	2.9	1.7	3.3	3.8	4.6	3.4	3.2	4.0	3.5	2.24	0.13	0.12

Where y is the actual value and p_1 and p_2 are the predicted values

From the table, we can observe that the calculated errors (RMSE) are within the calculated standard deviations (STDV) of the distribution. Thus, this result suggests that the performance of the fuzzy logic to predict the total hand value is excellent and within an acceptable range. Furthermore, the calculated relative mean percentage error (RMPE) is lower than 10%. This is likewise a good indication of the performance of the fuzzy logic prediction on the total hand value.

Prediction of the THV using ANN: Feed-forward backpropagation learning algorithm was applied to predict the total hand value of the functional fabric using an artificial neural-network system. In addition, Gradient descent with momentum and adaptive learning rate types of trained was performed. The data are divided into:

- Input values: the HV of the functional fabric given by a panel of experts;
- Target value: the THV of the functional fabric rated by the same panel of experts; and
- Sample value: average HV values given by a panel of experts.

Then, training was performed by neural-network tool (nntool) using matlab2017b®. The schematic view of the ANN architecture is displayed in Figure 6.6.

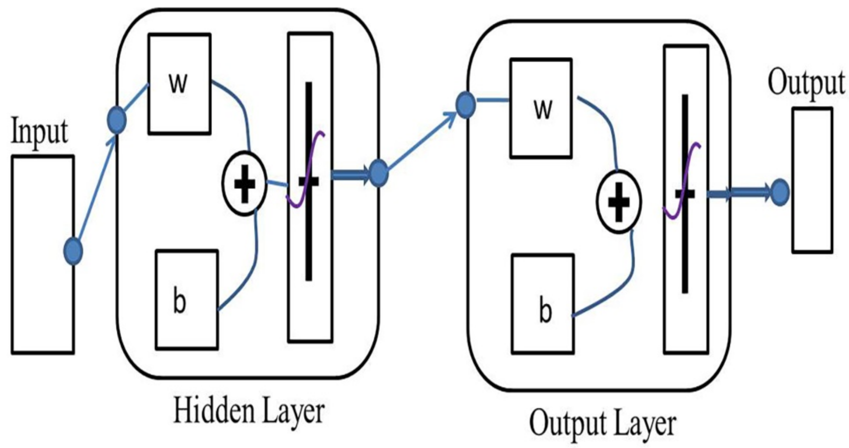


Figure 6.6 Feed-forward backpropagation ANN model

ANN training was performed until a sufficiently minimum and constant RMSE value was obtained and the final result of the simulation is shown in Table 5.6. From this table, we can observe that the prediction performance of the artificial neural network is in the acceptable range. The obtained RMSE values are within the standard deviations of the distribution and hence acceptable error ranges. The calculated relative mean percentage errors are also below 10% and this indicates that the ANN prediction model for the total hand value of the functional fabric is acceptable and could be exploited to predict the comfort of smart and functional fabrics.

Based on the investigations, fuzzy logic models could be used to predict the hand values of some functional fabrics using finishing parameters as an input data and total hand values of same fabric by make use of the hand values as an input data obtained by a panel of experts. When values are within on the lowest extreme, the prediction performance of the fuzzy logic became less. The prediction performance of the fuzzy model for both hand value and total hand value was effective; the RMPE values were less than 10% for most variables and the RMSE values were within the standard deviation values which are the variation of the real value and the predicted value was too small. Furthermore, the prediction performance of artificial neural-network on the total hand value was quite good and similar to that of the fuzzy logic model, where low RMPE and RMSE values were obtained. Thus, FLM and ANN-based prediction of the comfort of functional fabrics can be meant for the development and production of these fabrics in a flexible way.

6.4 Conclusions

Fabric hand values and the total hand values of the functional fabrics have been predicted using fuzzy logic and artificial neural network algorithms. In order to predict the hand values of the functional fabrics, finishing parameters used as an input parameters. Taken into account on this prediction, the relative mean square error (RMSE) values are within the range of the standard deviations of the population. This indicates that the forecast performance of the fuzzy logic simulation model on the hand values of the functional fabric was acceptable range. However, there are some values whose relative mean percentage error (RMPE) is greater than 10%. The prediction performance of the fuzzy logic was inadequate in the case of bipolar attributes whose rating scales are too low. The prediction performance of the fuzzy logic and the artificial neural network on the total hand values of the functional fabrics was a tolerable range. The relative mean square error values in both cases are within the range of the standard deviations. This reveals that the prediction performance is quite good. The relative mean percentage error (RMPE) values in both cases are less than 10%. This is an additional confirmation that both fuzzy logic and artificial neural network can be used to predict the total hand values of the functional fabrics. With the help of these two models, it is possible to predict functional fabrics sensory comfort from finishing parameters and perceived blind and visual features of the sample with acceptable values.

Chapter 7 General Conclusions and Future Works

7.1 General Conclusions

This thesis aimed to establish the quality inspection and evaluation techniques for the smart and the functional textile fabric using skin contact mechanics principle so that a sensory profile data can be drawn. The interaction of the fabric with the wearer in terms of tactile/sensory properties was investigated using human subjects (experts system) and Kawabata's evaluation systems.

This thesis has two main parts: collecting and developing smart and functional textile fabrics using different state-of-the-art technologies such as digital inkjet, printing, 3D printing technology, or incorporation of smart fibers during knitting operations. The second part was to study the contact mechanics of the collected and developed smart and functional textile fabrics. The subjective and the objective data of the sample fabrics have been collected using human subjects (experts system) and Kawabata's evaluation systems, respectively for the quality inspection and wearability evaluations of the sample fabrics.

As reported in the previous chapters and sub-chapters, the objectives of this thesis have been achieved. Figure 7.1 summarizes the main findings of the thesis.

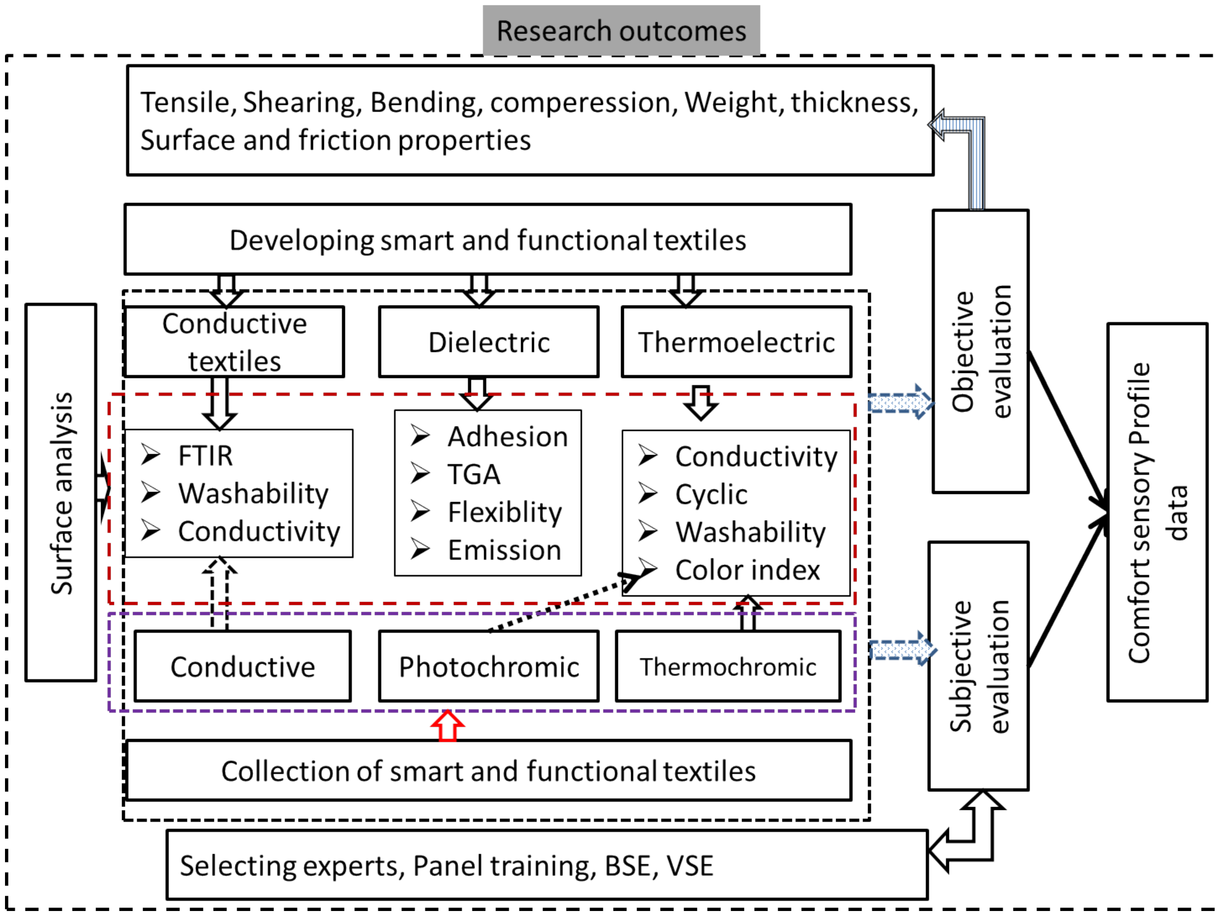


Figure 7.1 Summary of research and contributions; the structure shows the main tasks performed during the whole thesis work procedures starting from development and collection of smart and functional fabrics up to the tactile evaluation via skin contact mechanics using subjective (experts method) and an objective evaluation (KES). Tactile predictions using intelligent systems are not included.

At this time, standards have been already drawn up to evaluate and inspect the quality of traditional textile fabrics used for both in the winter and in the summer wearing suits and dresses. However, until now, there is no such defined set of standards that can facilitate the evaluation and inspection of smart and functional textile fabrics in terms of tactile comfort evaluation. This is a big barrier not only to the smart and functional textile manufacturing industry but also for the customer's satisfaction in terms of smart and functional fabric comfort dimensions. Both have been performed using the traditional way of comfort checking.

In **chapter 1**, we reviewed state of the art technologies used to develop smart and functional textiles fabrics using unique state of the art technologies. Furthermore, surveys on quality inspection and evaluation trends of wearable textiles have been made. Meanwhile, physiological and psychological comfort dimensions of textile-based materials have been reviewed and assessment has been made if it can fit in the case of smart textiles comfort evaluation. Under this, the techniques used to measure the hands of the textile-based structures such as subjective evaluations techniques and the details of the procedure have been elucidated. Kawabata's evaluations systems have been reviewed. Based on the basis discussed in chapter 1, all other chapters are constructed. This chapter explores the fundamental and theoretical backgrounds that have been occurred for the development of smart and functional textile fabrics as well as the quality inspection and evaluation sections. This chapter gives the clue and a brief clarification to the succeeding chapters.

In **chapter 2**, we conducted **three** experimental (**Experiment I, II and III**) researches in the area of smart and functional fabrics development sections; we produced conductive and dielectric samples that could further be evaluated by subjective and objective means. So, this chapter fundamentally deals with the development of smart and functional textile fabrics.

Experiment I: In this sub-chapter, the feasibility of intrinsically conductive polymers to produce conductive textile fabrics has been investigated. To be more specific; the properties and applications areas of the poly (3, 4-ethylenedioxythiophene): poly (styrene sulfonate) (PEDOT-PSS) coated onto textile substrates have been explored. The use of organic liquids such as polyethylene glycol, methanol, and ethylene glycol as a conductivity enhancer using immersion methods has been examined. Surface resistance values of the coated and immersed-polyester fabrics utilizing the aforementioned chemicals have been investigated using four probe measurement principles. The results have been supported by further investigating the samples using Fourier transform infrared (FTIR) and scanning electron microscopy (SEM) analysis methods. The obtained surface resistance values have been dropped by a factor of 100 due to the addition of conductive enhancers. Varying immersion time and temperature conditions (air and vacuum) haven't brought any change to the surface resistance of the samples.

FTIR reports support that PSS chain has been partially removed due to the addition of conductive enhancers. This should be ascribed to the hydroxyl ion (OH) of the conductive enhancers could form a hydrogen bond to PSS cation. The SEM images have shown that PEDOT-PSS has been evenly distributed on the surface of the substrate. In addition, contact angle measurement has been carried out to prove the change in the morphology of the samples and the hypothesis has been right that fabrics accompanying morphology changes after treatment. To prove the electromechanical resistance of the produced samples, washing fastness test has been performed and the result affirmed that the samples have been quiet conductive after 10 washing cycles.

Experiment II: In this experiment, we have produced smart fabrics by combining the knowledge obtained in **experiment I** (coating) and adding a new knowledge of 3D printing technologies. We have manufactured textile-based electroluminescence (EL) device. The device is very flexible and lightweight and could be incorporated with wearable garments.

Thermogravimetric analysis (TGA) was performed to check the stability of the NinjaFlex (TPU) against the temperature; as a dielectric material; the applications for the electroluminescnce device needs to connect to the voltage supply; it needs to check if it can able to support some current flow between the two conductors. After asserting that TPU could withstand temperatures up to 150ºC (using TGA), we have manufactured the EL device. The EL device manufacturing procedure has been as follows: First, we have been coated polyester fabric (rear electrode) using PEDOT-PSS. Secondly, we have been used for 3D printing technology to print TPU filament on top of the coated-fabric. Thirdly, phosphor blue paste (emitter) has been coated onto the 3D-printed TPU. Finally, BendLay filament (transparent and insulating; to protect short circuit) has been 3D-printed on top of phosphor paste by sandwiching copper fabric (front electrode) between the two.

AC current (12 V) has been supplied between the rear and front electrode to give an emission to the dark environment. Furthermore, an adhesion test has been made and the result (4160 N/m) has been confirmed that the TPU has sufficient adhesive properties on the textile substrate. The bending lengths have been increased only by a factor of 0.082 at 0.1 mm TPU thickness as supported by Shirley stiffness tester to check the drapability of the product against bending which proves the flexibility of the EL device.

Experiment III: In this sub-chapter, the electrical surface resistance of the elastic conductive fabric using polyamide-lycra composite was investigated with elongations of 100% that were applied at a rate of 10 mm/min at the wale direction. Cyclic resistance changes were noted during the mechanical elongation-relaxation process. Surface resistance was soundly reversed to its initial value after one minute relaxation time. The electrical surface resistance is amplified during the elongation process and reduced when the relaxation process with 100% extension. This could be attributed to polymer film breaks apart during elongation; even though there is better contact within yarn on stretching. Coated samples could be stretched up to 700% though still practically conductive. The resistance increases only by insignificant amount when samples were stretched cyclically by stretching 100%. Generally, samples prepared by the immersion method kept improving conductivity while stretching than those by the coating method. The sample was proved to be used as a thermoelectric material by measuring the Seebeck coefficient which was ≈ 16 μVK. The flexible conductive materials have been investigated by using SEM images and the results confirmed that the immersion method is better than that of the coating method in terms of even distribution of the polymers on the substrate.

In chapter 3 (Experiment IV): In this chapter, we have extended the investigations on the comfort of the smart and the functional textile fabrics using the traditional subjective evaluation of fabrics. The subjective evaluation of smart and functional textile fabrics have been conducted by textile professionals recruited voluntarily from the same geographical background, mainly students and lecturers from the university. Training has been provided as they were not participated in the subjective evaluation of fabrics. Blind subjective evaluation (BSE) and visual subjective evaluation (VSE) techniques have been carried out according to subjective quality evaluation standards. Fabric-skin-contact and comfort-related properties such as warm/cool, itchy/silky, rough/smooth, heavy/light, hard/soft and other ten bipolar attributes have been selected to assess the ease of the fabric subjectively.

The statistical data analysis method has demonstrated that the maximum and the minimum consensus distance that occurred between judges were 1.61 and 0.58, respectively. This confirms the reliability of the methods employed on the subjective evaluation is acceptable. The correlation coefficient between judges has been up to 96% which indicate the good agreement level on the sensorial perception of the samples between them. The correlation coefficients observed during visual subjective evaluation have shown a better result than that of the blind subjective evaluation.

Therefore, vision is important in the sensorial investigations of the functional fabrics due different patterns and colors created during finishing processes. In conclusion, we can suggest smart and functional fabric manufacturers to use subjective evaluation techniques in a similar manner employed for the traditional fabrics evaluation methods.

Chapter 4 (Experiment V): Chapter 4 extended the quality evaluation techniques using Kawabata's evaluation system of traditional textile into the smart and functional textile fabrics. Fabric samples are the same that used in chapter 3. In this chapter, the low-stress mechanical properties such as tensile, shearing, bending have been scrutinized using KES-F1, KES-F1, and KES-F2, respectively have been determined. Furthermore, compressional, surface and frictional characteristics of the fabric samples have been investigated using KES-F3 and KES-F4, respectively.

Accordingly sixteen fabric-skin-contact interrelated characteristics of the fabric samples have been drawn. These results have led us to differentiate the most comfortable functional fabric among the tested samples. This data can be further used as a quality inspection and evaluation of smart and functional textile fabrics.

Therefore, the smart and functional fabric objective measurement affords a scientific communication channel between the smart fiber producers, smart yarn manufacturers, smart and functional fabric manufactures, and finishers by providing the standardized applications of engineering processes to product standardization, quality control, quality inspection, and product development and manufacture in the smart and functional textile fabric producer industries.

Chapter 5 (**Experiment VI**): This chapter established intelligent systems that can be used to predict the hand values and the total hand values of the smart and functional textile fabrics using finishing parameters and the subjective evaluation given by the panel of experts as an input data. Fuzzy logic and artificial neural-network tools have been employed for the prediction purpose. Functional fabrics have been assessed by a trained panel of judges and finishing and production parameters such as inkjet printing, coating, screen printing, knitting, 3D printing has been taken as the input parameters.

The prediction performances of for both methods were effective as described by calculating the root mean square errors and the relative mean percentage errors. The root mean square errors were within the standard deviation of the population values of the relative mean percentage error were less than 10% for most of the bipolar attributes. This is an indication that both fuzzy logic and artificial neural network can be utilized for the prediction of the hand and the total hand values of the functional fabrics. This further avoids the complicated subjective evaluation methods in the future at least by half.

Chapter 6 (Experiment VII):

In this chapter, first, the comparisons between the subjective evaluation data obtained by human experts and the objective data obtained by Kawabata's evaluation system have been carried out. The relationship between the subjective data and objective data of the functional fabric shows a good correlation. The correlation between the total hand value, evaluated by the experts, and objective data measured by KES-F were also computed. The result shows that bending hysteresis (2HB), mean deviation of friction (MMD), and compressional energy (WC) has recorded the highest correlation coefficients. This indicates that the total hand value of the functional fabric greatly influenced by bending, surface friction and compressional characteristics. The result confirmed also it is possible to evaluate the handle of the functional fabrics both subjectively (human experts) and objectively (KES-F).

Secondly, equations developed for hand evaluation of men's suiting fabric have been employed to calculate the hand and the total hand value of the functional fabrics. The correlation coefficient between the calculated hand and total hand values was computed and the highest correlations were found. This indicates that the equations developed for the men's suiting fabric are suitable to predict the tactile comfort of to that of the functional fabrics.

As a final concluding remark, the work presented in this thesis will contribute in the quality inspection and evaluation of smart and functional textile fabrics using skin contact mechanics principle. The present work deals an opening and representative step ahead on the course of interrogating the feasibility of assessing the tactile comfort of smart and functional textile fabrics using skin contact mechanics principle by integrating the human perception to various tactile comfort descriptors to provide the sensory profile data to the smart and functional fabric developers and manufacturers. By using a vast number of fabric samples and large number of human experts, in the future, a complete sensory profile data that could be used as a standard quality data for the smart and functional textile fabrics manufacturing. By then, quality inspection and evaluation of smart and functional textile fabrics will be standardized. Last but not least when studying comfort, the incorporated materials comfort should not be forgotten. This is because most recently functionality has been introduced by the inclusion of functional or smart material part utilizing either mechanically (weaving, knitting) or chemically (coating, printing, and dyeing).

7.2 Future Works

The main objectives of this thesis work have been achieved, establishing an appropriate sensory profile data in the field of smart and functional textile fabrics. This dataset can be used as a design specification, quality inspection and evaluation based on the basis of the contact mechanics of the smart and the functional textile fabric and the human skin in order to obtain the best quality and wearability products. This result can also be used to develop high quality smart and functional textile fabrics used in the apparel sector which is compatible and comfortable with the human skin. However, further studies are recommended to have a complete data.

Developed sensory profile data need to be improved using a larger sample numbers and human subjects. In this thesis, only 9 fabric samples and 10 human judges were used to assess the subjective evaluation systems. The reasons for this were:

- We had had not sufficient time to produce more samples within the given study period;
- We had had clear-cut constraints in number of human judges;
- We don't have so many options of various smart and functional textile fabrics in the market;
- Optimizations of the subjective & objective assessment of the smart and functional textile fabrics are required to enable the fabric manufacturers to develop new products;
- Applying various equations developed by Kawabata and guarantee if it can be applied to the functional fabrics otherwise developing equations which can be able to predict the tactile comfort of the functional fabrics;
- Using virtual simulation or HAPTEC sensing of virtual textiles to facilitate the e-marketing.

- Developing contact mechanics between the functional fabric and the skin (bone, soft tissue, and tissue) using simulation software like LS Dyna (Finite element method) could be a probable extension of this study.

Various statistical and analysis and soft computing systems may have a better result than that obtained in this thesis work.

In this study, we only employed fuzzy logic and artificial neural network due to the constraint of data. Further numerical and simulation models can be employed based on the data obtained.

This study mainly focuses on the subjective evolution and objective evaluation of smart and functional fabrics and mainly focused on the tactile comfort dimensions. Further study can be suggested to include other comfort dimensions such as thermal comfort. As mentioned in the earlier chapters, this thesis work has two broad focus points namely; development of smart and functional textile fabrics and quality inspection and evaluation of the produced samples. For future, it could be more effective if it can be managed by two separate projects.

We have employed the Kawabata's evaluation system for the objective measurement of smart and functional textile fabrics. Further studies can include fabric assurance by simple testing (FAST), fabric touch tester (FTT) and other ways of objective measurement of the low-stress mechanical properties of the smart and functional textile fabric and results can be compared.

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List of Appendix

Appendix I: History of Functional Fabrics

Table A1. Sample history

Sample	Production details
1. Photochromic (Recipe developed by Sina Seipel. University of Boras. Sweden)	- Substrate: Almedahl-Kinna AB. plain weave ;159g/m^2,rinsed and ironed before printing - Ink: dye: concentration 2.5 g/color Reversacol Ruby Red from Vivimed dyes - Varnish: UV-curable, mixture of monomer. oligomer and photo initiator - Surface tension:30 mN/m; Viscosity =10.6 mPas (at 20 °C and 10000 1/s) - Printing : resolution 300dpi and print head temperature 35°C - Curing stetting :belt speed 100mm/s and UV LED light intensity 30% - Print layers :10 - K/S value (sample 1=1.5, sample2= 1.09 and sample3= 1.3 at 360 nm wave length) - CIE DE value (sample1=2.49,sample2=2.33 and sample3=3.41) - K/S value of grey woven 0.82 at 360 nm wave length - CIE DE value of grey woven =1.27
2. Conductive 3D printed (Recipe developed by Razieh Hashemi-University of Boras. Sweden)	- 4% carbon Nano tube (CNT) (rest poly lactic acid (PLA)) - Substrate: Almedahl-Kinna AB, plain weave ;159g/m^2.rinsed and ironed before printing - Extruder temp 260°C - Build plate temperature :220°C - Size 100x50x0.1mm - Filament dimeter:1.85mm - Sample is produced from the materials obtained by composite of 4% CNT with PLA - The extruder temperature is 250°C - Filament length 563.8 mm/8 min that means produced at a speed of 70.475 mm/min - 3 samples each 200x25x0.1 mm for adhesion - 2 samples each 100x50x0.1mm for subjective and objective evaluation - Plate temperature is room temperature - Plastic weight is 1.89 gram - Filament diameter is 1.85 mm - The sample is stored for 24 hrs. at standard temperature and

	relative humidity and the electrical resistivity was measured with Agilent 34405A multi-meter and reads an average of 0.780 Ω at 18.8°C and 33% RH
3.Dielectric -3D printed	- TPU 100% - Substrate: Almedahl-Kinna AB. plain weave mass of 159g/m^2.rinsed and ironed before printing - Orientation angle 45° - Infill 100% - Build plate temperature:30°C; Extruder temperature 230°C; Speed of machine 800 mm/s and Size 100x100x0.1mm
4. Conductive inkjet (Recipe developed by Melkie Getnet and Junchun Yu. University of Boras. Sweden)	- 1% w/w PEDOT:PSS in deionized water :glycerol in water (6:4 w/w) with 60:40 v/v - Substrate: Almedahl-Kinna AB. plain weave ; mass of 159 g/m^2;rinsed and ironed before printing - Surface tension≈29.mN/m - Viscosity ≈14 mPas (at 20°C and 10000 1/s) - Printing : resolution 300dpi and print head temperature 35°C - Curing 150°C for 10 minutes - Print layers :50 (256x50= 12800 layers) - Surface resistance (S1:0.158 KΩ/□; S2:0.166 KΩ/□; S3:0.181 KΩ/□); Three readings and average was reported (measured by 4-probe principle).
5.Conductive coated	- Substrate: Almedahl-Kinna AB. plain weaves, mass of 159g/m^2; rinsed and ironed before printing - Surface resistance (15x15 cm) (S1:8:08 Ω/□; S2:8.9 Ω/□;S3:6.97 Ω/□): Three readings and average was reported (measured by 4-probe principle) - Three samples with 20 cm x 20 cm also printed.
6.Conductive screen printing	- Substrate: Almedahl-Kinna AB. plain weave ;mass of 159 g/m^2.rinsed and ironed before printing - PEDOT:PSS (60 gram), DMSO (6%-),U2101 (6%) and BGL75N (9%) wt - Stirred (mechanical) at speed of 800 rpm for 15 minutes - Mesh size 70 PET (polyethylene terephthalate) - Dried at 90°C for 30 minutes - Printed 3 time to-and-fro motion - Sample size 21 x 21 cm (longest side is on warp direction) - Surface resistance (S1:4.82 Ω/□;4.38 Ω/□;4.03 Ω/□) Three readings

	and average was reported (measured by 4-probe principle)
7. Conductive knitted (By: Tommy M University of Boras. Sweden)	- composite of Cotton (30/1 Ne) and steel (0.1 mm ϕ; conductivity : 95 Ω/m - Surface resistance 69.1 Ω/□; three readings and average were reported (measured by 4-probe principle).
8. Conductive knitted (By: Tommy M. University of Boras. Sweden)	- Composite of polyester (76/47/1 Dtex ; 47 filaments;10.000 m : weigh 76 gm and 1 thread only) and copper (0.1 mm ϕ ; 2.5 Ω/m) - Surface resistance 0.158 Ω/□; three readings and average were reported (measured by 4-probe principle).
9.Thermochromic (Recipe developed by: Marjan K. University of Boras. Sweden)	- Substrate: Almedahl-Kinna AB. plain weave ;mass of 159 g/m^2.rinsed and ironed before printing - Thermochroic is ChromaZone reversible (Extender (binder)-Zenit / Swedish) - Ink is Variotherm AQ and its activation temperature is 32 ^{O}C - Recipe 5 gm (5 %) thermochromics (ink) and 95 gram (95 %) extender (Zenit) - Screen printed with 70 mesh size PET - Cured at 170 ^{O}C for 7 min - K/S (sample 1=4.4. sample 2=5.0 and sample 3= 4.5 @ 360 nm) - CIE DE value (color difference-sample 1=54.77. sample 2=56.14 and sample 3=51.32) - K/S value of(grey knitted =0.65 and grey woven 0.82 at 360 nm wave length - CIE DE value of (grey knitted=1.12 and grey woven =1.27)

Table A2. Sample Representation.

No	Description	Numeric representation	Alphabetic representation
1	Photochromic (inkjet printed)	1	A
2	Conductive (3D-printed)	2	B
3	Dielectric (3D-printed)	3	C
4	Conductive (inkjet-printed)	4	D
5	Conductive (Coated)	5	E
6	Conductive (Screen-printed)	6	F
7	Conductive (Knitted-Cotton/steel)	7	G
8	Conductive (Knitted-PET/copper	8	H
9	Thermochromic (Screen-printed)	9	I

Appendix II: Sensory Evaluation Questionnaires and other protocols

Subjective evaluation preparatory section

Table II.1 Subjective evaluator details

Evaluator details:
First of all we would like to thank you for participating for this study. The purpose of this survey is to assess the tactile sensation of various smart and functional textiles by skin contact mechanics method (Hand evaluation) for the PhD study of quality inspection and evaluation of smart textile fabric by skin contact mechanics. 1. Name/code --- 2. Gender ◻ male ◻ Female 3. Age ----------------------Nationality------------------------------ 4. Occupation--- 5. You are ◻ expert ◻ Consumer ◻ Other (Please specify)--------------------------- 6. Have you participated subjective evaluation before ◻ Yes ◻ No Please give your suggestions and feeling about the test--

Table II.2 b Tactile Quiz that helps experts to list bipolar attributes.

Names 1) ------------------------**2)** ----------------------- **3)** --------------------------

At the very beginning we would like to appreciate your participation!!! The purpose of this survey is to assess the tactile sensation of various smart and functional textiles by skin contact mechanics method (Hand evaluation) for the PhD study of quality inspection and evaluation of smart textile fabric by skin contact mechanics.

1. What characterstics of the feel of sandpaper you think it is uncomfortable?
   ....
2. What characterstics of silk fabric make it shine
   …………………………………………………………………………………
3. What is thicker, a book with 1000 pages or a book with 10 pages?
   ....
4. When you touch glue, what do you feel?
   ....
5. What feel properties do get in a tissue paper or bandage?
   ....
6. What specific appearance of characterstics of a hard woolen fabric influence on your skin when you wear next to the skin………………………………………..
7. When your skin feels moist /dry, what properties could describe it?
   ....?
8. What do you feel in a fabric product that makes it flexible/stiff
   ……………………………………………………………………………………

Assume you have smart/functional textile fabric on your hand. Mention as many attributes as you can that can describe when you stroke the surface of the fabric
……………………..

Table II.3 Complete list of bipolar attributes for hand evaluation.

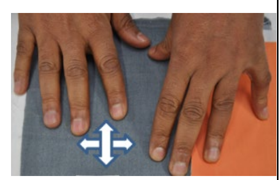
Evaluator________													
Fabric code________		Subjective rating scale											
S/N	Attribute	0	1	2	3	4	5	6	7	8	9	10	Attribute
1	Warm /Cald	Extremely warm					Average					Extremely cold	Cold /Rece
2	Itchy	Extremely Itchy					Average					Extremely Silky	Silky
3	Sticky /Lipicios	Extremely Sticky					Average					Extremely Slippery	Slippery /Alunecos
4	Rough/ Aspru	Extremely Rough					Average					Extremely Smooth	Smooth /Neted
5	Hard /Tare	Extremely Hard					Average					Extremely Soft	Soft /Moale
6	Thick /Gros	Extremely Thick					Average					Extremely Thin	Thin /Subțire
7	Non-compressed /Necomprimate	Extremely Non-compressed					Average					Extremely Compressed	Compressed/ Comprimat
8	Non-stretchable /Neelastic	Extremely Non-stretchable					Average					Extremely Stretchable	Stretchable /Elastic
9	Heavy / Greu	Extremely Heavy					Average					Extremely Light	Light /Usor
10	Stiff /Rigid	Extremely Stiff					Average					Extremely Flexible	Flexible /Flexibil

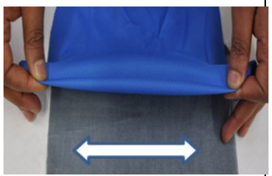
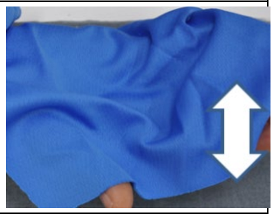
Semantic definitions of every point on the scale (in order to prevent miss scoring): We take Warm-cool as an example:

Table II.4 definitions of scales

Scale	Definitions
0	Extremely warm
1	Very warm
2	Reasonably warm
3	Fairly warm
4	Less than fairly warm
5	Neither warm nor cold
6	Less than fairly cold
7	Fairly cold
8	Reasonably cold
9	Very cold
10	Extremely cold

Table II.5 Definitions and handling techniques of bipolar attributes.

no	Attribute	Definition (+)	Way of evaluation/ sensation to appreciate	Pictures
1	Warm-cool	Giving a cooling /warming sensation when in contact with the skin	Put the fabric on back side of your thumb and feel the coolness and warmness of the surface.	
2	Itchy - silky	Having or causing an itching sensation # Itchy - Is a function of the density of high-load-bearing fiber ends at the fabrics surface & the area of contact between the fabric and the skin	Lay the fabric on the table and move your hand to-and-fro so that you feel itchy	
3	Sticky – slippery	Feeling the presence of greasy or sticky material on the surface # slippery - Sensation of surface character	Lay the fabric on the table and move your fingers on the surface #slippery : Lay the fabric on the table and make your index finger slip on it	
4	Rough - Smooth	Having the surface marked by irregularities or ridges # Rough: Large / small amount of small particles rise on fabric's surface. #Smooth: The surface of a smooth fabric will offer little resistance to slipping when rubbed.	Lay the fabric and move your hand lightly and feel hairiness of the surface # Rough: To put down the fabric on the base of "black box" and with the light pressure to move the palm of the hand across the surface of the sample. # Smooth: Fabric is taken between two fingers of both hands and it is pulled by one hand so that it would slide between two fingers.	

5	Hard-soft	Resistance / non-resistance to compression or bending	Squeeze the fabric sample between your thumb and index fingertips.	
6	Thick-thin	In sensory evaluation procedures, fabric thickness is described as the distance between the face and the backside of the fabric. The smaller the distance the finer the fabric is; likewise. the bigger the distance the thicker the fabric is	The panel member holds the fabric in his/her most used hand. squeezes it with his/her thumb and index finger and defines the fabric thickness according to how he/she feels it	
7	Non-compressible/compressible	Can be compressed Or the force required to compress (squeeze) the fabric	Fold the fabric 3 times and compress the fabric between the thumb and the index finger # The amount of force required to compress the gathered sample in the palm.	
8	Non-stretchable/stretchable	Stretching under pulling in both directions # Degree to which a fabric Stretches without tearing from its original shape.	Take the fabric in the middle of the widths and pull # The edges of the sample are held with both hands then stretched for three times in the same direction. # The degree to which the sample stretches from its original shape.	
9	Heavy-Light	Make an impression of lightness due to the weight of the samples	Lay the piece of fabrics down flat in the hand hollow and make it jump up and devaluate the weight when falling down.	

10	Stiff-Flexibl e	Flexible: Ability of the fabric to bend Stiff: The degree of fabric resistance to bending.	Pinch the center of the piece of fabrics and raise it. The more the fabric is falling. the more it is flexible. ¤ Fabric sample is taken in to the palm where it is clenched and unclenched for three times.	

Table II.6 Complete list of attributes for total hand evaluation

S/N	Fabric code_____	Subjective evaluation for total comfortability (Total handle) The fabric is used for smart and functional application that you can wear				
	Evaluators	**1**	**2**	**3**	**4**	**5**
		The most uncomfortable	Uncomfortable	Medium	Comfortable	Most comfortable
1						
2						
3						

This table was used to evaluate the total sensations of the fabrics intuitively.

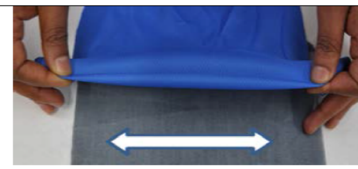
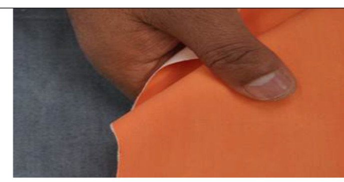
S/N	Physical bipolar attributes	Handling methods	S/N	Physical bipolar attributes	Handling methods
1	Warm.....Cool Cald.........Rece		6	Thick ....Thin Gros.........Subţire	
2	Itchy /silky		7	Non-compressed /Compressed Necomprimate /comprimat	
	Sticky /Slippery Lipicios /Alunecos		8	Non-stretchable /Stretchable Neelastic /Elastic	
4	Rough /Smooth Aspru / Neted		9	Heavy..........Light Greu..........Usor	
5	Hard........Soft Tare........Moale		10	Stiff...........Flexible Rigid...........Flexibil	

Fig. II.1 Handling techniques in subjective evaluation

In Fig.II.1. In addition to the English terms used, Romanian meanings to the word have been used. The reason is all the experts are from Romania so that more clear definitions of the words required.

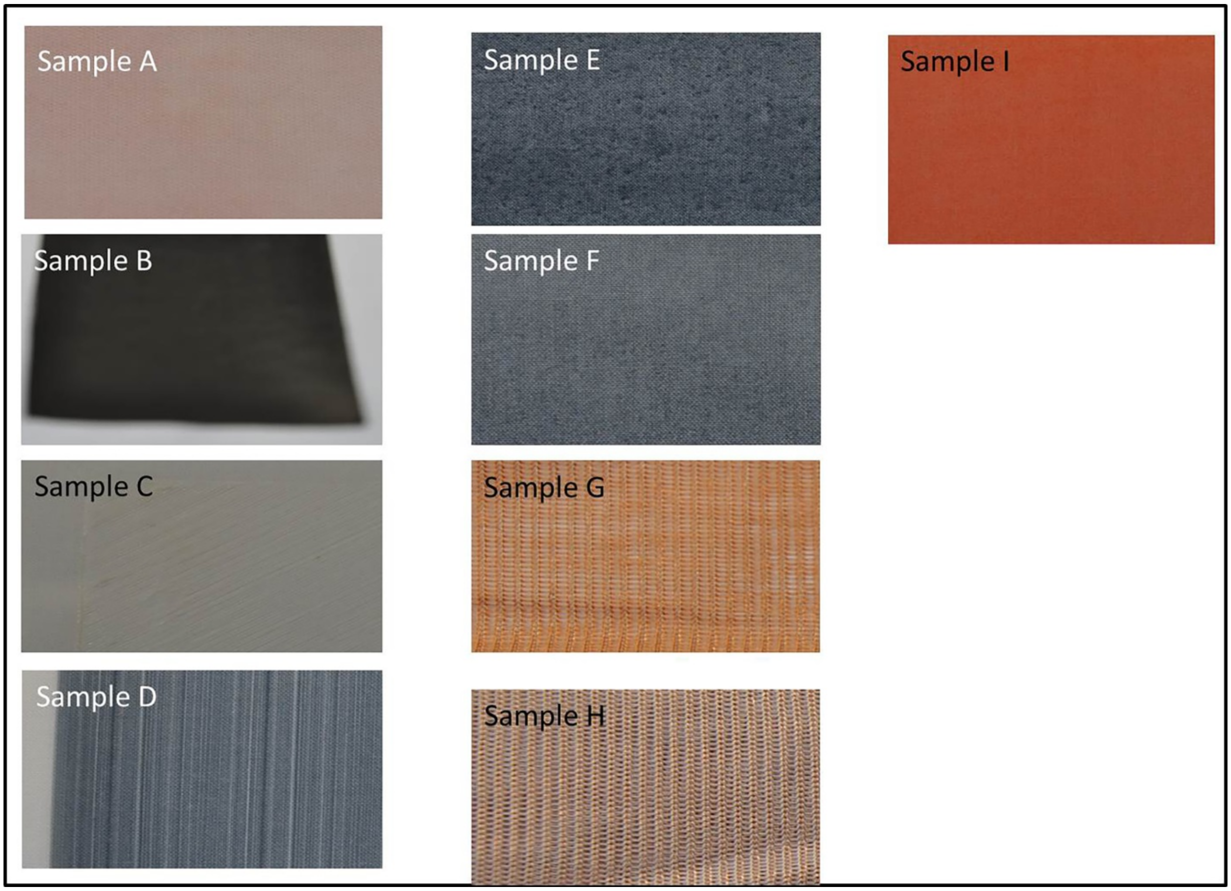


Fig.II.2 Complete list of samples

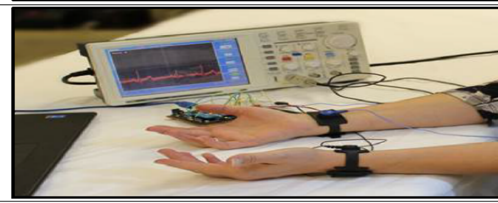
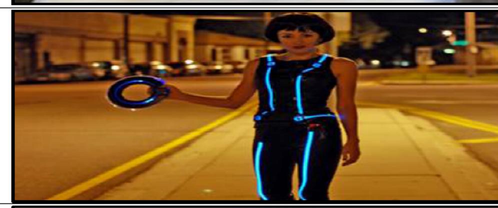
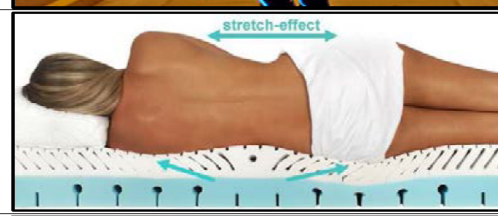
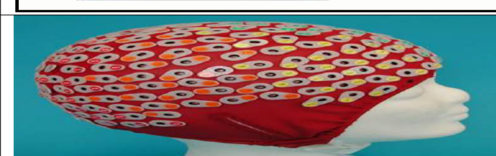
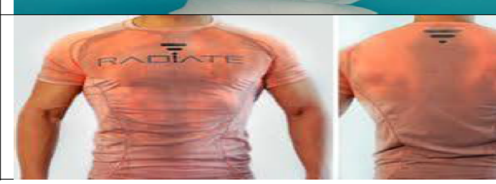
Sample code	Proposed used	Pictorial
A	T-shirts (coloration effects), UV-sensor	
B	T-shirts (Static and EMI shielding)	
C	Dresses (Fashion)	
D	Mattresses (medical)	
E	Military jacket	
F	T-shirts (ECG connection)	
G /H	Cape (EEG for scalp covering)	
I	T-shirts (aesthetic effect)	

Fig.II.3 Proposed applications of samples for total hand value evaluation

Subjective Evaluation Results

Table II.7 Subjective evaluation results for BSE

Fabrics	Variables	WC	IS	SS	RS	HS	TT	NCC	NSS	HL	SF
1	Mean	5.7	3.7	4.2	3.7	3.7	4.4	0.9	0.3	5.4	1.8
	STD	0.82	0.82	0.79	0.95	0.82	1.17	0.99	0.48	1.26	1.14
2	Mean	7.2	1.9	7.8	2.3	1.0	1.8	0.4	0.1	3.0	0.9
	STD	1.23	1.37	1.93	1.95	0.82	1.55	0.70	0.32	1.49	0.74
3	Mean	6.6	6.1	3.0	5.7	4.3	4.6	0.9	0.3	6.5	4.7
	STD	1.65	1.20	1.49	2.36	1.95	1.26	0.57	0.48	1.35	1.06
4	Mean	6.8	6.0	6.1	6.5	6.1	5.9	1.3	0.4	6.7	6.5
	STD	1.81	1.33	1.60	1.51	1.73	1.37	1.25	0.70	1.49	1.65
5	Mean	5.7	4.8	4.3	4.8	4.0	6.2	1.3	0.5	6.0	6.4
	STD	1.16	1.23	1.16	1.23	1.15	1.48	1.16	0.71	1.76	1.07
6	Mean	5.2	6.0	5.5	6.0	4.8	5.6	1.0	0.4	6.5	6.2
	STD	1.03	1.41	1.43	1.15	0.63	1.51	1.05	0.52	0.97	1.69
7	Mean	6.0	1.2	3.0	1.2	2.0	6.2	0.7	6.1	6.6	6.6
	STD	1.49	0.92	1.56	0.92	1.25	1.32	1.06	1.20	1.26	1.43
8	Mean	3.9	1.7	4.8	2.2	2.6	6.0	1.4	6.4	6.2	5.7
	STD	1.37	0.95	0.92	0.79	0.97	1.33	0.97	1.26	1.81	1.49
9	Mean	5.3	4.6	5.6	4.7	2.6	6.2	0.9	0.6	5.4	2.9
	STD	1.16	1.43	1.35	0.67	0.70	1.23	0.74	0.70	0.84	1.29

Table II.8 Subjective evaluation results for VSE

Fabrics	Variables	WC	IS	SS	RS	HS	TT	NCC	NSS	HL	SF
1	Mean	5.7	5.2	3.9	5.5	3.0	5.6	0.7	0.5	5.3	2.7
	STD	0.7	0.9	0.9	1.1	0.7	1.2	0.5	1.0	1.1	1.2
2	Mean	7.6	3.7	7.0	2.6	1.0	1.7	0.6	0.4	3.5	0.8
	STD	1.5	1.4	1.6	1.4	0.9	1.1	0.7	1.0	1.1	0.8
3	Mean	7.5	3.3	2.4	3.8	5.2	5.6	1.2	0.8	3.3	3.2
	STD	1.3	1.3	0.8	1.0	0.9	1.2	1.0	0.8	1.8	1.2
4	Mean	3.6	6.8	7.3	7.1	6.5	6.9	1.5	0.8	5.1	7.2
	STD	1.1	1.2	0.9	1.5	0.8	1.4	0.7	0.9	1.0	1.2
5	Mean	4.7	6.3	4.4	6.2	5.9	5.7	1.6	1.3	6.5	6.0
	STD	0.8	1.2	0.7	1.2	1.1	1.1	1.3	1.6	1.2	1.3
6	Mean	5.7	5.6	4.3	4.7	4.5	4.6	1.3	1.0	7.0	6.0
	STD	0.8	1.3	0.8	0.7	1.5	1.2	1.2	1.2	1.2	1.8
7	Mean	4.3	1.8	5.6	2.5	2.1	4.2	1.4	6.7	6.4	1.8
	STD	0.9	1.5	1.3	1.0	1.1	1.1	0.8	1.1	1.8	1.1

8	Mean	5.9	2.5	3.2	3.6	3.9	7.0	1.3	7.1	7.3	6.1
	STD	1.5	0.8	0.8	1.1	1.2	1.2	1.1	1.0	1.4	2.0
9	Mean	5.5	5.0	5.5	5.4	2.5	5.4	0.4	0.3	6.0	2.8
	STD	1.2	1.2	1.3	1.1	1.1	1.0	0.5	0.5	1.2	1.3

Objective Evaluation Results using KES-FB

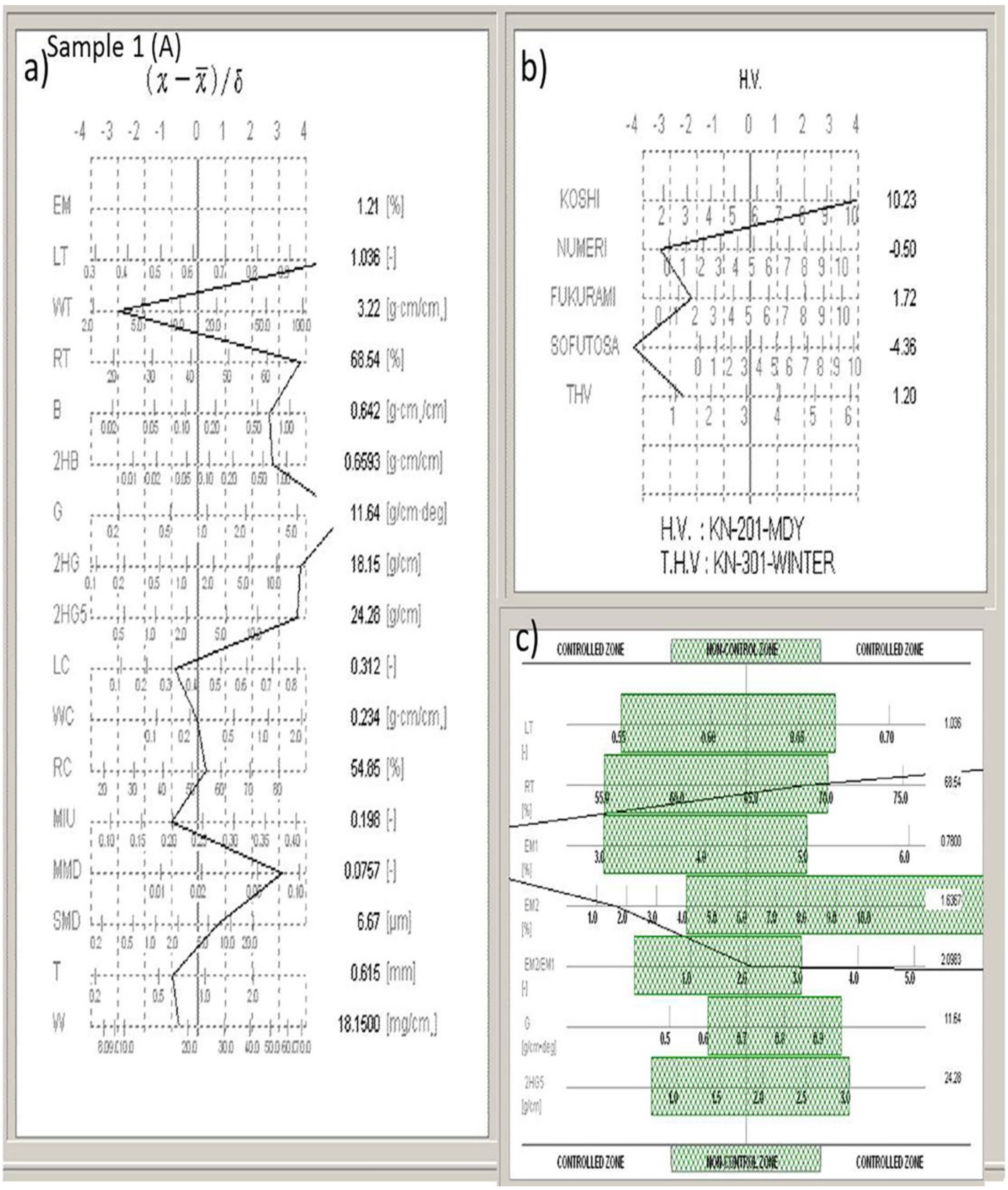


Fig.II.4 Data chart for sample 1 (A)

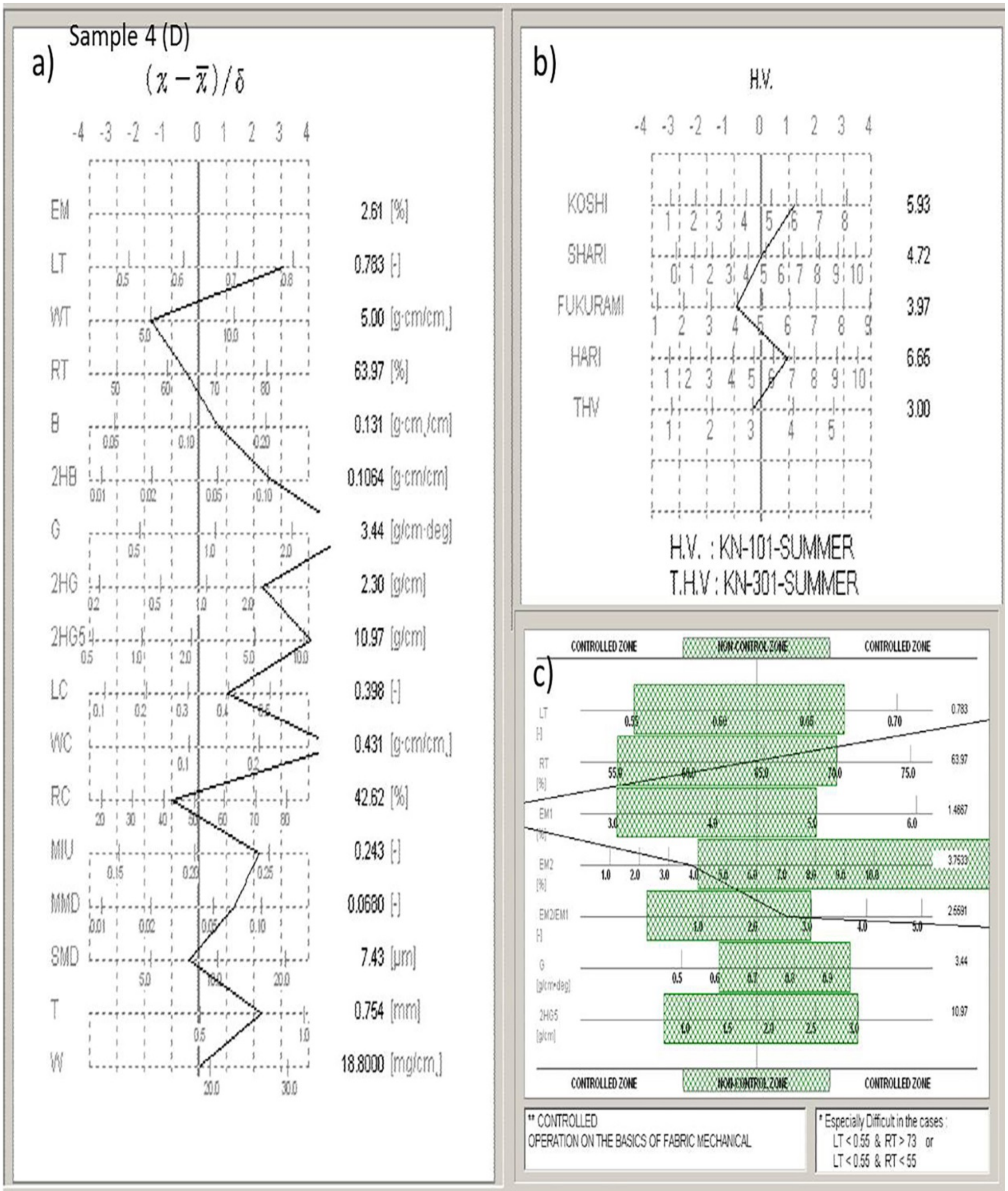


Fig.II.5 Data chart for sample 4 (D)

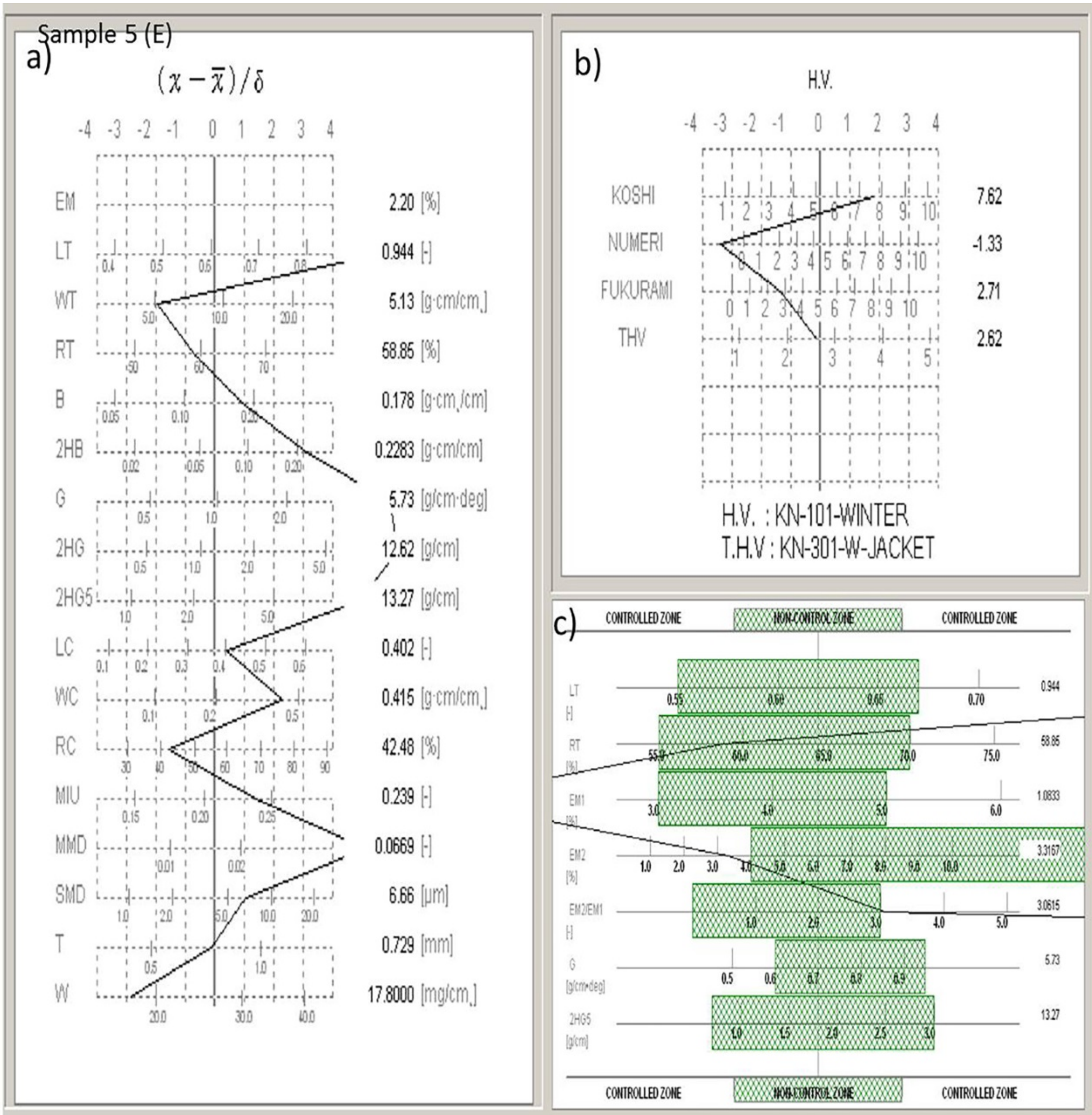


Fig.II.6 Data chart for sample 5 (E)

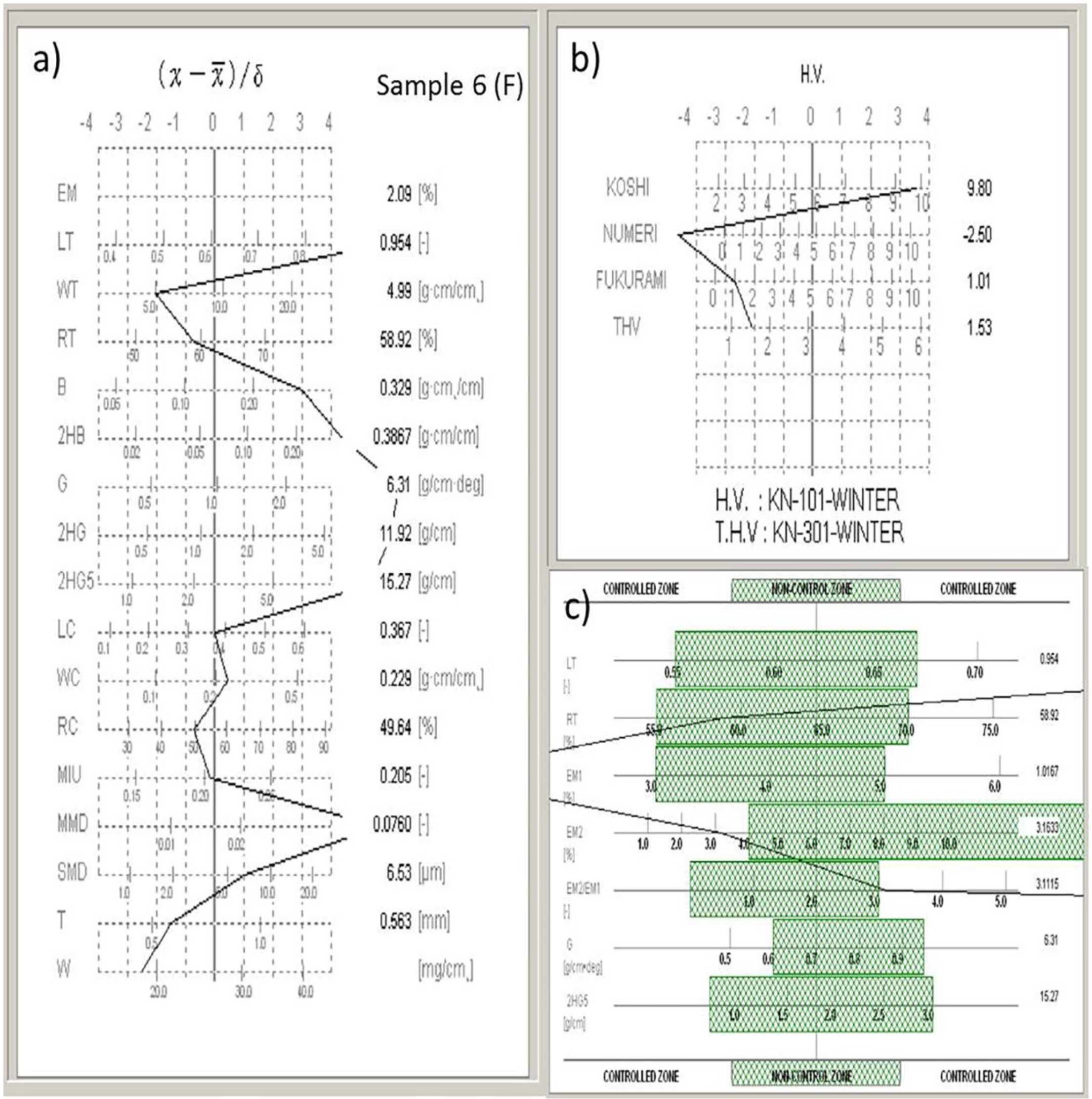


Fig.II.7 Data chart for sample 6 (F)

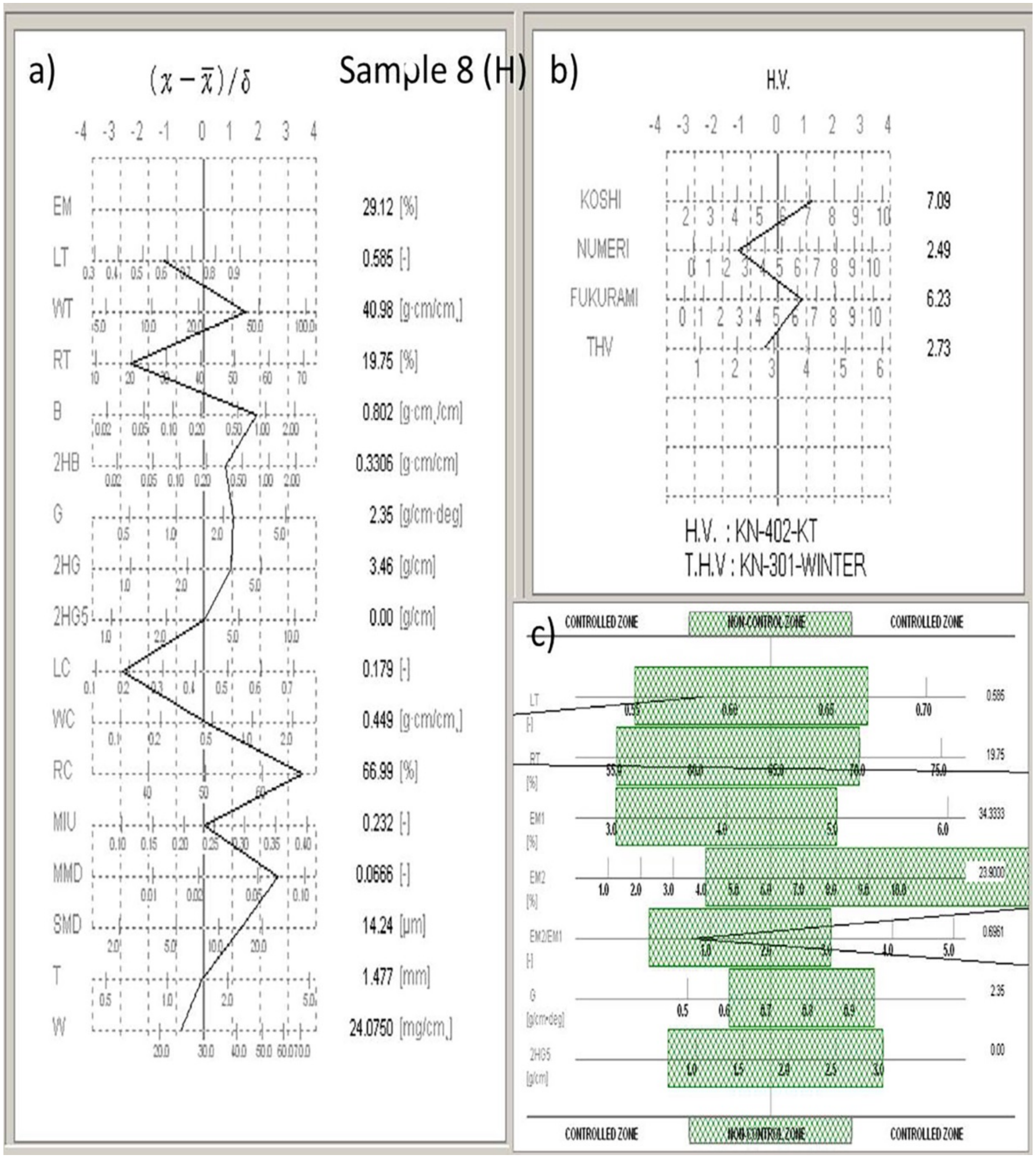


Fig.II.8 Data chart for sample 8 (H)

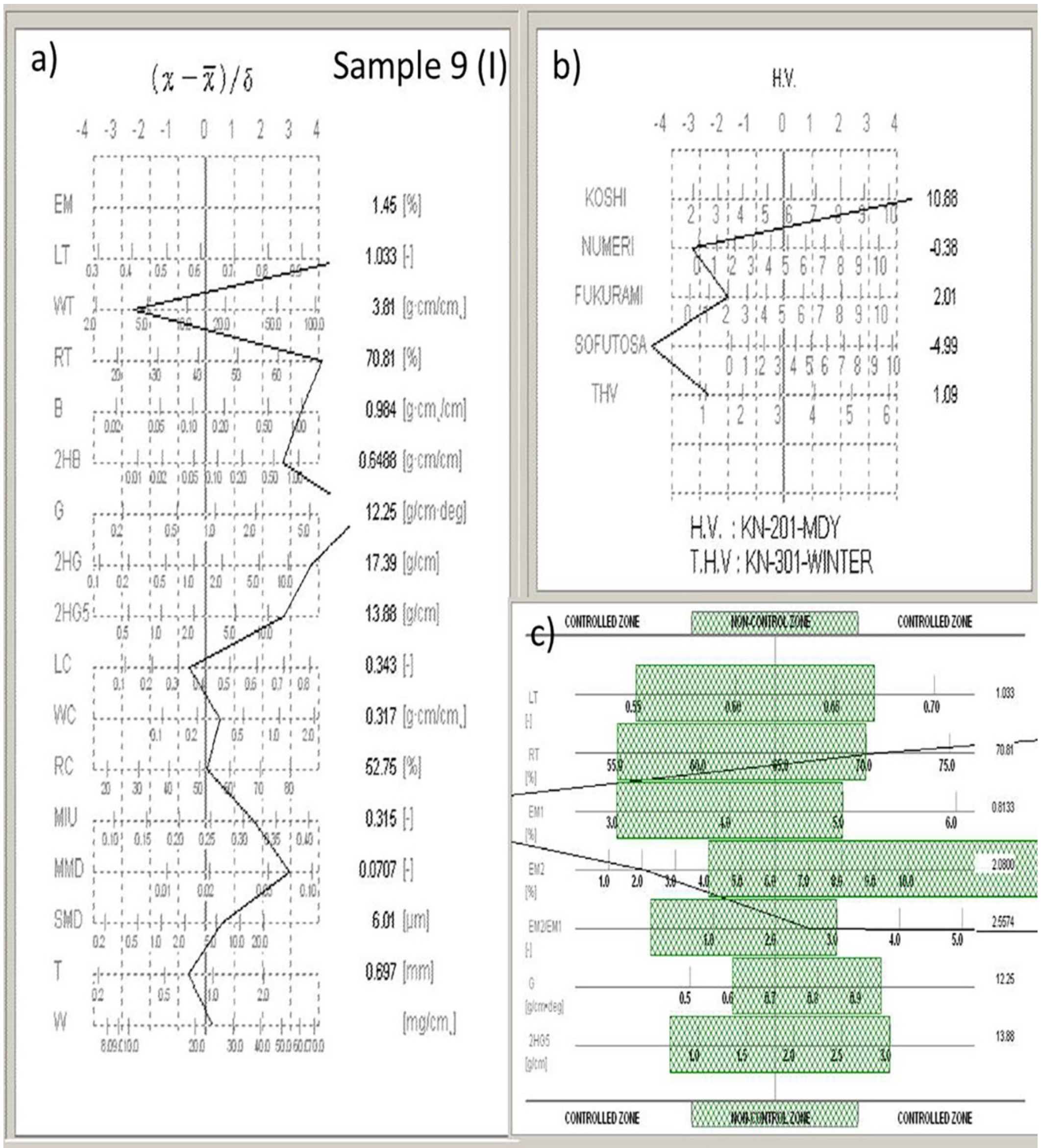


Fig. II.9 Data chart for sample 9 (I)

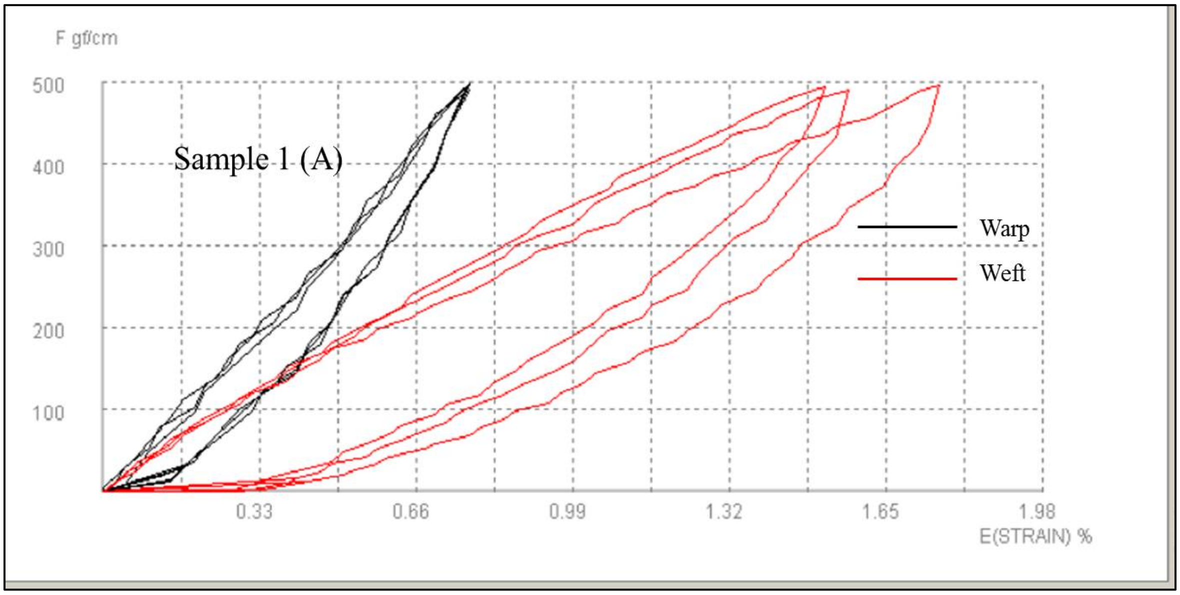


Fig.II.10 Tensile testing results for sample 1

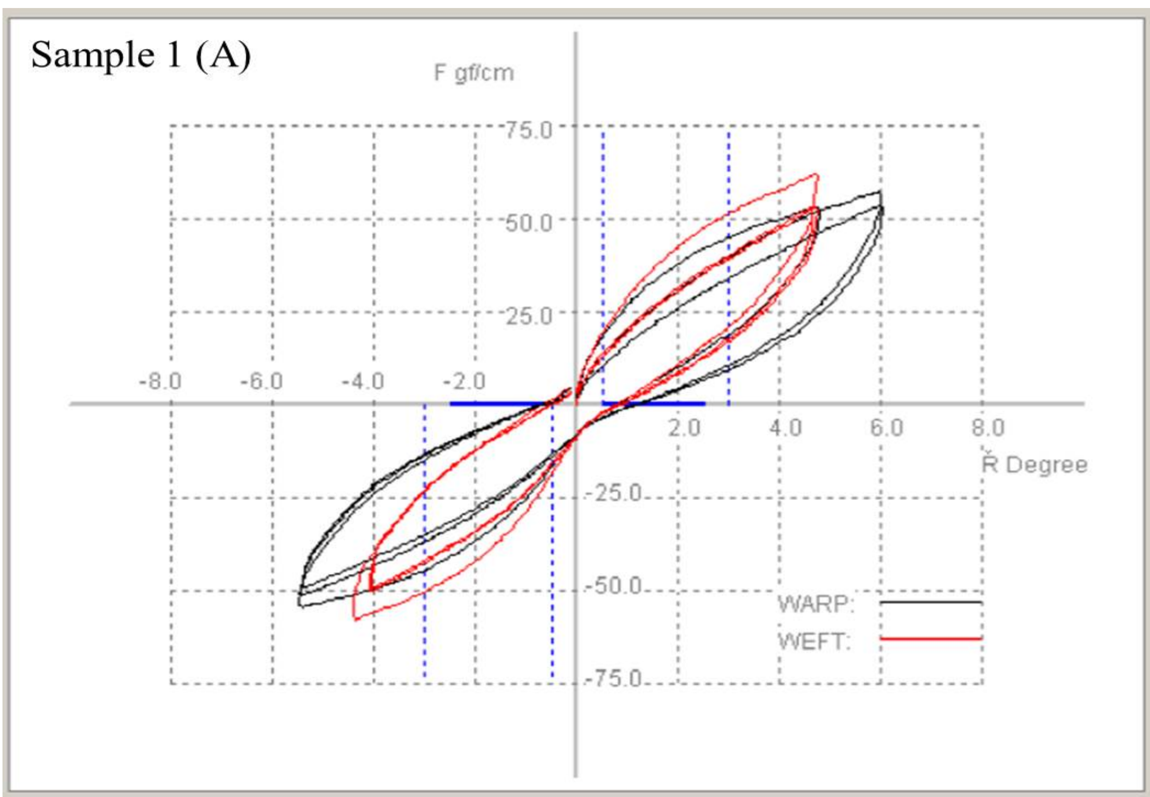


Fig. II.11 Shearing property results for sample 1

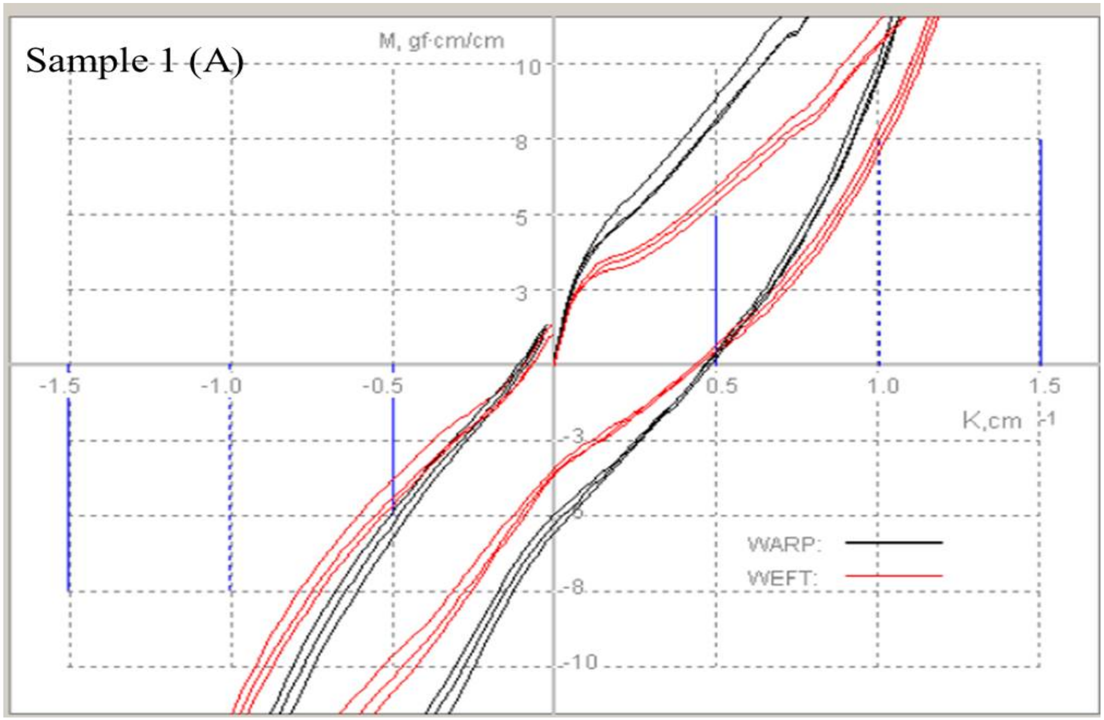


Fig. II.12 Bending property results for sample 1

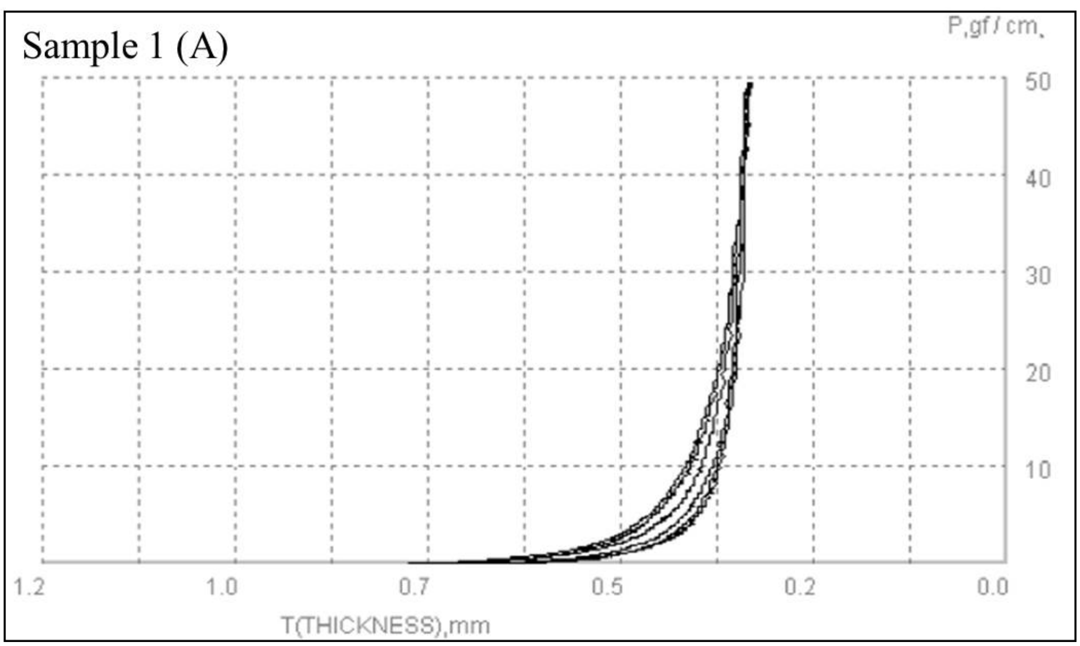


Fig. II.12 Compression property results for sample 1

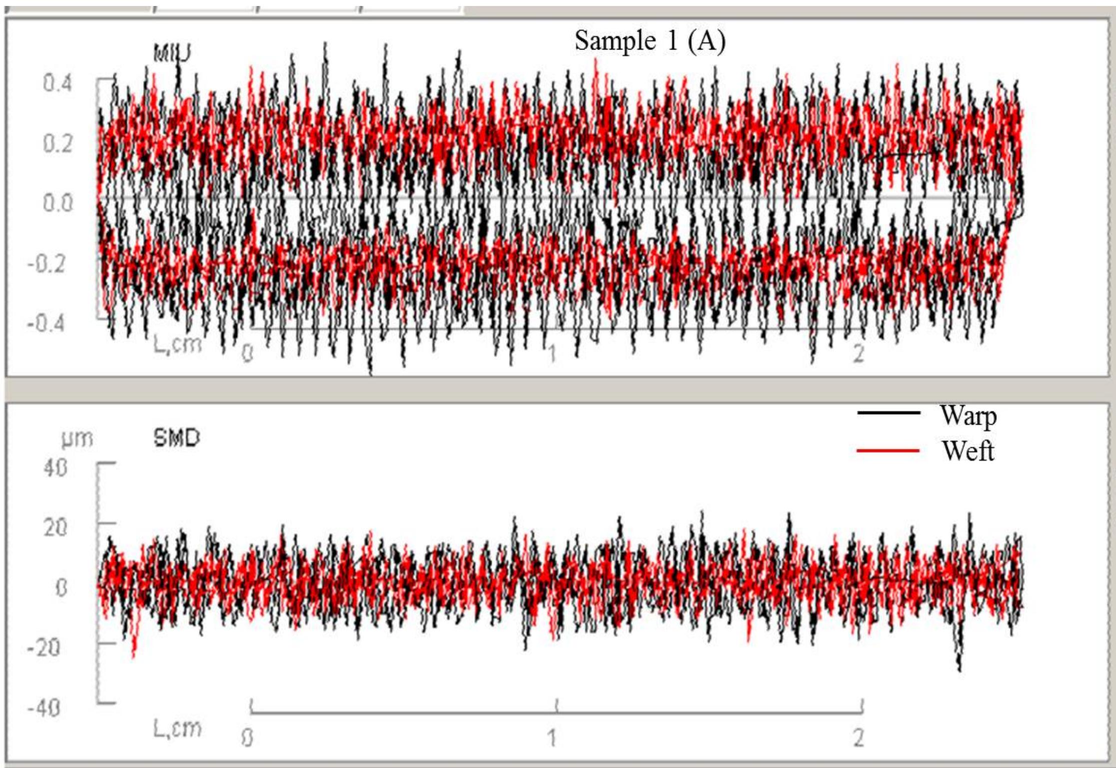


Fig. II.13 Surface friction property results for sample

Appendix III Other Sources

The following table was used to translate the low-stress mechanical properties of the functional fabric into hand values (KOSHI, NUMERI and FUKURAMI).

Table III.1 Parameters of equations KN-101-Winter for translating low-mechanical properties of the samples into hand values (Ci)

	KOSHI	NUMERI	FUKURAMI
0	5.7093	4.7533	4.9799
1	-0.0317	-0.0686	-0.1558
2	-0.1345	0.0735	0.2241
3	0.0676	-0.1619	-0.08897
4	0.8459	-0.1658	-0.0337
5	-0.2104	0.1083	0.0848
6	0.4268	-0.0263	0.0960
7	-0.0793	0.0667	-0.0538
8	0.0625	-0.3702	-0.0657
9	0.0073	-0.1703	-0.2042
10	-0.646	0.5278	0.8845
11	-0.0041	0.0972	0.1879
12	-0.0254	-0.1539	-0.0569
13	0.0307	-0.9270	-0.5964
14	0.0009	-0.3031	-0.1702
15	-0.1714	-0.1358	-0.0837
16	0.2232	-0.0122	-0.1810

Appendix IV: List of publications

Awards

1. From UDiManager electronic platform a reward on research result articles with registration number of PN-III-P1-1.1-PREECISI-2017-18220 on "Effect of liquid immersion of PEDOT:PSS-coated polyester fabric on surface resistance and wettability" *Smart materials and structures* published on May 16. 2017(impact factor 2.769)" (1150 EUR).

Poster presentation

1. **Melkie Tadesse**, Carmen Loghin, Dumitras Catalin, Yan Chen, Lichuan Wang and Vincent Nierstrasz "Subjective evaluation of functional textile fabrics" ITMC2017-*International Conference on Intelligent Textiles and Mass Customization* 15-18 October 2017, Ghent, Belgium
2. **Melkie Tadesse,** Vincent Nierstrasz, "Effects of Process Parameters on Electrical properties of PEDOT: PSS Coated Polyester Fabrics", *Aachen-Dresden-Denkendorf International Textile Conference*, November 24-25, 2016 Dresden, Germany.
3. **Melkie Tadesse**, Vincent Nierstrasz, Carmen Loghin, Dumitras Catalin, Yan Chen, Lichuan Wang "Quality inspection and sensory evaluation for smart textile fabric surface by skin contact mechanics", *16th World Textile Conference AUTEX 2016*, 8-10 June 2016, Ljubljana, Slovenia.

Oral presentations

2. **Melkie G Tadesse,** J Yu, Y Chen, L Wang, V Nierstrasz and C Loghin, "Effect of chemical concentration on the rheology of inkjet inks", *18th AUTEX world Textile Conference,* June 20-22, 2018, Istanbul, Turkey.
3. **Melkie Tadesse,** Luminita Ciobanu and Carmen Loghin, "Assessing the thermal comfort of functional fabrics", *Conference of the TUIASI Doctoral School "New Trends in Research, Innovation and Development"* May 23-24, 2018, Iasi, Romania
4. **Melkie G Tadesse**, Y Chen, L Wang, V Nierstrasz and C Loghin, "Objective evaluation of conductive knitted fabric using KES", *International conference on Innovative Research (ICIR Euroinvent 2018)*, May 17-19, 2018, Iasi, Romania.

5. **M G Tadesse**, D A Mengistie, C Loghin, Y Chen, L Wang, D Catalin, C Müller and V Nierstrasz, "Electromechanical properties of polyamide/lycra fabric treated with PEDOT: PSS" *17th World Textile Conference AUTEX 2017*, 29-31 May 2017, Corfu, Greece.

Paper publications

1) **Melkie Getnet Tadesse**, Carmen Loghin, Yan Chen, Lichuan Wang, Dumitras Catalin and Vincent Nierstrasz, "Effect of liquid immersion of PEDOT:PSS-coated polyester fabric on surface resistance and wettability" Smart Materials Structures *(IOP)* 2018, 26; 065016; (IF: 2.993).
2) **Melkie Getnet Tadesse**, Delia Dumitrascu, Carmen Loghin, Yan Chen, Lichuan Wang and Vincent Nierstrasz, "3D printing of TPU filament onto PEDOT:PSS-coated textile fabrics for electroluminescence applications", *Journal of electronic materials*: (Springer) 2018, 47 (3); 2082-2092 (IF: 1.579)
3) **Melkie Getnet Tadesse**, R Harpa, Y Chen, LWang, V Nierstrasz and C Loghin; "Assessing the comfort of functional fabrics for smart clothing using subjective evaluation", *J industrial textiles (Sage)*, 2019, 48(8); 1310–1326 (IF: 1.285).
4) **Melkie Getnet Tadesse,** Yan Chen, Lichuan Wang, Vincent Nierstrasz and Carmen Loghin, "Tactile Comfort Prediction of Functional Fabrics from Instrumental Data Using Intelligence Systems", *fibers and polymers (springer)*, 2019, 20 (1);199-209 (IF: 1.35),
5) **Melkie Getnet Tadesse** , Emil Loghin, Marius Pislaru, Lichuan Wang, Yan Chen2,Vincent Nierstrasz and Carmen Loghin "Prediction of Functional Fabric Comfort using Fuzzy Logic and Artificial Neural-Network from finishing parameters" *Textile Research Journal* (Sage), DOI: 10.1177/0040517519829008, (IF:1.53) (published online)
6) **Melkie Getnet Tadesse**, Ladislav Nagy , Vincent Nierstrasz, Carmen Loghin, Yan Chen and Lichuan Wang "Low-Stress Mechanical Property Study of Various Functional Fabrics for Tactile Property Evaluation" *Materials* (mdpi) 2018, 11, 2466.
7) **Melkie Getnet Tadesse**, Desalegn Alemu Mengistie, Yan Chen, Lichuan Wang, Carmen Loghin and Vincent Nierstrasz, Electrically Conductive Highly Elastic Polyamide/Lycra Fabric Treated with PEDOT:PSS and Polyurethane: DOI: 10.1007/s10853-019-03519-3, J Mater Sci (accepted).

Conference proceedings

2. **Melkie G Tadesse**, Y Chen, L Wang, V Nierstrasz and C Loghin, "Tactile comfort evaluation of conductive knitted fabric using KES-FB", IOP Conf. Series: *Materials Science and Engineering*, 374 (2018) 012056, doi:10.1088/1757-899X/374/1/012056.
3. **Melkie Tadesse,** Luminita Ciobanu and Carmen Loghin, "Assessing the thermal comfort of functional fabrics", Bul. Inst. Polit. Iasi, Vol. 64 (68), Nr. 1, 2018.
4. **M G Tadesse**, D A Mengistie, C Loghin, Y Chen, L Wang, D Catalin, C Müller and V Nierstrasz, "Electromechanical properties of polyamide/lycra fabric treated with PEDOT:PSS" IOP Conf. Series: Materials Science and Engineering 254 (2017) 072025 doi:10.1088/1757-899X/254/7/072025.