Clothing Patternmaking Method for Stretch Fabrics

Nareerut Jariyapunya, M.Eng.

SUMMARY OF THE THESIS

Title of the thesis: Clothing Patternmaking Method for Stretch Fabrics

Author: Nareerut Jariyapunya

Field of Study: Textile Technics and Material Engineering

Mode of study: Full-time

Department: Department of Clothing Technology

Supervisor: Ing. Blažena Musilová, Ph.D.

Committee for the defense of the dissertation:

Chairman: prof. Ing. Jiří Militký, CSc.	FT TUL, katedra materiálového inženýrství
Vice-chairman: doc. Ing. Lukáš, Čapek, Ph.D.	FT TUL, katedra technologií a struktur
prof. Ing. Karel Adámek, CSc.	
prof. Dr. Ing. Zdeněk Kůs	FT TUL, katedra oděvnictví
doc. Ing. Jan Krmela, Ph.D. (oponent)	Fakulta priemyselných technológií Trenčianska univerzita Alexandra Dubčeka v Trenčíne, katedra numerických metód a výpočtového modelovánia
doc. Ing. Miroslav Svoboda	FM TUL, Ústav mechatroniky a technické informatiky
Ing. Brigita Kolčavová Sirková, Ph.D.	FT TUL, katedra technologií a struktur
Ing Irena Lenfeldová, Ph.D. (oponentka)	FT TUL, katedra technologií a struktur
Ing. Viera Glombíková, Ph.D.	FT TUL, katedra oděvnictví

The dissertation is available at the Dean's Office FT TUL

Liberec 2019

Abstract

In garment industry, stretch fabrics are obtained from the elastomeric fibres that have widely been accepted for its properties especially for the production of tight silhouette and compression garment (CG). The peculiarity of mechanical characteristics of stretch fabric exerted on the part of the body is the pressure of clothing which it is originated from size differences between body dimensions and pattern construction abscissa. The advantage of realizing the importance of the pressure can be implemented and helped produce different types of garment including sportswear, body shaping, lingerie, medical treatment etc. Therefore, the methodology of scientific knowledge for calculating the size of patternmaking in order to obtain the specific pressure from the human body is considered to be one of the very most significant factors for pressure garment production.

Thus, the purpose of this research is to develop the clothing pattern construction abscissa according to human body physical dimensions and mechanical property of stretch fabric. The definition of the mechanical property of stretch fabric achieves from the force-elongation behaviour by tensile testing. The reason is because when fabric is being elongated by force, the amount of the pressure on the surface of the human body will occur. This certain fabric mechanical property will help improve the patternmaking method by determining the value of elastic coefficient which will have a significant influence on the pattern construction abscissa and on the pressure distributing of the stretch fabric. With these reasons, the clarification of both theoretical and practical research were required in order to orient towards the development of computational method that is applied in the process of pattern construction abscissa.

The aim of this work is to develop method of clothing patternmaking for stretch fabric and to define size of pattern construction abscissa by predicting mathematical modelling to achieve the exact shape and size of pattern construction net depending on the specific pressure required.

The experimental investigation is divided into two steps:

1. To define the method for determining the dimension of a particular structural segment of the pattern construction net that is capable of calculating the size of that pattern construction segment according to the dimension of human body thereof.
2. To define the method for calculating the extensibility of fabric from elastic coefficients of clothing that expresses the capability of its specific pressure required for correction of the dimension of a particular structural segment of the pattern construction net.

At the first step, determination of particular structural segment of the pattern construction net had been done by applying the regression method while, the dimension of pattern structural segment (dependent variable) can be calculated depending on the body dimension (independent variable). This research emphasizes on examining the two-dimensional (2D) of patternmaking on the upper part of female body where the body part is similar to the cylindrical shape.

During, the second step of the process, development of methodology was pursued by applying the elastic coefficient by the relevant part of the body and size of patternmaking. The variables are the elastic coefficient of fabric (dependent variables) by changing the value of pressure (independently variable).

Subsequently, a 2D pattern construction abscissa has been investigated and the elastic coefficients were applied in width and length dimensions.

The Elastic Coefficient in Width dimension (ECW) was obtained from the result of stress-strain curve while Elastic Coefficient in Length dimension (ECL) was detected by observing the deformation of fabric stretched behaviour by uniaxial loading and evaluated by digital image analysis using the MATLAB and NIS-Element software.

The prediction of the strain value from the mathematical modelling was related to the geometric model of the cylindrical shape as well as the human body shape and the Laplace's law theory was taken into account. This modelling confirmed the correctness of the strain results by mathematical modelling to calculate the elastic coefficient from the stress-strain curve.

The formulas of patternmaking were derived from elastic coefficient which were applied to the human body under a certain pressure that is necessary to ensure the amount of pressure required for CG applications. A default algorithm has been developed in order to calculate the size of pattern construction net only in particular part as a cylindrical shape of body including fuselage, arms, thighs etc.

This algorithm has successfully been tested to create an automated the block pattern by the PDS Tailor XQ with CAD system which allows the structural segment lines to be modified by inputting the parameter of elasticity coefficients in both ECW and ECL.

The goal of this thesis was successfully realized as well as the problematic area of patternmaking design of clothing for stretch fabrics. At the same time, calculation of the size of pattern construction abscissa investigated the clothing pressure capability was solved by the pilot project.

Keywords: patternmaking; construction abscissa; compression garments; stretch fabric; elastic coefficient; pressure

Anotace

Elastické plošné textilie se ve velké míře využívají pro výrobu oděvů přiléhavé siluety. V některých případech se jedná o kompresní oděvy (dále jen KO). Jejich charakteristickou zvláštností je tlak, kterým působí na tu část těla, na kterou jsou navlečeny, za předpokladu že existuje rozdíl mezi rozměry těla a rozměry výrobku. Mohou to být sportovní oděvy, tvarovací prádlo, oděvy určené pro tlakovou léčbu, apod. Pro jejich navrhování je důležitá znalost metody výpočtu rozměrové deformace při určitém tlaku, jímž výrobek působí na povrch lidského těla. Snahou výrobců KO je tedy vytvořit takový tvar střihové konstrukce, který odpovídá nejen tělesným rozměrům předpokládaného nositele, ale také tvaru těla a v neposlední řadě mít schopnost vhodně definovat závislost mezi fyzikálně mechanickými charakteristikami (silovými) plošné textilie, z které bude elastický oděv vyrobený, a tlakem kterým výrobek působí na povrch lidského těla. To však vyžaduje teoretický a praktický výzkum, který je orientovaný na vývoj výpočtových metod uplatňovaných v procesu navrhování elastických výrobků.

V této práci je experimentálně měřena roztažnost vybraných elastických pletenin na trhacím zařízení, která je charakterizována poměrným protažení při stanoveném zatížení. Důvodem je to, že když se elastický oděv menších rozměrů než je tělo natáhne silou na jeho povrch, vyvolá se jeho rozměrová deformace. Tato vlastnost plošné textilie, která je vyjádřená koeficientem pružnosti, nám pomůže zlepšit metodu tvorby střihové konstrukce. Bude mít významný vliv na stanovení přesných hodnot konstrukčních úseček v závislosti na požadovaném tlaku vybrané textilie. Z tohoto důvodu, cílem této práce je vývoj metody pro definici střihových konstrukčních parametrů KO výpočtovou metodou tak, aby bylo dosaženo přesného tvaru a velikosti střihových dílů v závislosti na potřebném specifickém tlaku.

Postup experimentálního zkoumání je rozdělen do dvou kroků:

1. definice metody pro stanovení rozměru určité konstrukční úsečky v konstrukční síti tak, aby bylo možné vypočítat změnu velikosti této úsečky na základě změny odpovídajícího rozměru lidského těla nebo jeho části.
2. definice metody pro výpočet koeficientu pružnosti elastické plošné textilie, uplatněné na výrobku tak, aby vyjadřoval jeho žádanou svěrnou schopnost a bylo tak možné provádět odpovídající rozměrové korekce konstrukčních úseček.

V první etapě práce se řeší problém popisu geometrie konstrukční sítě. Byla vybrána výpočtová metoda, s uplatněním typu regresní rovnice, pomocí které lze vypočítat rozměr konstrukční úsečky (závisle proměnné veličiny) na základě změny tělesného rozměru (nezávisle proměnné veličiny). Byl zkoumán 2D model střihu dámského elastického výrobku, a to trupová část válcového tvaru.

V druhé etapě práce se řeší problém tlaku, jímž má výrobek působit na příslušnou část těla, a otázka jak ovlivní rozměr střihové konstrukce. Použití vhodné metody pro stanovení koeficientu pružnosti plošné textilie (závisle proměnné veličiny) na základě změny tlaku (nezávisle proměnné). Následně jsou hodnoceny vybrané druhy elastických pletenin s cílem zjistit hodnotu koeficientu pružnosti, který bude uplatněný při modifikaci délkových a

šířkových konstrukčních úseček. Koeficient pružnosti pro šířky je zjištěn z výsledků hodnocení křivky napětí-deformace, zatímco koeficient pro délky byl zjištěn pozorováním deformace napnuté pleteniny jednosměrným zatížením a vyhodnocen analýzou digitálního obrazu pomocí SW MATLAB a SW NIS-Element. Predikce hodnoty deformace z matematického modelování se týkala geometrického modelu válce, válcové části lidského těla a teorie Laplaceova zákona. Toto modelování potvrdilo správnost výsledků zjištěné deformace pleteniny prostřednictvím matematického modelování a definici koeficientu pružnosti z křivky napětí-deformace.

Pomocí vzorců, které byly odvozeny pro výpočet koeficientu pružnosti elastické plošné textilie, která působí na lidské tělo pod určitým tlakem a které jsou nutné pro zajištění požadované hodnoty svěrné síly výrobku, byl vypracován výchozí algoritmus pro výpočty optimálních parametrů střihové konstrukce. Zejména částí, které pokrývají trup, paže, stehna a lze je geometricky definovat jako válec.

Tento konstrukční algoritmus byl úspěšně ověřen při tvorbě automatizované střihové konstrukce dámského tílka v prostředí CAD systému PDS Tailor XQ, který umožňuje korekce konstrukčních úseček prostřednictvím koeficientu elasticity materiálu jak ve směru šířky, tak délky. Cíl práce byl úspěšně realizován. Byla pilotně vyřešena problematika související s navrhováním elastických oděvů a výpočtem konstrukčních parametrů v souvislosti se zkoumáním svěrné schopnosti oděvu.

Klíčová slova: Střihová konstrukce, konstrukční úsečka, kompresní oděv, elastická plošná textilie, koeficient pružnosti, tlak.

Table of Contents

List of Figures

List of Tables

List of symbols

Symbol	Unit	Description
a	$[\mathrm{m}^2]$	Area cross-sectional of the fabric
A	$[\mathrm{m}^2]$	Surface contract area of the fabric
B_i	$[\mathrm{m}]$	Body dimension
C	$[\mathrm{m}]$	Circumference of the cylindrical model or the body
C_0	$[\mathrm{m}]$	initial circumference of fabric
ΔC	$[\mathrm{m}]$	fabric changed in circumference length
C_{PP}	-	Coefficient of pressure perturbation
C_{TP}	-	Coefficient of pressure perturbation due to local stretch
D	$[\mathrm{m}]$	Diameter of the cylindrical model or the body
D_s	$[\mathrm{m}]$	Sensor diameter
E_i	-	Elastic coefficient
ECL	-	Elastic coefficient in length dimension
ECW	-	Elastic coefficient in width dimension
F	$[\mathrm{N}]$	Force on the surface contact / Force applied
h	$[\mathrm{m}]$	Fabric thickness
h_s	$[\mathrm{m}]$	Sensor thickness
K_i	-	Regression coefficient
l	$[\mathrm{m}]$	Fabric stretched length
l_0	$[\mathrm{m}]$	Initial fabric length
Δl	$[\mathrm{m}]$	Fabric change in length
P	$[\mathrm{Pa}]$	Pressure
q_i	-	Absolute term
R	$[\mathrm{m}]$	Radius of cylindrical model
T	$[\mathrm{N.\,m^{-1}}]$	Tension of fabric stretched
U_i	$[\mathrm{m}]$	Construction abscissa
w	$[\mathrm{m}]$	Fabric width
w_0	$[\mathrm{m}]$	Initial fabric width
Δw	$[\mathrm{m}]$	Fabric change in width
δ	$[\mathrm{m}]$	displacement produced by force
ε	-	Engineering strain
$\varepsilon_{Circumferential}$	-	Circumferential strain
$\varepsilon_{Lateral}$	-	Lateral strain
ε_{long}	-	Longitudinal deformation
ε_{trans}	-	Transversal deformation
σ	$[\mathrm{Pa}]$	Fabric stress
φ	$[°]$	Angle of surface area of fabric stretched

1 Introduction

Compression garments (CG) is a special type of clothing that has widely been researched and utilized in the fields of medical, athletic and body shaping applications [1, 2]. The method to help produce CG is rather challenging to achieve especially its specific pressure that depends on the aforementioned application functions. Due to the types of CG are different proposes, therefore, there is a need for differential pressure value for the right performance based on the types of CG [3, 4]. Currently, CG is mainly made from stretch fabric that consists of elastomeric fibre while its commonly used structure for production is the knitted one. This type of structure could be applied for enhancing the performance of CG for better extensibility and higher recovery rate that corresponds to the pressure from fabric stretched that comforts the wearer's body [5, 6]. In garment engineering, there is some confusion existing with patternmaking process of stretch fabric, especially, when attempting to coordinate the degree of extensibility inherent in stretch fabrics and the amount of modification needed to estimate the reduction size of patternmaking. Due to the mechanical property of each stretch fabric its unique and the stretch behaviour is insufficient and has the stretch capability differing in course and wale directions of the fabric. Systematic information about patternmaking methodology of the relationship between stretch fabrics and CG forms is less evident in the publication.

The purpose of this thesis is to develop the systematic patternmaking method for stretch fabric according to the pressure required for customized CG and the four processes of the method are as follows. First, acquisition of body size measurement to achieve the actual size of the human body will be conducted. Second, evaluation the performance of the mechanical property and deformation of stretch fabrics. Third, estimation of patternmaking size will be done by making prediction of strain value based on the relationship between Laplace's Law theory and the result of stress-strain curve. Lastly, development of a new method of patternmaking for stretch materials using CAD systems and inputting the parameter of the elastic coefficient will be done in order to automate the pattern construction abscissa under the regression formula of construction abscissa [2, 7].

2 Purpose and the aim of the thesis

The aim of this research study is to develop a new method of patternmaking for stretch fabric focusing and implementing specifically for the upper part of female body. Additionally, the pressure value of clothing will also be determined by applying Laplace's Law formula into the mathematical model of the strain values of fabric stretched to find out the reduction of elastic coefficient for producing the patternmaking of CG. Thus, the main objectives of this research are four-fold as follows:

2.1 Study of fundamental block pattern garment to define mathematical formulas for pattern abscissa

The block pattern for garment is considered the first step before any modification to reach the advance design and thus, main parameters for making the pattern construction abscissa of body measurements should be defined predominantly in order to elicit mathematical formulas for making pattern construction abscissa. This research will focus on the upper part of female and use a mannequin according to European standard size 38 for investigation before applying with

3D capturing technologies of 3D scanner so as to find out the somatotype of the body in 3D which can further provide more details on the body measurement.

2.2 Study of mechanical properties of stretch fabrics and their performance evaluation

The objective of this study is to evaluate the performance of stretch fabrics undergoing stretch and the properties of stretch fabrics were compared with different factors of elastane composition and knitted structures. The fabrics properties will be tested for stress-strain behaviour using Testometric universal testing machine based on standard EN ISO 13934-1 for testing tensile properties, the standard BS EN 14704-1 for testing the elasticity of fabrics as well as the fabric behaviour of stress relaxation, DWR and deformation were analysis in order to evaluate the fabric performance into the right applications for CG.

2.3 Defining the relationship between stress- strain behaviour and pressure theory to apply on patternmaking

In this part of the research, development of mathematical modelling will be achieved by applying the relationship between the pressure theory of Laplace's law and the result of stress-strain curve. The focused objective is to predict strain value according to specific pressure required and predicted strain result can then be calculated the ECW.

2.4 Development of patternmaking method for specific pressure clothing by using elastic coefficient

The aim of the thesis is to develop the patternmaking method from the pressure required by using the results of fabric property and fabric deformation to find out two mains elastic coefficients of ECW and ECL. Moreover, the patternmaking technology of CAD used in this research is PDS tailor XQ software and a method for calculation of the construction abscissa formula under the regression equation will be used in this research.

3 Overview of the current state of the problem

Currently, the development of patternmaking method for stretch fabric has still been lacked in terms of scientific knowledge that could be used for developing the engineering patternmaking method to achieve the right target of CG. A majority of CG production in garment industries used their own experience to estimate the amount of percentage to reduce the size of patternmaking. Meanwhile, little information is known about patternmaking method based on mechanical property of stretch fabrics which is considered a high demand for the application of CG and thus, with this concern, a solution should be made in order to find out appropriate mechanical properties of fabric that would help determine the applicable patternmaking method to achieve the precise levels of pressure in clothing.

With these mentioned reasons, the researcher of this thesis has been very enthusiastic and tempted to give its full interest in studying patternmaking for stretch materials in order to find out the solution for modifying the methodology of pattern abscissa that has an actual mechanical property of fabric.

4 Methods used, studied materials

4.1 Materials

The materials for this research represent eight commercially produced knitted fabrics with different types of stretch knitted fabrics were varied in percentages for their elastic compositions and structures as shown in Table 1, characteristics of mentioned elastic knitted fabrics were obtained.

Table 1. Elastic knitted fabrics characteristics

Sample	Polyamide		Elastane		Structurer
	(%)	(dtex/ply)	(%)	(dtex/ply)	
S1	90.79	44×2	9.21	22	Single Jersey
S2	87.59	44×2	12.41	33	Single Jersey
S3	74.52	44×2	25.48	78	Single Jersey
S4	94.38	78×2	5.62	22	Single Jersey
S5	92.94	78×2	7.06	33	Single Jersey
S6	83.46	78×2	16.54	78	Single Jersey
S7	72.00	-	28.00	-	Locknit
S8	70.00	-	30.00	-	Interlock

4.2 Methods

Steps in the implementation process to develop the patternmaking method could be divided into three main methods including the making of pattern abscissa, the testing of fabric performance and prediction and investigation of strain value and as shown in Figure1.

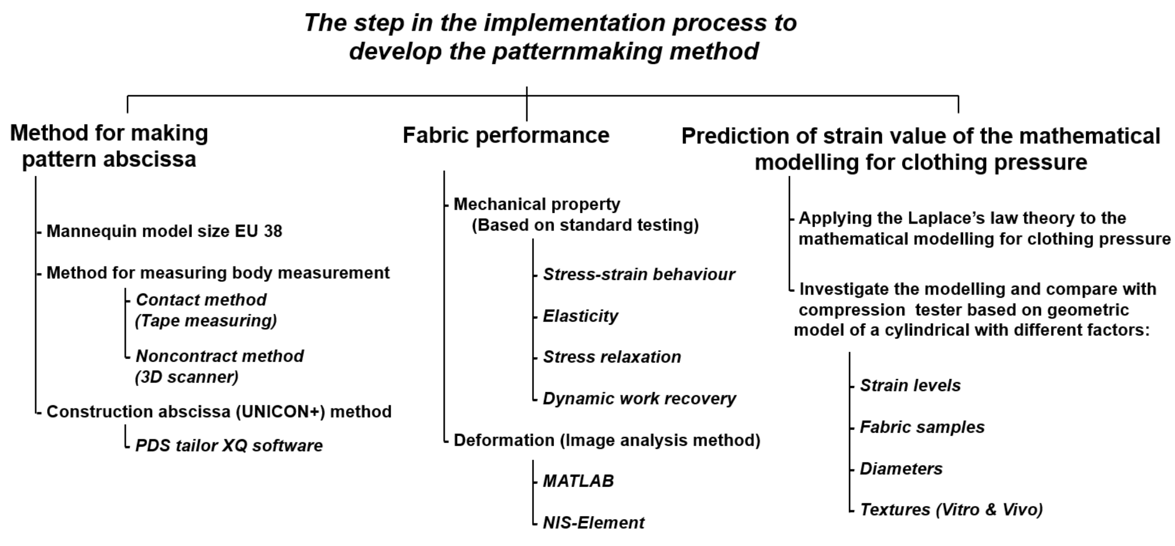


Figure 1. A schematic flowchart of the procedure patternmaking development for stretch fabrics

4.2.1 Patternmaking development method for pressure garments

4.2.1.1 Determination of the patternmaking modification: Determine the patternmaking in this experiment, a female mannequin is used to define the area on the body for the adjustment of patternmaking which is related to the cylindrical shape as shown in Figure 2. The analysis of patternmaking to find out the ECW and ECL on the pressure area is illustrated in yellow.

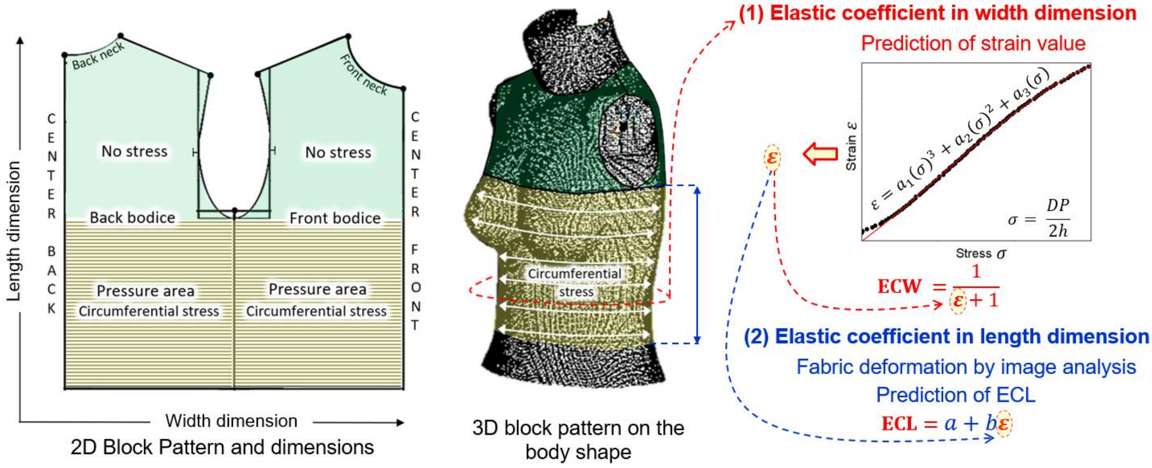


Figure 2. Analysis patternmaking for pressure garment based on pressure area

4.2.1.2 Determination of elastic coefficient: Referring the human body as similar as the cylindrical model as shown in the Figure 3 where illustrates the fabric deformation changed when fabric was stitched without ΔC gap and the fabric was stretched covering on the body. Thus, the compression pressure occurs according to the level of strain value, therefore, it can be indicated that the magnitude of the pressure from stretch fabric can determine from fabric strain which can be calculated by the following equations.

$$\text{Circumferential strain: } \varepsilon_{Circumferential} = \frac{\Delta C}{C_0} \quad (1)$$

$$\text{Lateral strain: } \varepsilon_{Lateral} = -\frac{\Delta w}{w_0} \quad (2)$$

$$\text{Elastic Coefficient: } E_i = \frac{1}{\varepsilon + 1} \quad (3)$$

$$\text{Elastic Coefficient in width dimension: } ECW = \frac{1}{\varepsilon_{Circumferential} + 1} \quad (4)$$

$$\text{Elastic Coefficient in length dimension: } ECL = \frac{1}{\varepsilon_{Lateral} + 1} \quad (5)$$

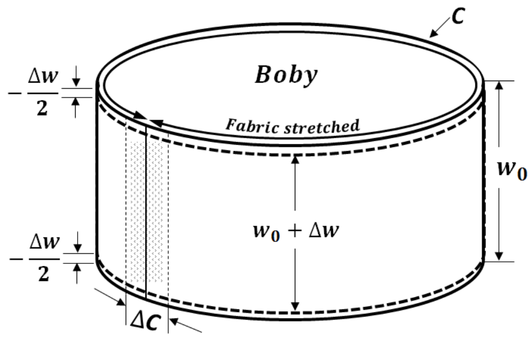


Figure 3. The deformation changed of stretch fabric of circumferential and lateral strain

4.2.1.3 Applying the elastic coefficient coordinate with the body measurement: Figure 4., 2D pattern construction and 3D construction garment are represented to describe two basic steps of calculating construction abscissa including the bust part and the development method of the construction abscissa formula by multiplying the elastic coefficient from the equation (6) is as follows:

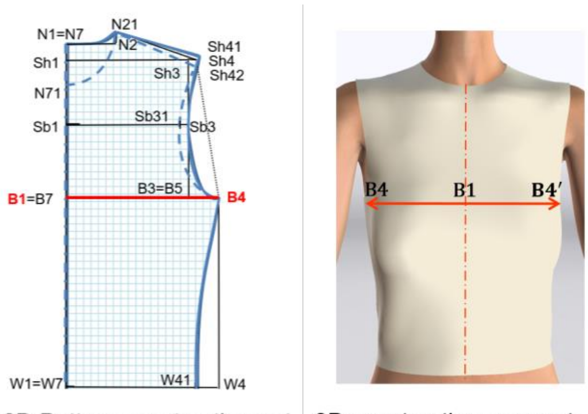


Figure 4. Construction abscissa of 2D pattern net and 3D garment

Construction abscissa development

$$\overline{B1B4} = \left(\frac{\overline{B4B4'}}{2}\right) \times E_i \qquad (6)$$

4.2.1.4 Applying the patternmaking method by CAD software: The development of pattern construction method for this research was conducted by applying PDS tailor XQ software to create the patternmaking through CAD system. Unikon+ method was applied to PDS tailor XQ software to calculate the construction abscissa under the regression formula from the equations.

Primary step of construction abscissa [8]

$$U_{i(p)} = K_i \times B_i + q_i \mp e_i \qquad (7)$$

Secondary step of construction abscissa

$$U_{i(s)} = K_i \times U_{i(p)} + q_i \qquad (8)$$

Construction abscissa development

$$U_{i(s)} = (K_i \times U_{i(p)} + q_i) \times E_i \qquad (9)$$

Where, U_i is Construction abscissa, K_i is regression coefficient, B_i is body dimension, q_i is absolute term, e_i is easy allowance and E_i is elastic coefficient.

4.2.2 Fabrics performance for pressure garments

4.2.2.1 Determination of weight per unit area: The determination of Gram per Square Meter (GSM) is measured according to ASTM D 3776 - 96 standard test methods [9].

4.2.2.2 Determination of thickness: Digital Thickness Gauge M034A was used to determine the thickness of the fabric. Fabric thickness was measured according to standard ISO 5084 the determination of thickness of textiles and textiles products [10].

4.2.2.3 Determination of wale and course per unit length: The number of loops in wale per centimetre and course per centimetre were counted using a pick glass from ten different places and the average of ten readings was taken for both wale and course of fabrics respectively.

4.2.2.4 Determination of strength and elongation properties: Testometric universal testing machine was used to test the tensile of stretch fabrics according to standard ISO 13934-1 [11].

4.2.2.5 Determination of stress-strain behaviour: The stress-strain curve uses the result from the force-elongation behaviour of the experiment of strength and elongation properties is aforementioned to calculate the stress and strain from the equation (10) and (11) respectively.

- Definition of stress σ (Pa) is defined as the force per unit area of a material.

$$\sigma = \frac{Force}{Area\ cross{-}sectional} = \frac{F}{a} \qquad (10)$$

- Definition of strain ε is defined as extension per unit length.

$$\varepsilon = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0} \qquad (11)$$

4.2.2.6 Determination of the elasticity: The elasticity of elastic fabric testing according to standard EN 14704-1 strip test [12].The results of the graph can be calculated force decay due to the time, un-recovered elongation, recovered elongation and elastic recovery.

*4.2.2.7 Determination of the stress relaxation***:** The relaxation procedure of elastic fabrics was investigated by the holed the fabric strain that the test specimens were stretched up to 0.5 with the tensile testing machine and left in this fixed strain for 60 seconds.

$$Stress\ relaxation = \frac{max\ stress\ from\ final\ cycle - max\ stress\ after\ holding\ period}{max\ stress\ from\ \ final\ cycle} \times 100 \qquad (12)$$

4.2.2.8 Determination of dynamic work recovery: The recovery behaviour of fabric or garment is considered to be important in terms of enhancing power of the sports person involved in strenuous sports activity.

$$Dynamic\ Work\ Recovey\ \% = \frac{Area\ under\ the\ unloading\ curve}{Area\ under\ the\ loading\ curve} \times 100 \qquad (13)$$

4.2.3 Fabric deformation measurement by image analysis

This work presents an investigation on local textile deformations during the tensile testing of stretch fabrics in course direction using image analysis technique as shown the Figure 5. The concept of gradient deformation tensor was employed to estimate the relative displacement of marked points on textile surface with dot pattern under different stretch loading of 10 %, 20 %, 30 % and 40 % extension. The distance of marked points between the dots kept at 1 cm both in X axis and Y axis all over the fabric surface. Later, the obtained results were validated with simulated images generated by MATLAB image processing tool box.

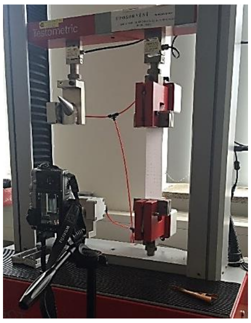


Figure 5. Experimental for setup for image analysis

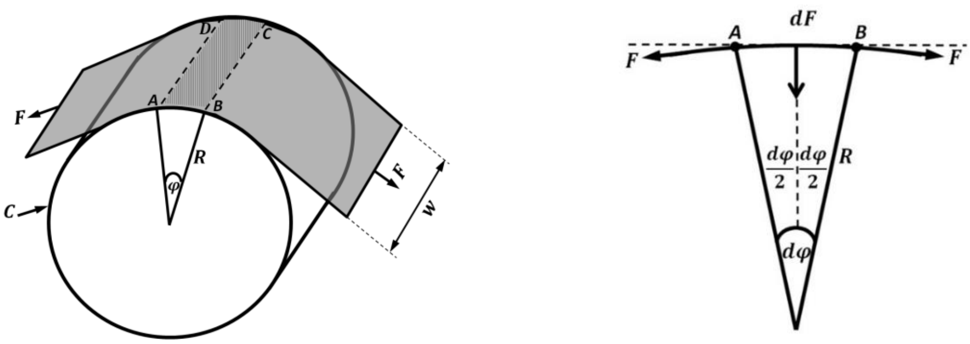
4.2.4 Applying the Laplace's law for CG and evaluating the pressure

4.2.4.1 Applying Laplace's law theory to practice on pressure garment: The aim at this part of the experiment is to describe the compression of pressure garment at which fabric was extended during wearing on the body that is based on Laplace's law theory application.

The following assumptions were accepted in the considerations:

1. The relationship between the pressure of compression garment and force by pulling the fabric extended is described by Laplace's Law as shown in equation (14).
2. The experiment defined fabric extension in a cylindrical shape as similar to human body shape.
3. The circumferential stress is the focus of the testing; therefore, the ratio of thickness to the centre diameter of the cylinder with very less can be neglected.
4. The relation between stress-strain curve will be determined on basic of experiment characteristics for the stress-strain phase of the stretch fabric in 5^{th} hysteresis cycles.

The geometric form of the cylinder is assumed to represent human body figure. Figure 6 (a) illustrates the fabric stretch on areas of (A, B, C, D) shown in cylindrical model below and in Figure 6 (b), contact pressure was demonstrated on the cylinder with a small element of fabric from position A to B.



(a) Fabric stretch on the cylindrical model (b) The pressure contacts on surface area

Figure 6. Fabric stretch showing the force directions on the cylindrical model

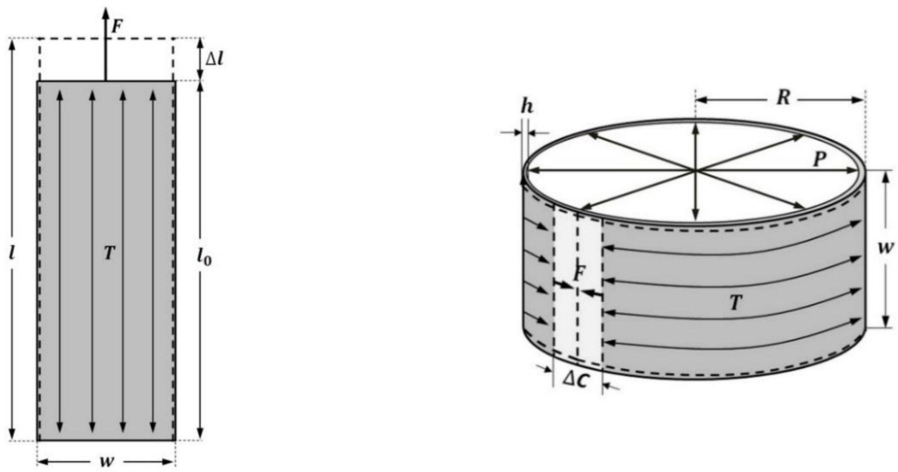
Pressure P is defined as a measure of the force applied over a unit area. Referring, fabric acts at the small area of the rectangle element in Figure 6 (a and b). Finally, adding the contribution from the two-direction we arrive at the Laplace's law for the pressure discontinuity due to force of fabric stretched. It could be observed when dealing with surface tension of stretch fabric, application of Laplace's Law is widely taken part in pressure prediction [6].

$$P = \frac{dF}{dA} = \frac{Fd\varphi}{Rd\varphi w} = \frac{F}{Rw} = \frac{Tw}{Rw} = \frac{T}{R} \qquad (14)$$

In case of considering whole area of cylindrical model, it could be defined that $\varphi = 360^{\circ}$ or 2π as found in the following equation [6]:

$$P = \frac{dF}{dA} = \frac{Fd\varphi}{Rd\varphi w} = \frac{F2\pi}{R2\pi w} = \frac{Tw2\pi}{Cw} = \frac{T2\pi}{C} \qquad (15)$$

4.2.4.2 Prediction of strain value using the mathematical modelling: Referring the tension acting of fabric stretched by tensile testing machine in Figure 7(a) illustrates the loading force F and tension T acting on the fabric and relate to Figure 7(b) represents force F and tension T acting of fabric on cylindrical model.



(a) Fabric tension acting from tensile strength machine (b) Fabric tension acting on cylindrical model

Figure 7. Fabric tension acting on cylindrical model

Stress σ is the ratio of applied force to a cross section area is defined as the force per unit area of a material [6].

$$\sigma = \frac{F}{a} = \frac{Tw}{hw} = \frac{T}{h} \tag{16}$$

Applied the tension $T = \sigma h$ from equation (16) into the equation (15) as follow:

$$P = \frac{\sigma h 2\pi}{C} \tag{17}$$

Then it can be applied for calculating the stress σ as related to the fabric which was extended by pulling force and it is so called the circumferential stress [13].

$$\sigma = \frac{DP}{2h} \tag{18}$$

The stress–strain data points were fitted with a third-order polynomial function is accurate enough to predict the dependence available of strain ε value at the magnitude of independence available of fabric stress σ. The equation, it can be described with the following the model for prediction equation (21).

$$\varepsilon(\sigma) = a_1\sigma^3 + a_2\sigma^2 + a_3\sigma \tag{19}$$

Predicted mathematic modelling of circumference stress, substituting independence from equation (18) of fabric stress in to the cubic function (19) then it obtains the prediction of strain value equation (20) as function prediction model of its dimeter of the cylindrical model D or dimeter of body, pressure P, fabric thickness h and mechanical characteristics of stretch fabric (leading coefficients a_1, a_2 and a_3) [6].

$$\varepsilon = a_1\left(\frac{DP}{2h}\right)^3 + a_2\left(\frac{DP}{2h}\right)^2 + a_3\left(\frac{DP}{2h}\right) \tag{20}$$

4.2.5 Designing experiments to investigate the mathematical modelling with the compression tester

4.2.5.1 Determination of measuring the pressure in vitro model: The experiment on the predictive mathematical modelling method was carried out to find out the pressure values according to the level of strain values of stretched fabric. Conducting an experiment, the strain value of the fabric stretches on the rigid cylindrical model was used at 0.79 m and 0.505 m circumferences and the initial circumference of the fabric length of was determined from the strain value at 0.1, 0.2, 0.3, 0.4 and 0.5. The initial circumference C_0 was calculated by following equation [6, 14].

$$C_0 = \frac{C}{\varepsilon+1} \tag{21}$$

4.2.5.2 Effect of sensor thickness for measuring the pressure: Concerning the usage of compression tester PicoPress®, it could be found that when thickness was 0.2 mm, no inflation occurred, however; in case of 3.00 mm, inflation did occur significantly [15, 16]. With this reason, predictive modelling should be applied on the particular area of the sensor. Concerning sensor determination, sensor diameter is D_s 50.00 mm where the area of sensor contacts on fabric and creates the angle φ by radius of the cylindrical model as shown in the Figure 8.

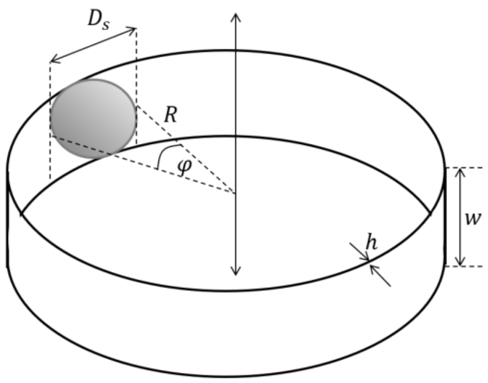
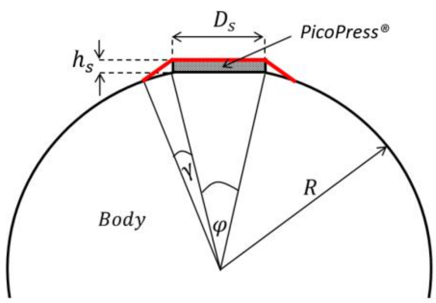


Figure 8 The sensor area of compression tester [6]

Due to the thickness of the PicoPress® sensor itself when measuring compression, an overestimation of pressure had occurred as shown in the Figure 9. Thus, to eradicate the problem, a reduction of the over stress will be taken part in order to unravel the overestimation [17]. As proposed by Vinckx [18] in the model, equation (22) was applied to estimate the pressure perturbation or coefficient of pressure perturbation (C_{PP}).



$$C_{PP} = \frac{sin(\frac{\varphi}{2}+\gamma)}{sin(\frac{\varphi}{2})} \tag{22}$$

$$\varphi = \frac{D_s}{R}$$

$$\gamma = arccos(\frac{R}{R+h_s})$$

Figure 9. The sensor of compression tester acting under fabric stretched on the cylindrical model [6]

The stress area as mentioned in equation (23) represents the local area of sensor diameter D_s and sensor width w. It is a necessity to determine the coefficient of pressure perturbation due to local stretch C_{TP} under the sensor as shown in the following equation (24) [6]:

$$P = \frac{F}{A} = \frac{F\varphi}{R\varphi w} = \frac{\sigma h w \varphi}{D_S w} \tag{23}$$

$$C_{TP} = \frac{\sigma h w \varphi / D_S w}{\sigma h w \varphi / \pi \left(\frac{D_S}{2}\right)^2} = \frac{\pi {D_S}^2}{4 D_S w} \tag{24}$$

The total pressure perturbation then can be calculated by [19].

$$\mathit{The\ total\ pressure\ perturbation} = C_{PP} \times C_{TP} \tag{25}$$

Where C_{PP} is coefficient of pressure perturbation due to sensor dimension and C_{TP} is coefficient of pressure perturbation due to local stretch.

The correction factor for the measuring the pressure values can be applying by following Khaburi, Dehghani-Sanij, Nelson and et al. [17] equation:

$$\mathit{Correction\ factor} = \frac{1}{\mathit{The\ total\ pressure\ perturbation}} \tag{26}$$

The equation (26) was used for calculating the correction factor of the compression tester PicoPress® in order to get the actual pressure results for this experiment.

4.2.5.3 Determination of measuring the pressure in vivo model: The experiment was used the same procedure of measuring the compression pressure with rigid cylindrical model. Conducting an experiment, the strain value of the fabric stretch on the thigh part of the human body was used at 0.505 m circumferences which the thigh shape assumed as a cylinder shape.

4.2.6 Development and application of a novel tensile measurement device

4.2.6.1 Determination of the elasticity: The experimental design of the manual tensile testing device as shown in Figure 10 was referred to the elasticity of elastic fabric testing.

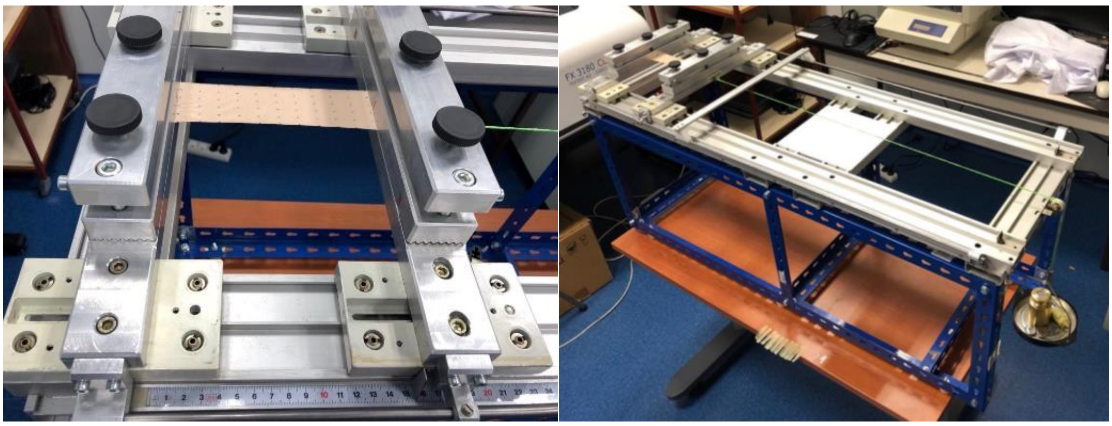
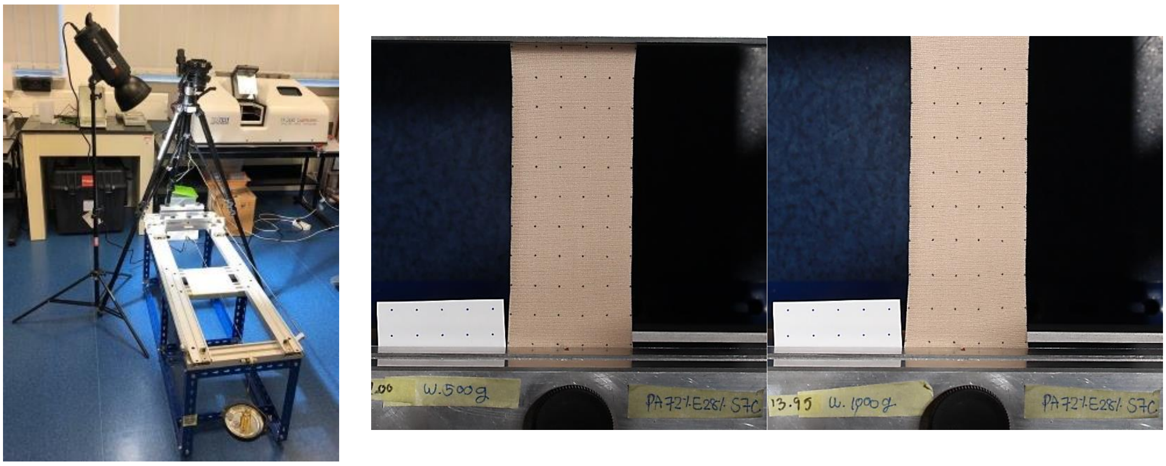


Figure 10. The experimental design and testing of manual tensile testing device

4.2.6.2 Determination of fabric deformation measurement using NIS-Element: The image acquisition and analysis, the specimen was applied with black dot pattern and the distance between the dots kept at 1 cm both in X axis and Y axis all over the fabric surface. The setting method as shown in Figure11(a) and the deformed images are shown in Figure 11(b).



(a) Camera and lighting set up for the experiment

(b) The fabric deformation by images from sample S7

Figure 11. The experimental design for capturing the images from manual tensile testing device

5 Summary of the results achieved

5.1 Mechanical properties of elastic fabrics suitable for CGs

5.1.1 Preliminary testing of elastic fabrics to obtain preliminary data of fabrics

Preliminary data results for GSM, thickness, stitch density of wale and course per unit length, fibre composition of Polyamide (PA) and Elastane (EA), fineness of yarn and structure of knitted fabrics were determined as per standard testing methods shown in the Table 2.

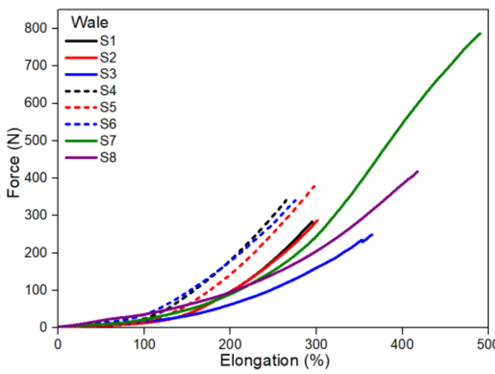
Table 2. Elastic knitted fabric characteristics

Sample	GSM (g/m^2)	Thickness (mm)	Wale per cm.	Course per cm.	PA (%) (dtex/ply)	EA (%) (dtex/ply)	Structure
S1	215.21 (±0.017)	0.55 (±0.004)	24 (±0.196)	35 (±0.196)	90.79 (44×2)	9.21 (22)	Single jersey
S2	218.18 (±0.011)	0.55 (±0.005)	24 (±0.261)	35 (±0.261)	87.59 (44×2)	12.41 (33)	Single jersey
S3	260.47 (±0.012)	0.50 (±0.004)	21 (±0.196)	39 (±0.261)	74.52 (44×2)	25.48 (78)	Single jersey
S4	270.87 (±0.012)	0.60 (±0.005)	19 (±0.196)	32 (±0.196)	94.38 (78×2)	5.62 (22)	Single jersey
S5	305.14 (±0.01)	0.61 (±0.004)	19 (±0.196)	35 (±0.196)	92.94 (78×2)	7.06 (33)	Single jersey
S6	318.49 (±0.01)	0.57 (±0.004)	19 (±0.196)	34 (±0.196)	83.46 (78×2)	16.54 (78)	Single jersey
S7	319.66 (±0.01)	0.79 (±0.006)	21 (±0.392)	36 (±0.523)	72.00	28.00	Locknit
S8	310.00 (±0.007)	0.64 (±0.005)	20 (±0.392)	38 (±0.392)	70.00	30.00	Interlock

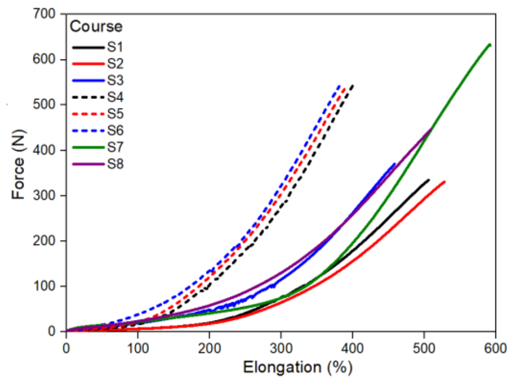
Note: *"±"is the upper and lower 95% confidence interval of the mean*

5.1.2 Physical testing for performance and serviceability of fabrics

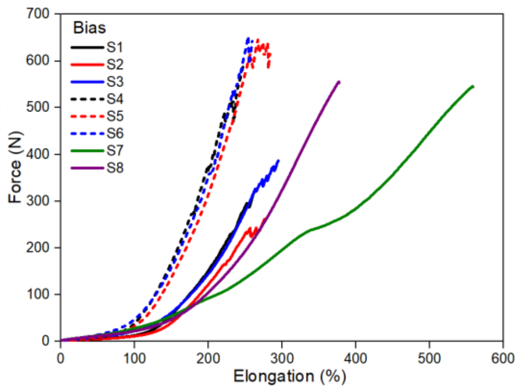
5.1.2.1 Force and elongation characteristics: Figure 12 (a, b and c) It was observed that locknit structure work done, and efficiency possessed higher extensibility values than single jersey and interlock of knitted fabrics structures when compared. Overall, types of knitted structure and fabric direction signified an influence on the performance of extensibility. When mentioning the fabric direction, course direction has outperformed the wale and bias directions and thus, the course direction is rather suitable for pattern construction along the body circumference.



(a) Graph force-elongation in wale direction



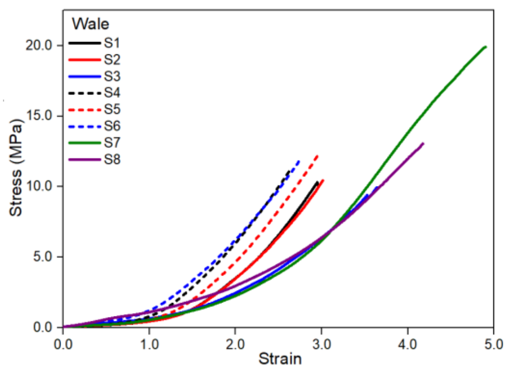
(b) Graph force-elongation in course direction



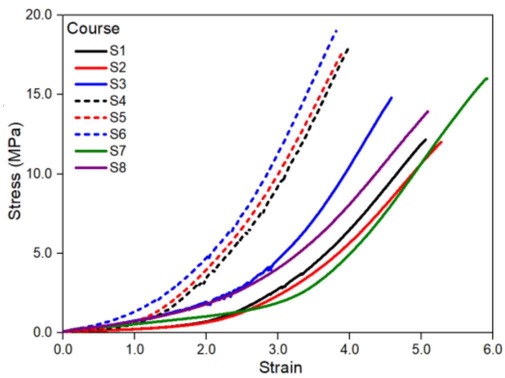
(c) Graph force-elongation in bias direction

Figure 12. Graphs of force-elongation characteristics in different directions

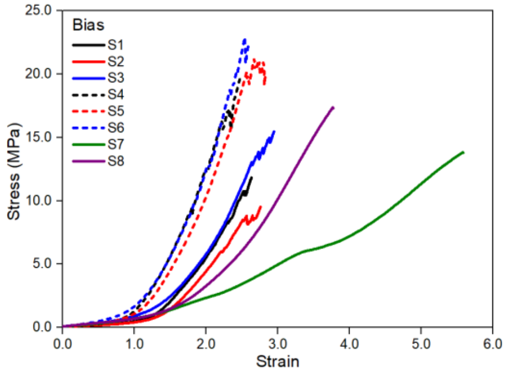
5.1.2.2 Stress and strain behaviour:



(a) Graph Stress-strain in wale direction



(b) Graph Stress-strain in course direction



(c) Graph Stress-strain in bias direction

Figure 13. Graphs Stress-strain different directions of 8 samples

The graphs in Figure 13 (a, b and c) illustrates the stress-strain curves in wale, course and bias directions. The results were analysed in accordance to the fabric structure and the samples of single jersey structure (S1 -S6) were compared with different yarn count of elastane at the number 22 dtex (black), 33 dtex (red) and 78 dtex (blue) and constant yarn count of Polyamide at 44 dtex (line) and 78 dtex (dash line) as shown in the graphs. It could be found that the number of yarn count of elastane has a significant influence on the stress value when yarn count number of elastane has higher stress value.

5.1.2.3 Elasticity: The experiment was determined the limit of patternmaking allow for reduction size of patternmaking at the maximum 50% of the actual size of block pattern.

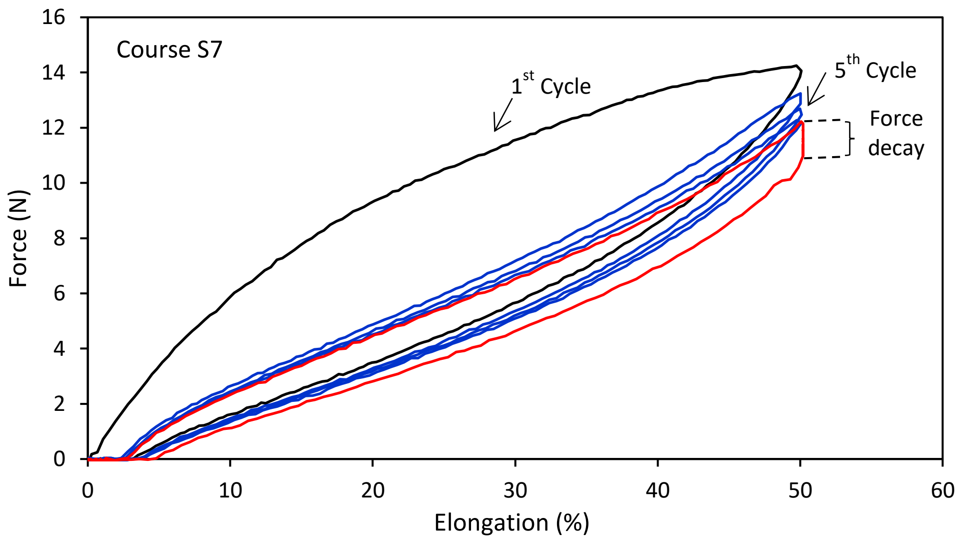
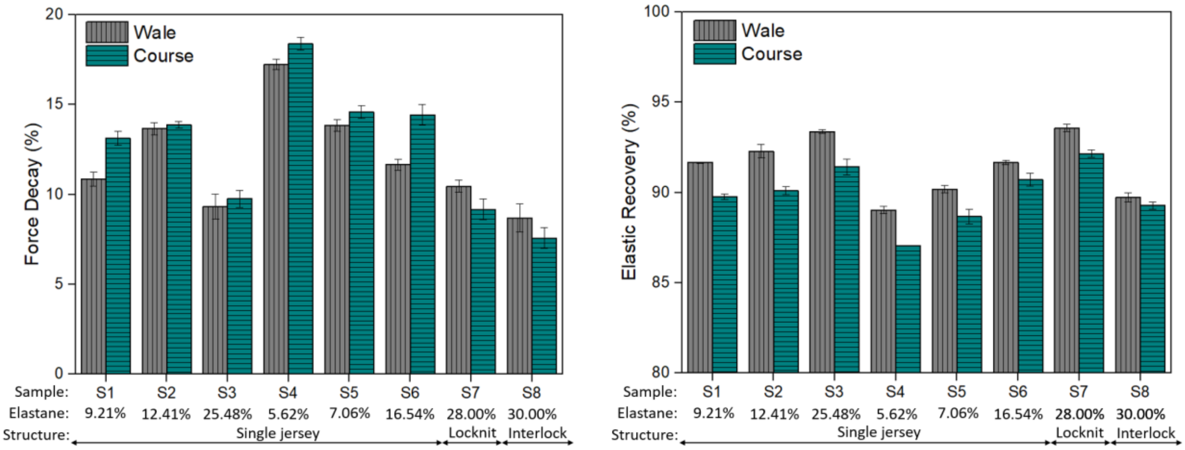


Figure 14. The hysteresis loops 5th cycle of S7 in course direction

Figure 14 illustrated the hysteresis loops of the sample S7 in course direction and obviously, at the 1st loading, there was an extremely high force value. Due to the inertia in fabric, the effect on friction among yarns in course and wale directions at the first time has occurred. While after first loading, the friction was less and the results of force values were very close ones. The graphs of comparative force decay and elastic recovery are given in the Figure 15 (a and b) respectively.



(a) The graph comparative force decay over the time (b) The graph comparative elastic recovery

Figure 15. Graphs comparative the influence of elastane composition on force decay and elastic recovery

In this section, One-way ANOVA is analysed and the selected value of significance for all statistical tests in the study shall be 0.05. The One-way ANOVA statistic results were found that the percentage of elastane has significantly influenced on the percentage of elastic recovery ($F_{Critical} < F_{Statistic}$) and ($P < 0.05$). Whilst, percentage of force decay has insignificantly been affected by the percentage of elastane. The statistical analysis indicated that the group of the percentage elastane, force decay over the time and elastic recovery are significantly different.

5.1.2.4 Stress relaxation: Stress relaxation is considered as one of the main factors that may take an effect on compression garment. This experiment was conducted to fix strain at 0.5 in the fifth cycle that could hold the elongation period up to 60 seconds. The results of stress value were compared and expressed in Figure 16.

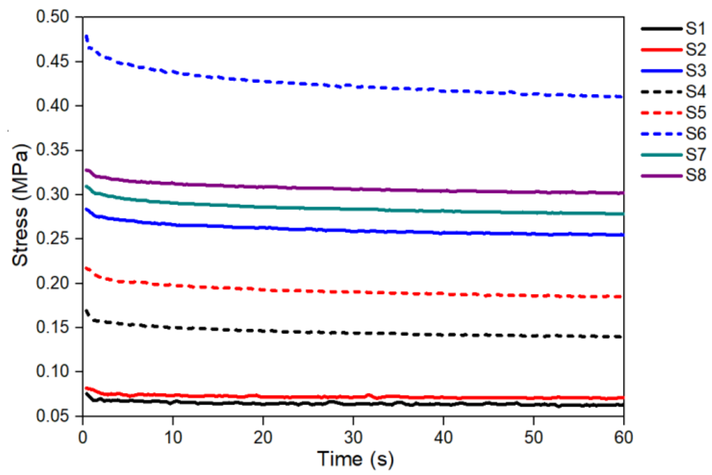


Figure 16. Comparative the stress relaxation over the time

It was found that the stress value is rather higher when yarn count of elastane is higher as found in S3, S2 and S1from high to low respectively. Furthermore, the group of Polyamide yarn count 78 dtex of the samples (S4 – S6) also illustrated that the stress values did have influence on elastane yarn count, and the stress values are considered from high to low in S6 (78 dtex), S5 (33 dtex) and S4 (22 dtex) respectively.

5.1.2.5 Dynamic work recovery: Analysis of dynamic elastic behaviour is an objective evaluation of stretch and recovery performance of elastic knitted fabrics. The analysis of this dynamics will help engineer improve performance of sportswear and compression garment.

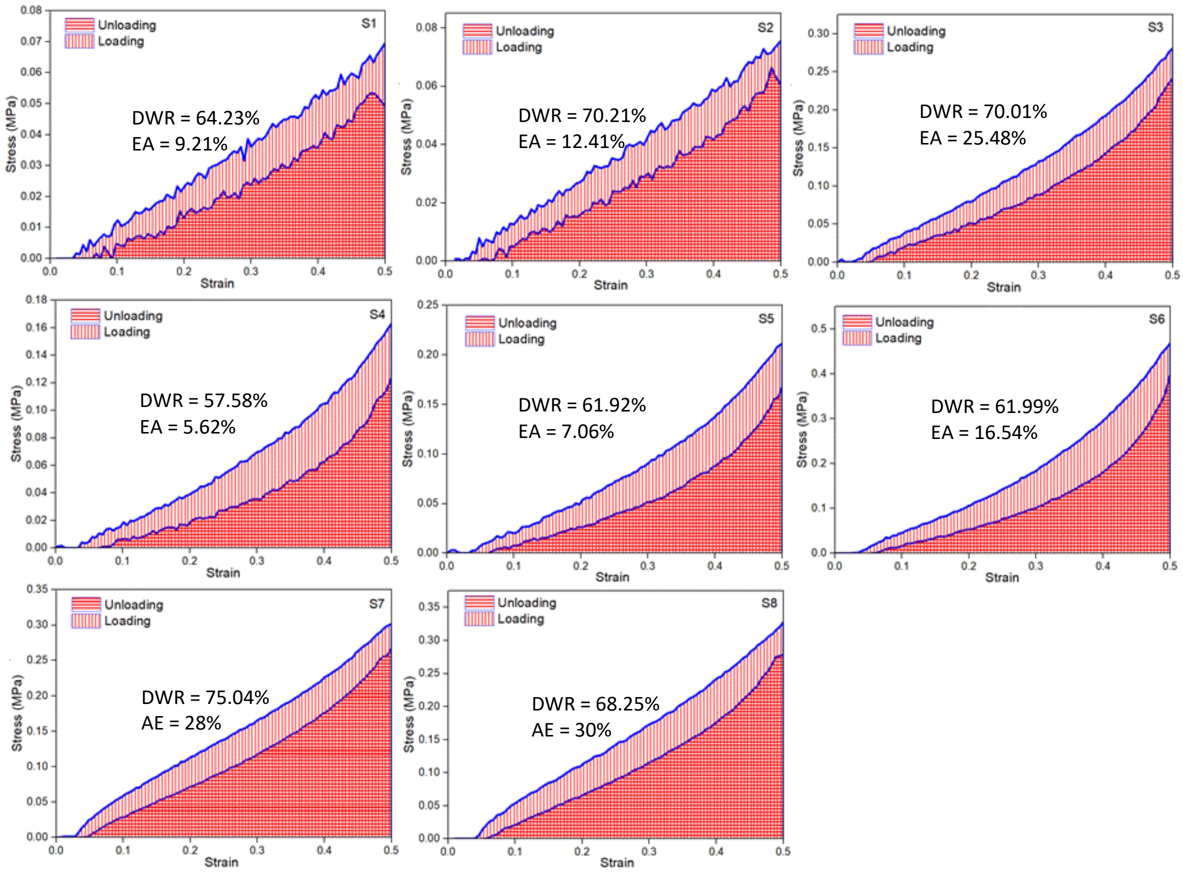


Figure 17. Graphs of Dynamic Work Recovery at the fifth cycle of eight samples

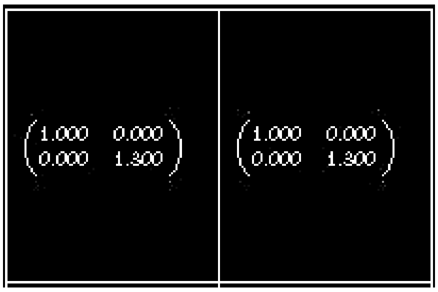
The results of dynamic work recovery were obtained the energy between area under loading and unloading and then were calculated for the DWR % and the lack of energy inside the hysteresis loop is the energy loss in fabric. When considering grate dynamic recovery DWR % of sample S7 at 75.04%. has it could be found that the sample is considered to have high AE composition at 28%, and in the meantime, samples S2, S3 and S8 have AE composition at 12.41%, 25.48% and 30.00% while DWR% was at 70.21%, 70.01% and 68.25% respectively. In sample S4, has lowest EA of 5.62% lowest DWR% of 57.85% were revealed. And thus, it could be concluded that the percentage of elastane might be helping for adjustment to improve the performance of fabric recovery and value of DWR% could be used for further improvement on clothing function such as active sportswear for athletes.

5.2 Characterization of stretch fabric tensile deformation by image analysis

This novel experiment presented the digital image analysis technic by MATLAB for the measurement of local deformations of knitted fabrics. The image analysis approach was selected to calculate the gradient deformation tensor under the extension ranging from 10 % to 40 % in course direction.

5.2.1 Validation of results with simulated images

In order to ensure the accuracy of calculated gradient deformation tensor values, the results were validated with simulated images generated by MATLAB image processing tool box. The deformation tensor is obtained by [20, 21]:



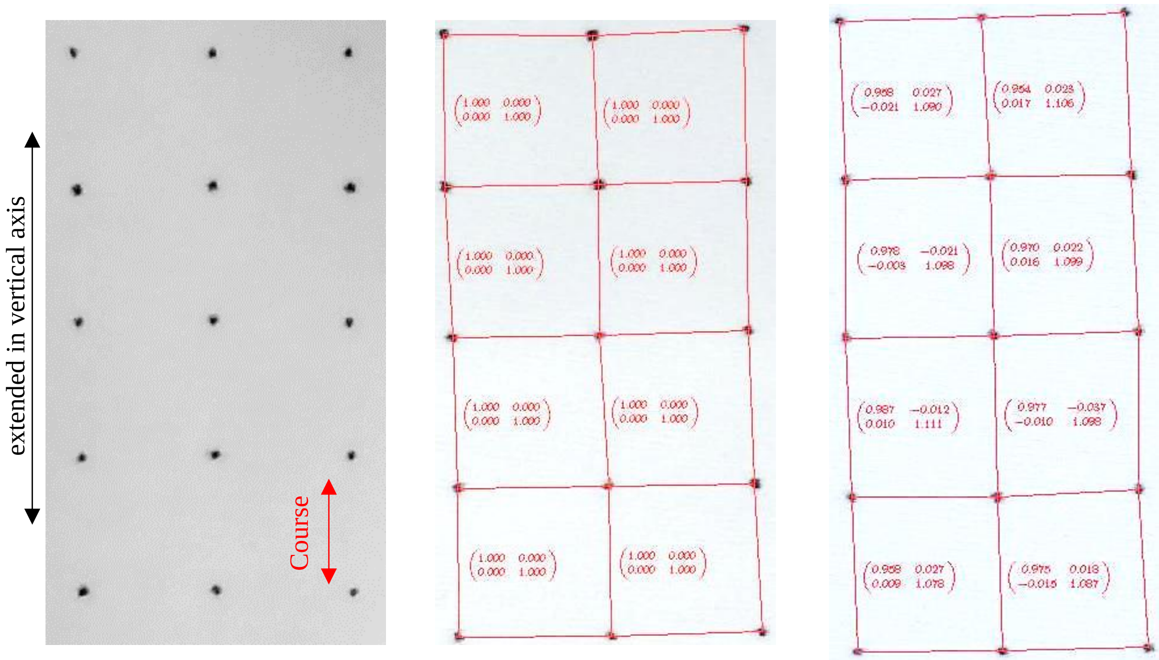
$$F = \begin{pmatrix} 1 + u_{11} & u_{12} \\ u_{21} & 1 + u_{22} \end{pmatrix}$$

Figure 18. Simulated images from MATLAB image processing toolbox [20]

Figure18 shows the simulated image 30 % extension in vertical axis and the Cartesian components of $(1 + u_{11})$ describe the deformation of distance changed in width or shrink direction and $(1 + u_{22})$ describe the deformation of distance changed in length or extended of fabric direction. This successfully validated the concept of image analysis for determination of elastic distribution properties of fabrics.

5.2.2 Fabric deformation image was extended by tensile testing machine

Figure 19 (a-c) shows the calculated values of gradient deformation tensor for RGB image, 0 % and 10 % extension in course direction of knitted fabric of the sample S6. It is clear that the images got stretched along with the points marked on them under different extension. The calculated gradient deformation tensor values were also found to change in similar percentage for each case, which proved to have accurate estimation of image analysis.



(a). RGB image (b). No extension (c). 10 % extension

Figure 19. Gradient deformation tensor for course direction by tensile testing machine

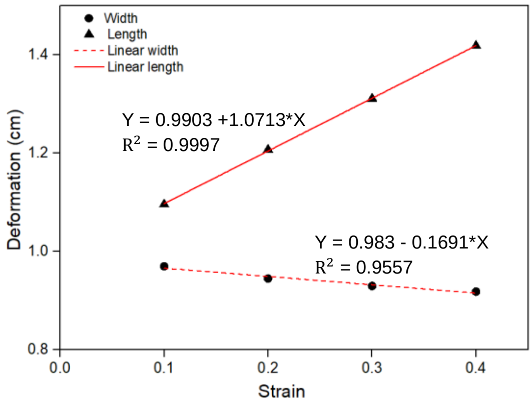


Figure 20. Deformation behaviour of stretch fabric of the sample S6

The deformation distribution between length and width of stretch fabric is given in Figure 20. It was found that the length was higher when the extended level was higher while width of fabrics was shrunk when fabrics extended. The One-way ANOVA statistic results were found that the deformation of fabric extended in course direction was significant different at the ($F_{Significance}$<0.05) are given in Table 3.

Table 3. Prediction of extension deformation behaviour of knitted fabrics using different fabrics directions

Equation: Y= a + b*X		Value	Standard Error	Adj R-Square	$F_{Statistic}$	$F_{Significance}$	Significant ($F_{Significance}$<0.05)
length	Intercept	0.9903	0.0028	0.9997	11111.18	8.99E-05	Significant
	Slope	1.0713	0.0102				
width	Intercept	0.9830	0.0057	0.9557	65.7948	0.0149	Significant
	Slope	-0.1691	0.0209				

5.2.3 Comparison of fabric deformation with Engineering stress and True stress

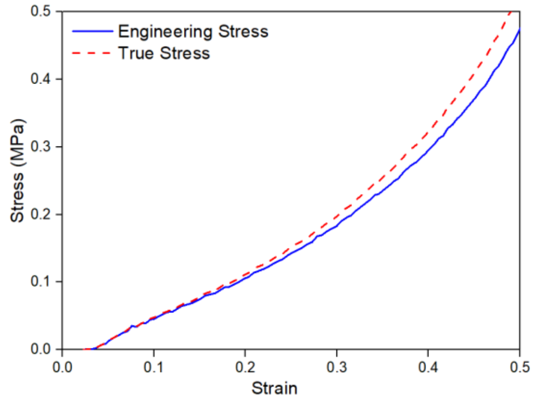


Figure 21. The comparative the stress values between TS and ES

The deformation image results under fabric stretched in width was obtained and then being applied by predictive equation ($Width_{Predicted} = 0.983 - 0.1691 \times Strain_{Experiment}$) to calculate the actual width under the strain level from the tensile testing experiment in order to find out True Stress (TS). Figure 21 it was found that TS and ES had close values under the strain level 0 - 0.2 but they are slightly different in terms of TS which was a bit higher than ES from strain 0.2 - 0.4. It could be confirmed that under the strain level of fabric stretched when compared stress values between TS and ES, it is acceptable to use ES instead of TS.

5.2.4 Prediction of the elastic coefficient of ECL from fabric deformation

Regarding results of the mean values in width dimension by image analysis, they were used to calculate the later strain and elastic coefficient as given in Table 4 and then further predicted to determine the elastic coefficient as shown in Figure 22.

Table 4. Fabric deformation of later strain and elastic coefficient

Strain	Width (cm)	Lateral strain = $-\frac{\Delta w}{w}$	Elastic Coefficient = $\frac{1}{\varepsilon_{Lateral}+1}$
0.1	0.970	- 0.030	1.031
0.2	0.945	- 0.055	1.058
0.3	0.930	- 0.070	1.075
0.4	0.918	- 0.082	1.089

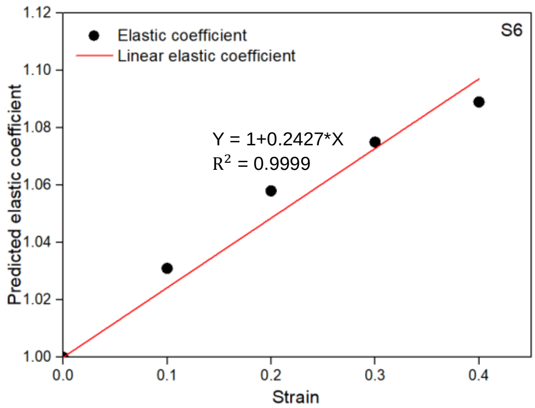


Figure 22. The prediction of elastic coefficient of the sample S6

The predictive of elastic coefficient are significant different as given the adjusted coefficients of determination 0.9999 and the correlation validates the accuracy of the measured results and proves the novel technic of image processing by MATLAB. This predicted equation was done which was helpful enough to find out the ECL for estimating the size of pattern construction under the strain level.

5.3 Application of Laplace's law pressure theory on pressure for garments

5.3.1 Applying the mathematic modelling for prediction of the strain value

Figure 23. shows the fabrics elastic behaviour between the predicted strains (dependent variable) at the magnitude of stress (independent variable) from standard EN 14704-1. The results were predicted in the strain values by statistical analysis of 3rd order polynomial fitting-lines which are given on Table 5 and the equations were used to perform the analysis of modelling results of the strain values by ORIGIN®9.1 software shown in Figure 24. (a-f).

Table 5. The predictive modelling of strain value of eight samples

	Predictive modelling	***h***		Predictive modelling	***h***
S1	ε = 3.45E-16σ^3-6.05E-11σ^2+9.90E-06σ	0.55	S5	ε = 2.97E-17σ^3-1.71E-11σ^2+4.66E-06σ	0.61
S2	ε = 1.14E-16σ^3-2.71E-11σ^2+8.05E-06σ	0.55	S6	ε = 3.47E-18σ^3-4.26E-12σ^2+2.31E-06σ	0.57
S3	ε = 1.29E-18σ^3-3.90E-12σ^2+2.78E-06σ	0.50	S7	ε = -8.92E-18σ^3+2.87E-12σ^2+1.58E-06σ	0.79
S4	ε = 6.27E-17σ^3-2.86E-11σ^2+6.10E-06σ	0.60	S8	ε = -1.52E-18σ^3-6.08E-13σ^2+1.89E-06σ	0.64

*h is thickness unit mm, ε is strain and σ is stress unit is Pa.

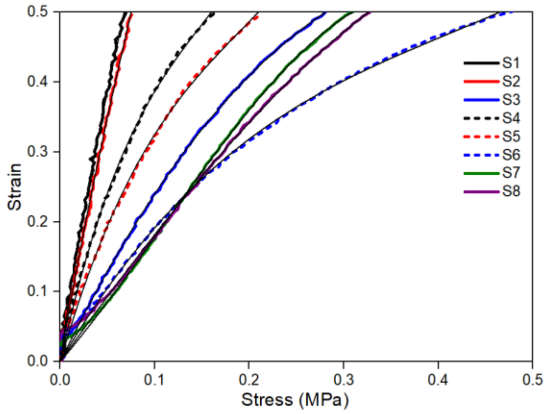
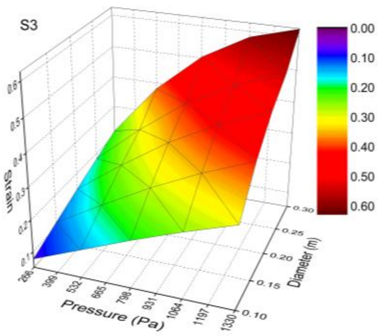
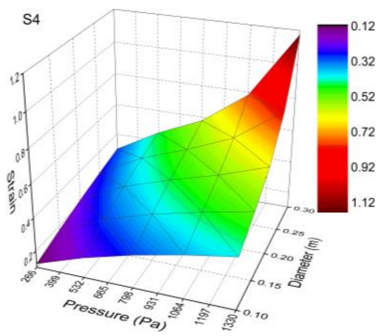


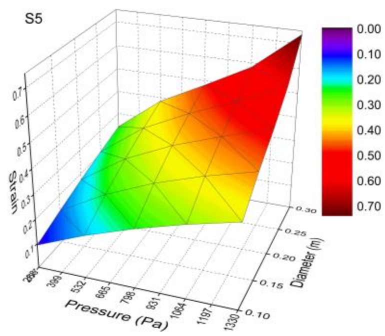
Figure 23. The actual mechanical characteristic from stress-strain curves of eight samples



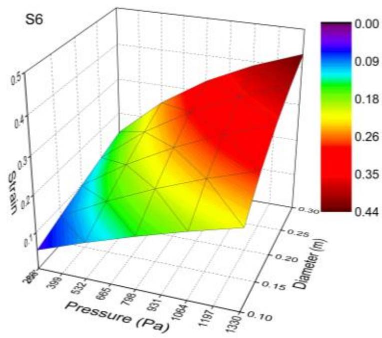
(a) S3



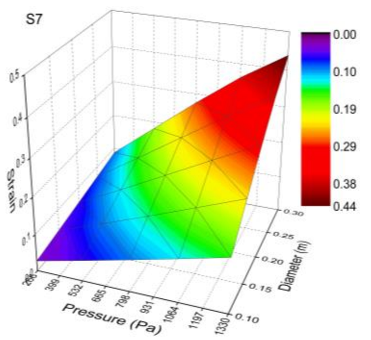
(b) S4



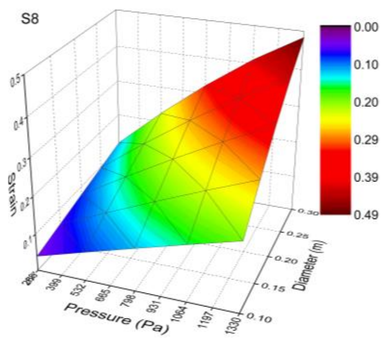
(c) S5



(d) S6



(e) S7



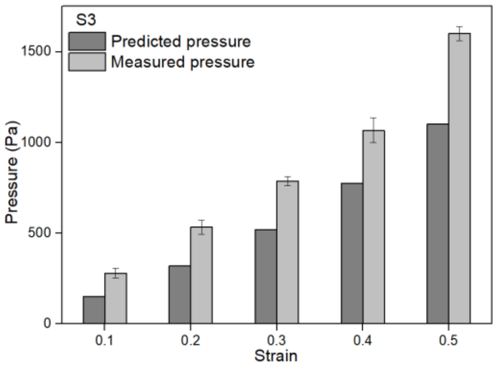
(f) S8

Figure 24. The stretch fabric effect of pressure and diameter on the strain

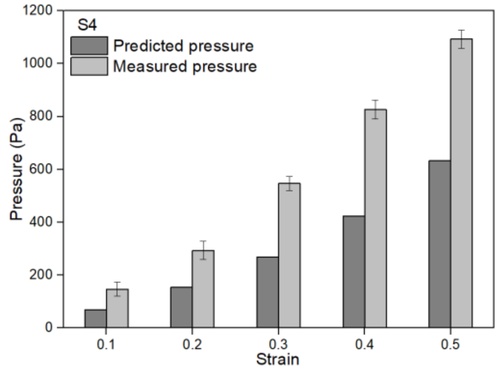
5.3.2 Evaluation of the mathematical modelling of pressure garments

The experiment was designed to investigate the predictive modelling application based on Laplace's law theory that accuracy enough to find out the pressure values and strain values of stretched fabric. Additionally, the correction factor was introduced to get rid of the pressure perturbation from sensor thickness effect.

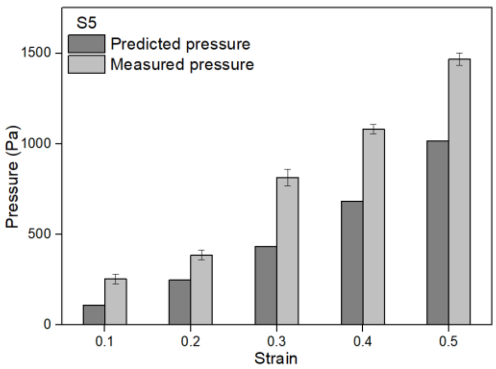
5.3.2.1 Measurement of pressure garments in vitro model: Conducting an experiment, the strain value of the fabric stretches on the rigid cylindrical model was used at 0.79 m. It could be observed from the results that the measured pressure values are over estimating. Due to this reason, the compression tester PicoPress® might be having some negative effects during measuring on the pressure perturbation as shown the Figure 25 (a-d).



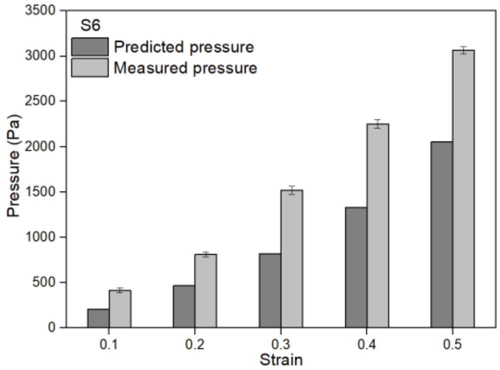
(a) S3



(b) S4



(c) S5



(d) S6

Figure 25. Comparison of pressure values between predicted pressure and measured pressure

5.3.2.2 The effect of the sensor thickness in vitro model: In this particular part of the experiment, the compression tester PicoPress® was used for measuring the interface pressure under the fabric stretch. The effect of the sensor thickness measured on the rigid cylindrical model is shown in the Figure 26.

$$C_{PP} = \frac{\sin\left(\frac{22.93°}{2} + 12.39°\right)}{\sin\left(\frac{22.93°}{2}\right)} = 2.03$$

$$\varphi = \frac{0.05}{0.1258} = 0.4 = 22.93°$$

$$\gamma = arccos\left(\frac{0.1258}{0.1258+0.003}\right) = 12.39°$$

$$C_{TP} = \frac{3.14 \times 0.05^2}{4 \times 0.05 \times 0.05} = 0.785$$

$$Correction\ factor = \frac{1}{2.03 \times 0.785} = 0.628$$

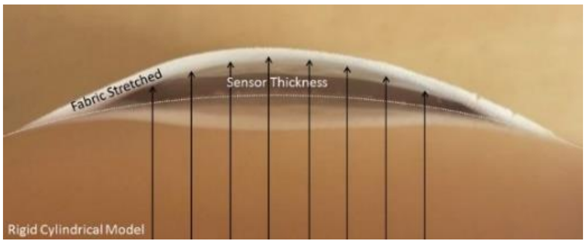


Figure 26. Effect of sensor thickness under fabric stretched on rigid cylindrical model [6]

According to in Figure 27, the graph represents the effect of sensor thickness using PicoPress® and thus the correction factor is 0.628 by sensor thickness (h_s) 0.003 m, sensor diameter (D_s) 0.05 m and the circumference of the cylindrical model (C) 0.79 m and body radius (R) 0.126 m. The graph of effect of thickness, it is very clearly seen that the pressure perturbation effect will not occur when the thickness sensor is lesser than 0.00025 m. On the other hand, the thickness increase, the pressure perturbation become increasing continuously. While the correction factor dramatically decreases during the thickness starts from 0.00025 m to 0.0035 m subsequently the correction factor decreases gradually.

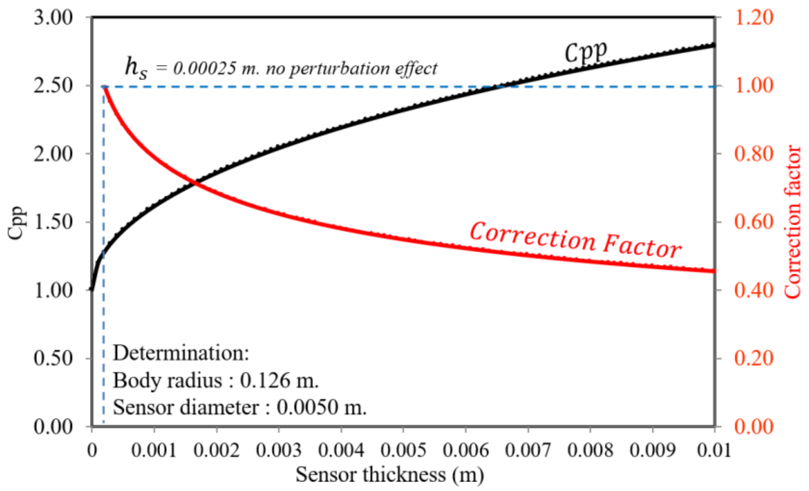


Figure 27. Effect of sensor thickness between correction factor and *Cpp* [6]

The results of measured pressure were then multiplied with the correction factor by 0.628 to get the actual pressure which is so called the corrected measured pressure and the results will be compared. Figure 28 (a, b, c and d) shows the comparison of pressure values obtained from three methods of calculation which are compared with different strain values of the circumference at 0.79 m.

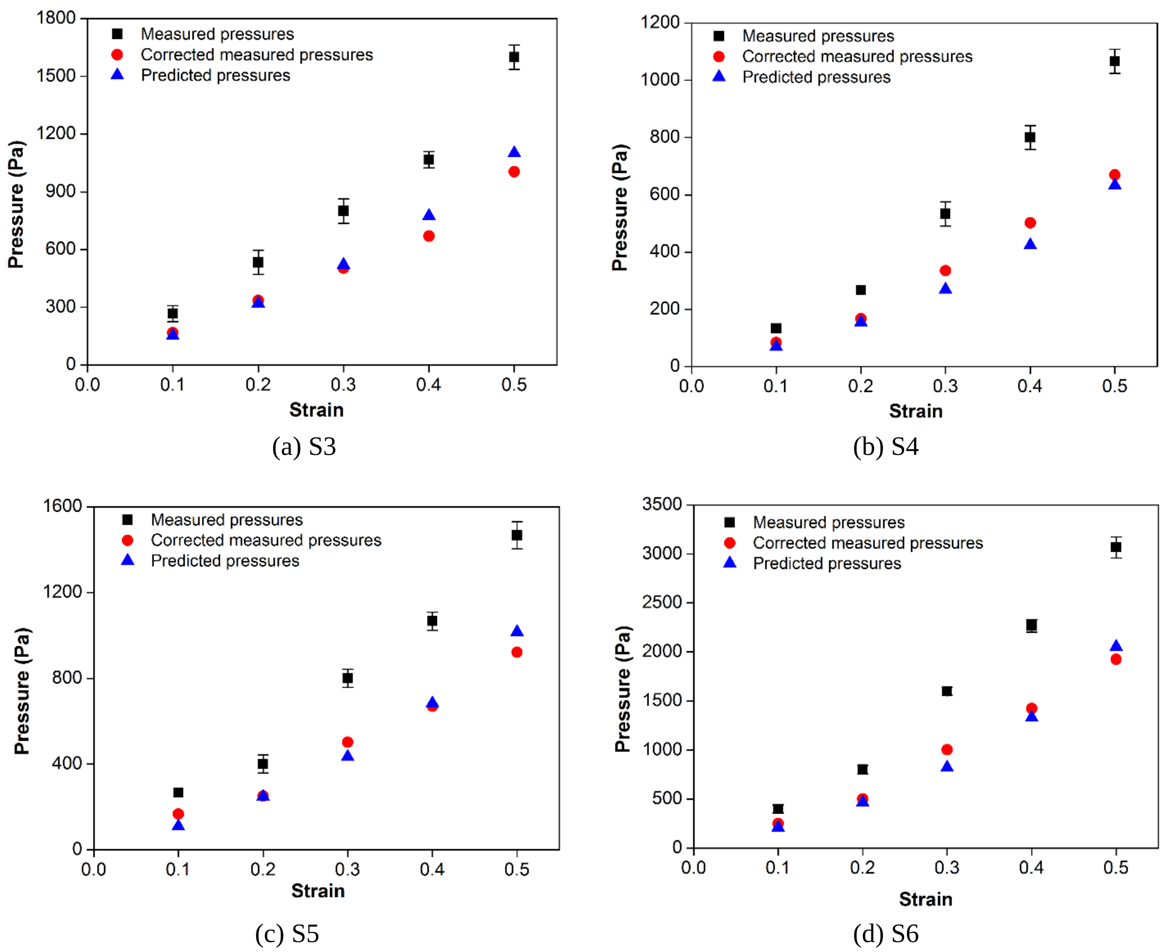
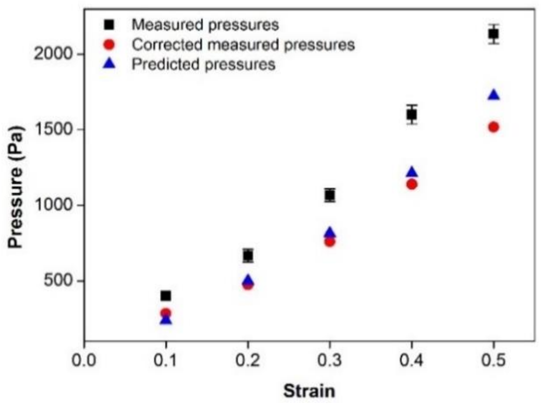


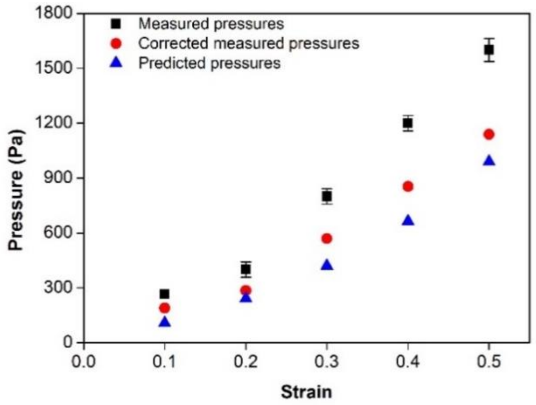
Figure 28. Comparison of the pressure values methods with the circumference at 0.79 m [6]

Apparently, the corrected measured pressure values as illustrated in the graphs are very close to the ones predicted pressure values. While the means of the measured pressure values by PicoPress® illustrate that those pressure results are the highest values when compared with another two methods.

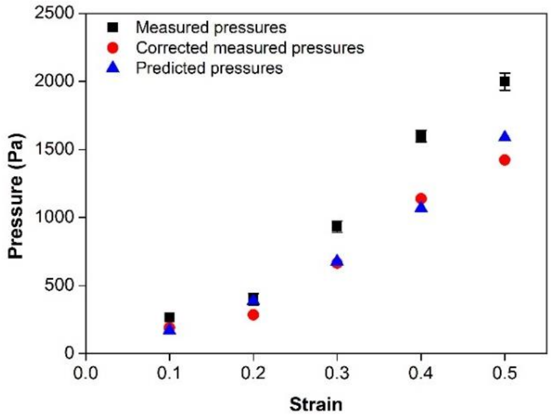
5.3.2.3 Measurement of pressure garments with difference circumferences: Relating to the experiment aforementioned, same method was applied but the circumference was decreased from 0.79 m to 0.505 m. The body radius (R) 0.0804 m was then calculated by applying correction factor at 0.712.



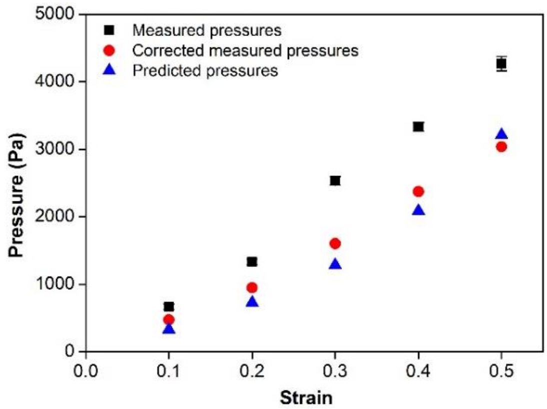
(a) S3



(b) S4



(c) S5



(d) S6

Figure 29. Comparison of the pressure values methods with the circumference at 0.505 m [6]

In Figure 29 (a, b, c and d), the graphs illustrated the comparison results of pressure values of the pressure correction and pressure prediction methods which are very close when correction factor was calculated. In this part of the experiment, it could be proven that the mathematical modelling to predict the pressure based on Laplace's Law and the correction factor are applicable for making precise estimation of pressure in vitro model.

5.3.2.4 Measurement of pressure garments in vivo model: Relating to the experiment above, same method was applied at the circumference 0.505 m and correction factor at 0.712. The experiment used rigid cylindrical model as shown in the Figure 30 (a) and a real human body at thigh part similar to the cylindrical shape were compared to find out pressure values measured by PicoPress® in Figure 30 (b).

(a) Measurement of pressure value in vitro model

(b) Measurement of pressure value in vivo model

Figure 30. Measurement of pressure values between vitro model and vivo model [6]

Interestingly, pressure values of the soft tissue surface (vivo) at the thigh part show close results to the predicted pressure values and corrected measured pressures of the rigid body as shown the Figure 31 It could have been assumed that skin human body was soft and unessentially an influence on the pressure perturbation of sensor thickness during measurement.

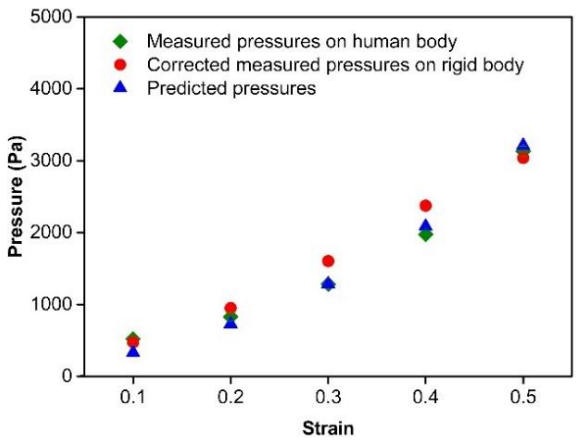


Figure 31. Comparison of S6 pressure values with different models between vitro and vivo [6]

5.3.3 Evaluation of the mathematical modelling for prediction of the strain value

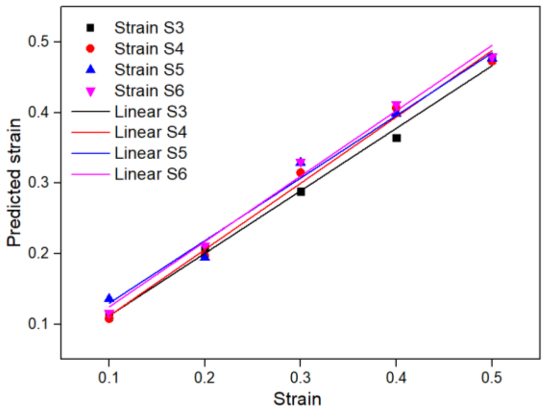


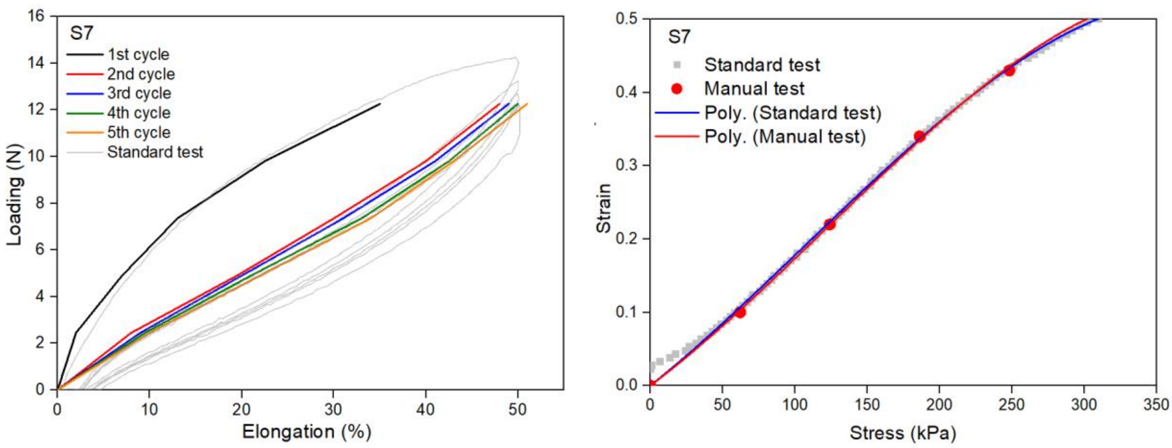
Figure 32. The correlation of predicted strain VS experimental strain of sample S3, S4, S5 and S6

The objective of this experiment was to design the method that could be used for investigating the prediction of the strain value on the mathematical modelling and the experiment was then carried out to find out the strain values of stretched fabric form the measured pressure by PicoPress®. Figure 32 indicates the correlation of the strain value between the predicted strain versus experimentally determined strain level at the cylindrical model of 0.79 m circumference. It can be seen that the correlation of the predicted strain and experimental strain of samples S3, S4, S5 and S6 are found to be well correlated with adjusted coefficients of determination 0.9948, 0.9896, 0.9807 and 0.9865 respectively.

5.4 Performance of novel tensile measurement device

5.4.1 Measurement of fabric properties by novel tensile measurement device

The experimental of a novel tensile measurement device was considered successful and the results of loading from the calibration weight and elongation. The result of sample S7 was obtained and were plotted in graph as shown Figure 33 (a) in order to compare the fabric characteristic of loading-elongation curves between manual test and standard test.



(a) Comparison of loading-elongation between manual test and standard test of S7

(b) Comparison of the correlation of strain values between manual test and standard test of S7

Figure 33. Comparison of fabric property results of sample S7 between manual test and standard test

Figure 33 (b) the predicted stain of polynomial fitting line from manual test was very close to the standard test and the correlation matched well to the adjusted coefficient of determination at 0.9985 and 0.9997. Conclusion could be drawn that manual tensile testing device is considerably applicable for testing measurement on elongation of fabric stretched by using the calibration weight instead. Additionally, with its low cost and high accuracy in fabric stretched measurement, this device is considered very beneficial.

4.4.2 Fabric deformation image by manual tensile testing

The image analysis results were done by NIS-Elements software which is used to calibrate the deformation of fabric stretched under the different weight interval 250 g. The image analysis results of fabric length and width can be applied to help predict the ECL of samples S6, S7 and S8 by using statistical analysis as shown in Figure 34. The graph illustrates the obtained linear regressions watch are found to be well correlated with adjusted coefficient of determination at 0.9998, 0.9993 and 0.9999 respectively.

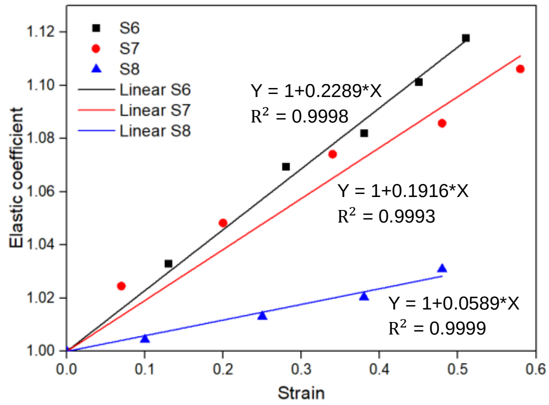


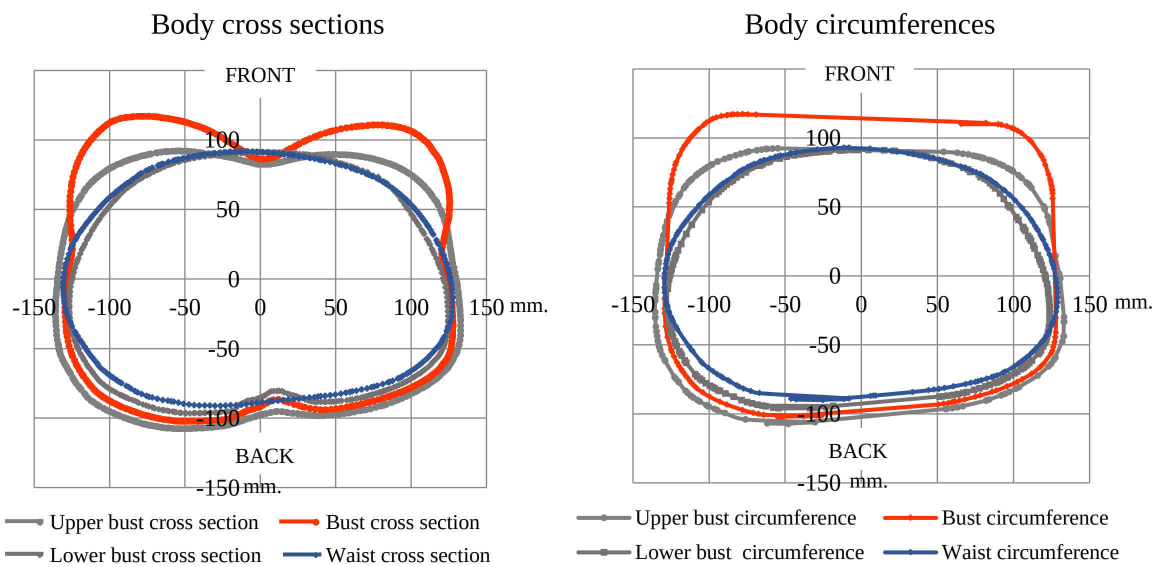
Figure 34. The prediction of the elastic coefficient (ECL) of sample S6, S7 and S8

5.5 Defining patternmaking development procedure for stretch fabrics

The final part of the research emphasizes to develop the method how to modification the size of patternmaking method for stretch fabrics. Through the experiments, the researcher has integrated the knowledge to predict the strain value based on the factors are the body diameter and specific pressure required. The main key factor to estimate the size of patternmaking is the elastic coefficient of ECW and ECL where can be calculated from the predicted stain and then the patternmaking size will be appraised.

5.5.1 Body measurement

During procedures of the measurement, sense^{TM}2 3D scanner was applied to create 3D image of female mannequin and blender software was then used to analyse and process the accurately size of the body cross section at main different parts of the female body for the creation of patternmaking as shown in Figure 35(a). Figure 4.26 (b) the body circumferences were used for prediction of the strain value in order to calculate the size of patternmaking of this experiment.



(a) Body cross section with different parts (b) Body circumference with different parts

Figure 35. The graphs of cross sections and circumferences with different parts of the body

5.5.2 Investigation of elastic fabric performance

The results of circumference (C) in the different parts of the body from Figure 35 (b) were used to calculate the body diameter (D) for the predicted strain value by mathematic modelling equations as shown in Table 5. In this experiment investigated the fabric performance for producing the compression garment by defining, specific pressure (P) applied on the body at 1.15 kPa (8.63 mmHg) which is suitable for medium compression garment and was conducted to make prediction for strain values. In Table 6, the stress values results were calculated by applying pressure value, diameter and thickness of each fabric into the modelling of polynomial equations in order to predict strain values ranging in different parts of the body.

Table 6. The results of predicted strain values with different parts of the female body at pressure 1.15 kPa.

Body part	D (m)	$\sigma = \frac{DP}{2h}$; (Pa)				Strain ε by prediction equation			
		S1	S2	S3	S4	S1	S2	S3	S4
Upper bust	0.251	262,409	262,409	288,650	240,542	4.6	2.31	0.51	0.69
Bust	0.276	288,545	288,545	317,400	264,500	6.11	2.81	0.53	0.77
Lower bust	0.232	242,545	242,545	266,800	222,333	3.76	1.98	0.49	0.63
Waist	0.228	238,364	238,364	262,200	218,500	3.59	1.92	0.48	0.62
		S5	S6	S7	S8	S5	S6	S7	S8
Upper bust	0.251	236,598	253,202	182,693	225,508	0.54	0.37	0.33	0.39
Bust	0.276	260,164	278,421	200,886	247,969	0.58	0.39	0.36	0.41
Lower bust	0.232	218,689	234,035	168,861	208,438	0.51	0.35	0.31	0.35
Waist	0.228	214,918	230,000	165,949	204,844	0.51	0.35	0.30	0.34

* D is diameter of body circumference, P is pressure unit Pa, h is thickness unit mm, ε is strain and σ is stress unit is Pa.

The predicted strain values in Table 6 could be evaluated to determine the performance of elastic fabric that can led to three mains garment applications such as low compression garment, medium compression garment and medical compression garment applications. For the investigation of results, compression value at 1.15 kPa based on the comfort sensation for medium compression [22, 23] were applied to analyse and discuss as follow:

In the group with low level of compression pressure (samples S1 and S2), predicted strain values, as shown in Table 6, were considered to be high and unsuitable for high CG production. Thus, this group of fabric is optimal to produce fitting garments when pressure is lowered to less than 1.15 kPa and the sense of discomfort had yet to be found.

Concerning the second group with medium compression pressure (S3, S4 and S5), they appeared to have an optimal predicted strain at 1.15 kPa with strain approximately at 0.5 as shown in Table 6. This particular group samples are suitable for manufacturing medium CG for sportswear, swimming suit, etc.

For samples S6, S7 and S8 known as a group with highest level of compression garment, the values of the predicted strain are lower than 0.4 at the pressure 1.15 kPa. These samples could effectively be used for producing various types of high compression garment including medical application, athletic application and body shaping application. And thus, S6, S7 and S8 were selected to determine higher pressure from 1.15 kPa to 2.4 kPa (18 mmHg) in order to predict the strain value for high compression garment and the strain results are obtained in Table 7.

Table 7. The results of predicted strain values with different parts of the female body at pressure 2.4 kPa

Body part	D (m)	$\sigma = \frac{DP}{2h}$; (Pa)			Strain ε by prediction equation		
		S6	S7	S8	S6	S7	S8
Upper bust	0.251	528,421	381,266	470,625	0.54	0.52	0.59
Bust	0.276	581,053	419,241	517,500	0.58	0.54	0.60
Lower bust	0.232	488,421	352,405	435,000	0.52	0.52	0.58
Waist	0.228	480,000	346,329	427,500	0.51	0.52	0.58

* D is diameter of body circumference.

Referring strain prediction values in Table 7 , they were used for the circumferential strain parameters and the results were calculated to determine the initial circumference by multiplying the elastic coefficient in width dimension from the equation (3.4) $ECW = \frac{1}{\varepsilon_{Circumferential}+1}$ and used for an estimation of patternmaking size in width dimension as shown in Table 8.

Table 8. The size of patternmaking with different parts of the body under the pressure at 2.4 kPa

Body part	C (cm)	$C_0 = C \times ECW$; (cm)			$\overline{ab} = \overline{cd} = C \times ECW \times \frac{1}{4}$; (cm)		
		S6	S7	S8	S6	S7	S8
Upper bust	78.8	51.17	51.84	49.56	12.79	12.96	12.39
Bust	86.6	54.81	56.23	54.13	13.70	14.06	13.53
Lower bust	72.7	47.83	47.83	46.01	11.96	11.96	11.50
Waist	71.5	47.35	47.04	45.25	11.84	11.76	11.31

*C is the body circumference and C_0 is initial circumference of fabric.

In Table 9, procedural steps of calculating the elastic coefficient in width and length dimensions in different parts of the body circumferences are offered. Column number (1) symbolizes the predicted strain modelling in order to calculate the strain values as shown in column number (2) and finally elastic coefficients in width dimension could be found in column number (3). Likewise, the strain values from column number (2) were used in order to calculate the elastic coefficient in length dimension by predicted equations in column number (4) and the values of ECL are obtained as found in column number (5).

Table 9. The elastic coefficient for 2.4 kPa pressure in width and length dimensions in different body parts

No	Body part	Width dimension (Course-wise direction)			Length dimension (Wale-wise direction)	
		(1)	(2)	(3)	(4)	(5)
		Mathematic modelling for predictive strain	Strain	ECW	Predictive elastic coefficient	ECL
S6	Upper bust	3.47E-18σ^3-4.26E-12σ^2+2.31E-06σ	0.54	0.649	1+0.2289ε	1.124
	Bust		0.58	0.633		1.133
	Lower bust		0.52	0.658		1.119
	Waist		0.51	0.662		1.117
S7	Upper bust	-8.92E-18σ^3+2.87E-12σ^2+1.58E-06σ	0.52	0.658	1+0.1916ε	1.100
	Bust		0.54	0.649		1.103
	Lower bust		0.52	0.658		1.100
	Waist		0.52	0.658		1.100
S8	Upper bust	-1.52E-18σ^3-6.08E-13σ^2+1.89E-06σ	0.59	0.629	1+0.0589ε	1.035
	Bust		0.6	0.625		1.035
	Lower bust		0.58	0.633		1.034
	Waist		0.58	0.633		1.034

5.5.3 Patternmaking development method for stretch fabrics

Figure 36 illustrates the matrix dimension points for the adjustment of patternmaking development that are related to block pattern (black line). There are nine important matrix points that present direction of the pattern which were moved by X axis and Y axis. The pattern in blue line represents the patternmaking at the pressure 1.15 kPa and the green line is the patternmaking at the pressure 2.4 kPa from the sample S7. In order to define point number 3, calculation is done by multiplying waist circumference with ECW and then plus the length dimension from armhole line to waist before multiplying with ECL. In case of point number 4, calculation can be done by multiplying the bust circumference with ECW. While in relationship of points number 5 and 6, adjustment of pattern from point number 4 will create a new armhole line and shoulder line.

Figure 36 describes the final patternmaking by calculating the elastic coefficient of ECW and ECL of the sample S7 at the specific pressure 2.4 kPa and focuses on only particular area as the cylindrical shape at the shadow area.

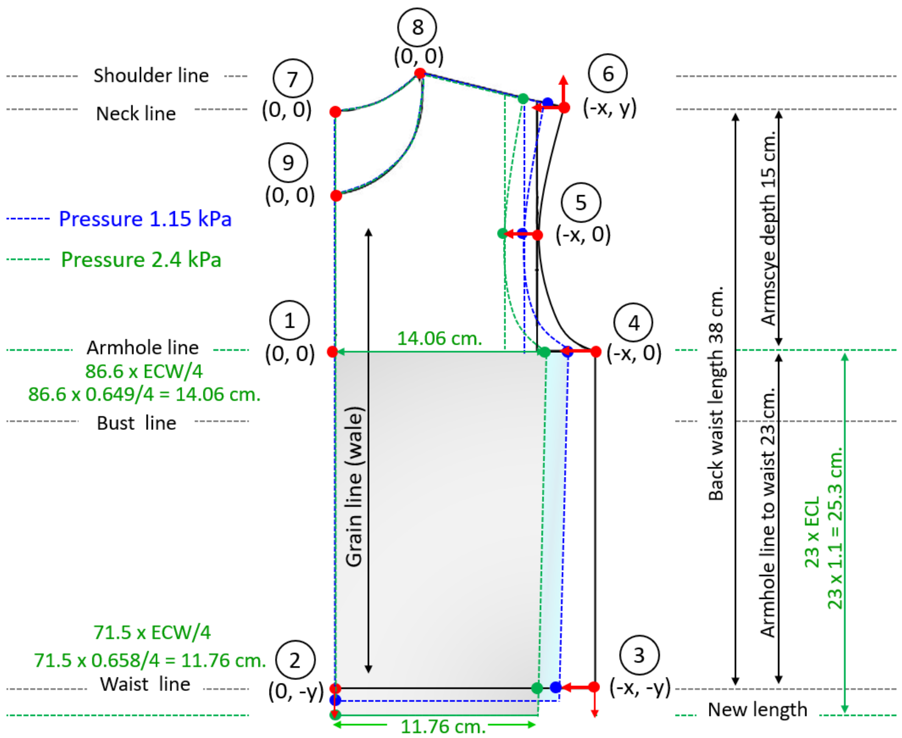


Figure 36. The reduction of patternmaking method based on fabric tensile property of sample S7

5.5.4 Application of patternmaking reduction with standard sizing system

This research endeavours to create as a guideline for the fundamental of patternmaking for stretch fabric referring to the standard sizing system which would be helpful to understand the importance of body measurements that can be applied and integrated by the elastic coefficient to achieve accurate size of pattern dimensions. Table 10 represents body measurement according to standard ASTM D5585 for adult female of size 6, 7 and 8 for case study example describing the method by multiplying the elastic coefficient of ECW and ECL from the formulas were discovered.

Table 10. Modification standard sizing system of body measurement by applying elastic coefficient

Body measurement	Symbol	Size (cm)			Multiply elastic coefficient
		6	8	10	
Nape to waist	nw	40.6	41.3	41.9	×ECL
Armscye depth	ard	18.7	19.0	19.4	No reduction
Bust girth	bg	86.4	89.0	91.4	×ECW
Waist girth	wg	66.0	68.5	71.1	×ECW
back width	bw	36.5	37.1	37.8	×ECW
Neck girth	ng	35.6	36.2	36.8	No reduction
Shoulder length	shl	12.9	13.0	13.2	No reduction

Note: ECW is elastic coefficient in width dimension and ECL is elastic coefficient in length dimension.

Eventually, this technique of modifying standard sizing system of the body measurement could be conducted by applying the elastic coefficients which could help develop the patternmaking and thus, application of the method could be considered very helpful for the garment industries to manufacture compression garments in mass production.

5.5.5 Application of patternmaking by using PDS tailor XQ software

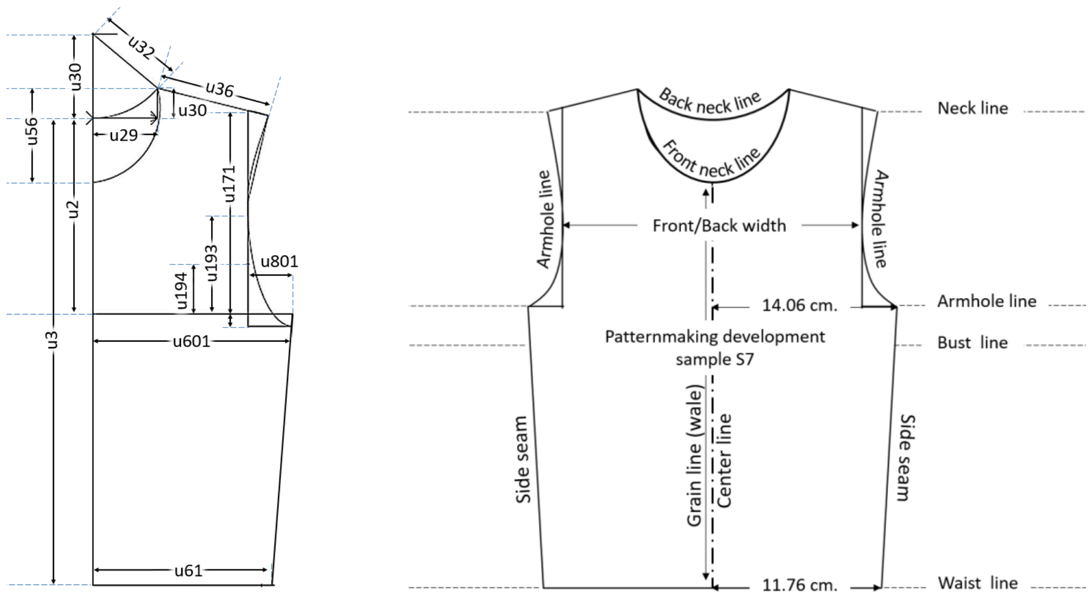
In Table 11, parameters of body measurement are obtained by applying PDS Tailor XQ software.

Table 11. Modification of the pattern construction abscissa PDS Tailor XQ software

Variable	Type	Descriptive Text	Formula	Value (cm)
		MATERIAL ALLOWANCES		
Ed	C	Length elasticity coeff. of material	1-KEd	1.100
Eš	C	Width elasticity coeff. of material	1-KEš	0.658
Eh	C	Elasticity coeff. of material at bust	1-KEš*KEh	0.649
		ABSOLUTE TERMS OF CONSTRUCTION SEGMEN		
B	C	Garment length	L1	38.000
		CONSTRUCTION SEGMENTS - NETWORK		
u1	U	Garment length	(B+a1)*Ed+p1	38.000
u2	U	Chest line placing	(T39+a2)*Ed+p2	15.000
u3	U	Waist line placing	(T40+a3)*Ed+p3	38.000
u6	U	Total chest width	(0.5*T16+a6)*Eh+p6	28.120
u601	C	Chest half-width	0.5*u6	14.060
u801	U	Arm scye half-width	(K801*T16+a801*Eh+p801	3.722
u10	V	Arm scye depression	(K10*(T40-T39)+a10)*Ed	0.930
u171	C	Arm scye depth	(0.5*T38+a171)*Ed+p171	17.907
u193	C	Arm scye lower part construction	0.5*(u171+u10)	9.419
u194	C	Arm scye lower part construction	0.25*(u171+u10)	4.709
		CONSTRUCTION SEGMENTS - BACK PART		
u29	U	Back part neck width	(0.185*T13+a29)*Eh+p29	5.354
u30	U	Back part neck height	(0.065*T13+a30)*Ed+p30	2.286
u32	V	Back part neck radius	(0.23*T13+a29)*Eš+p29	6.943
u335	V	Shoulder line angle	z335	76.000
u36	V	Back part shoulder line enlargement	K36*T47+a36	1.750
		CONSTRUCTION SEGMENTS - FRONT PART		
u56	U	Front part neck depth	(0.2*T13+a56)*Ed+p56	5.354
u57	V	Front part neck radius	(0.18*T13+a57)*Eš+p57	6.273
u61	U	Waist width measuring	(0.25*T18+a61)*Eš+p61	11.760

The benefit of software for predicting the pattern construction under the parameters of body measurement and elastic coefficient of elastic material. The parameters can automatically help determine the size of patternmaking with elastic coefficients under the regression formulas method. Moreover, the software will also help define patternmaking through CAD system as shown in Figure 37 (a and b).

However, some parts of the pattern dimensions are not precisely as the estimating pattern reduction method, but the software can adjust the pattern in order to fix the size of patternmaking such as the construction segment of total chest-width “u6”, chest half-width “u601” and waist width measuring “u61”.



(a) Pattern construction chart (b) Patternmaking for CG at the pressure 2.4 kPa of the sample S7

Figure 37. The patternmaking by applying PDS Tailor XQ software

Referring the pattern construction abscissa chart of the construction segments created from the PDS Tailor XQ software shows the variables of pattern construction segment which are coordinated as shown in Figure 37(a). While Figure 37(b) presents the final patternmaking, for CG at the pressure 2.4 kPa of the sample S7 which created by PDS Tailor XQ software.

Overall, the PDS Tailor XQ software has a great efficacy to create patternmaking from stretch fabrics by inputting the parameters of elastic coefficient into the software and the database in the software could also be linked with the standard sizing system. Besides, various types of patternmaking garment designs in the software can help create patternmaking that can be transferred to CAD system. However, the pattern dimension distances are somewhat slightly different, but the final step can be adjusted for accurate size of pattern determination.

6 Evaluation of results and new finding

Efficacy of elastic fabric for pressure garment is very important to achieve the correct fabric for the garment applications end used. The mechanical fabric property could be examined and evaluated the fabric performance by classify type of compression garments applications. Due to some fabric properties, they are unsuitable to produce high compression garment applications. Therefore, the propose of this research is to define and evaluate the capacity of fabric for compression garments and fill the knowledge gap and develop a systematic pattern construction method for high performance for pressure garment applications. By conducting a series of theoretical study and experimental investigation, the objectives of the study have been achieved and summarised as follows:

Tensile property is the initial examination of the efficacy of fabric by the percentage of elongation. It was found that a good extensibility should be over than 400 % elongation and a fabric is suitable for produce the high compression garments such a medical compression garment where it should have the fabric elongated minimum reach to 500%. As for the well-fitted garment on the body, the extensibility up to 200% is sufficient to produce the slight pressure garment less than 1.15 kPa.

Elasticity of fabric found the elastane composition of fabric is significantly different of the influence on the elastic recovery and the results could be concluded that higher elastane composition will have higher elastic recovery. In elastane in the fabric over 10%, the elastic recovery has excellently preformed between 90 - 92% of dynamic testing.

Stress relaxation results showed that at the elastane 5.62% in the fabric the force decay rapidly decreased and reached to 18.38% of stress relaxation from the initial stress holding. In the fabrics that have elastane over than 25%, then the stress relaxation was lesser than 10%. It could be concluded that the efficacy of elastic fabric for producing the CGs that the elastane should have minimum at 25% will have a great elastic recovery and less stress relaxation.

Dynamic work recovery, of this thesis found that the percentage of elastane might be an influence on the energy loss when fabric high percentage of elastane, the less energy loss during dynamic test. It could be helpful for the sportswear application to investigate the fabric performance to improve the garment applications.

Fabric deformation of knitted structure including single jersey, interlock and locknit. The fabric deformation results agreed with the theoretical background of the appearance properties that the single jersey structure has poor dimensional stability and tendency to curl at the edge of the fabric. While the fabric structures of locknit is a bit tendency to curl at the edge and interlock is very good dimensional stability and without any curling effect when fabrics extended.

Image process by MATLAB, was well done and successful by a novel technique method to simulate the images then processing gradient deformation tensor. This new technique is accurate in calculation of the gradient deformation tensor under the different extension levels and it could be predicted the ECL.

Engineering stress (ES) VS True stress (TS), this research examined the results of ES and TS to compare the stress value. The experiment found that at the strain between 0-0.2, the TS is quite equal with ES. Then, the stress values are slightly different until the strain at the maximum 0.5 the TS is a bit higher than ES only 3%. Therefore, it could be assumed that the fabric stretches at the strain maximum 0.5 that the value of ES can be accepted for analysis of this research.

The prediction of the strain value from the mathematical modelling was successful for estimating the predicting strain in order to calculate the ECW. The designing experiment method investigated and compared with different parameters including fabric samples, strain levels, diameters and models (vitro and vivo). The results were well done to get the accurate results and agreement with the mathematical modelling based on theoretical of Laplace Law. I hope that a new modelling finding will gainful to estimate the fabric stretch depending on the pressure requirement.

Effect thickness of the compression tester, this research found that the effect of thickness sensor perturbation has occurred with the solid (vitro) cylindrical model. Therefore, the correction factor can be calculated to achieve the actual pressure results from compression tester. While the thickness sensor does not have the effect on the human skin (vivo), so the correction factor was unpractised. However, this research was used one compression tester which it is called Picopress® and it could be assured for this device that it is accuracy and effective for measuring the pressure value and calculating the correction factor.

Pattern development well done and successful to used fundamental block pattern and was applied by using the PDS Tailor XQ software. The experiment found that the PDS Tailor XQ software quickly computed the patternmaking based on function of elastic coefficient ECW and ECL. However, the construction formulas are complicated but in the final step can be adjusted the patternmaking and accuracy size of pattern requirement. Moreover, this research achieves the solution for coordinate with the standard sizing system of the body measurements then was applied the elastic coefficient to find out the reduction values before calculated with the fundamental patternmaking method.

This thesis finding in this study enhance the knowledge of patternmaking engineering technology for accomplishing a purpose a new systematic patternmaking method for stretch fabrics. However, the development of patternmaking method is applied to assume the body shape like the cylindrical shape which related to the Laplace's low theory for prediction of the strain values and could be proved that the mathematical modelling for predicting strain value is considered to be accurate for cylindrical shape from the experimental results. In fact, the body shape is not exactly cylindrical shape and thus the estimation of the size of patternmaking is suitable for some parts of the body that is similar to cylindrical shape. Hopefully, this thesis would be useful for garment industries to produce pressure clothing applications with high compression products by scientific methodology.

7 References

[1] Wang, L., Felder, M., & Cai, J. (2011). Study of properties of medical compression garment fabrics. *J. Fiber Bioeng. Inform, 4*, 15-22.

[2] Ying, X., & Tao, X. (2018). Compression garments for medical therapy and sports. *Polymers, 10*(663), 3-19.

[3] Macintyre, L. (2007). Designing pressure garments capable of exerting specific pressures on limbs. *Burns, 33*(5), 579-586.

[4] Makabe, H., Momota, H., Mitsuno, T., & Ueda, K. (1991). A study of clothing pressure developed by the gird. *J. Jpn. Res. Assoc. Text. End-Uses, 32*, 424–438.

[5] Jariyapunya, N., Musilová, B., Geršak, J., & Baheti, S. (2017). The influence of stretch fabric mechanical properties on clothing pressure. *Vlakna a Textil, 24*(2), 43–48.

[6] Jariyapunya , N., & Musilová, B. (2018). Predictive modelling of compression garments for elastic fabric and the effects of pressure sensor thickness. *The Journal of The Textile Institute,* 1-9.

[7] Musilová, B. (2012). *Predikce konstrukčních parametrů střihů korzetových výrobků.* Liberec: Technická univerzita v Liberci, Fakulta textilní, Katedra oděvnictví.

[8] Musilová, B., & Nemčoková, R. (2013). Implementing Mass Customization into Clothing Production. *Vlákna a textil*, 20(4), 12-19.

[9] *ASTM D 3776-96 :* (2002). *Standard Test Method for Mass Per Unit Area (Weight) of Fabric.* United States: ASTM Internationa.

[10] *EN ISO 5084:* (1996). *Textiles-Determination of Thickness of Textiles and Textile Products* . European Committee for Standardization.

[11] *ISO 13934-1:* (2013). *Determination of maximum force and elongation at maximum force using the strip method.*

[12] BS EN 14704-1: (2005). Determination of the elasticty of facrics part 1: Strip tests.

[13] Bansal, R. (2010). *Strength of Materials.* New Delhi: LAXMI PIBLICATION (P) LTD.

[14] Jariyapunya, N., Musilová, B., & Havelka, A. (2018). Prediction of Pattern Dimensions for Pressure Garment. *22nd International Conference Structure and Structural Mechanics of Textile.* Liberec.

[15] Mosti, G., & Rossari, S. (2008). The importance of measuring sub bandage pressure and. *Acta Vulnol, 6*, 31-36.

[16] Khaburi, J. A., Dehghani-Sanij, A. A., Nelson, E., & Hutchinson, J. (2011). Measurement of Interface Pressure Applied By Medical Compression Bandages. *International Conference on Mechatronics and Automation.*

[17] Khaburi, J. A. (2010). *PhD Thesis Pressure Mapping Of Medical Compression Bandages Used For Venous Leg Ulcer Treatment.* Leeds: The University of Leeds School of Mechanical Engineering.

[18] Vinckx, L., & Boeckx, W. (1990). Anslysis of the pressure perturbation due to the introduction of measuring probe under an elastic garment. *Medical & Biological Engineering & Computing, 28*, 133-138.

[19] Khaburi, J. A., Dehghani-Sanij, A. A., Nelson, E., & Hutchinson, J. (2010). The effect of sensor thickness on the interface pressure measurement induced by medical compression bandages. *12th Mechatronics Forum Biannual International Conference, 1,* pp. 91-98. Zurich, Switzerland.

[20] Baheti, S., Jariyapunya, N., & Tunák, M. (2017). Image Analysis for Characterizing Tensile Deformation of Knitted Fabric. *Vlákna a textil(Fibres and Textiles), 24*(2),54-58.

[21] Jariyapunya, N., & Baheti, S. (2017). Application of Image Analysis Method for Measurement of Fabric Stretch Deformation. *Materials Science and Engineering,* IOP Conference Series.

[22] Liu, H., Chen, D., Wei, Q., & Pan, R. (2013). An investigation into the bust girth range of pressure comfort garment based on elastic sports vest. *The Journal of The Textile Institute, 104*(2), 223–230.

[23] Liu, Y., & Dongsheng, C. (2015). An analysis on EEG power spectrum under pressure of girdle. *International Journal of Clothing Science and Technology, 27*(4), 495-505.

8 List of papers published by author

8.1 Journal Publications

[1] **Nareerut Jariyapunya** and Blažena Musilová, Predictive modelling of compression garments for elastic fabric and the effects of pressure sensor thickness, *The Journal of The Textile Institute,* DOI:10.1080/00405000.2018. 1540285, ***IMPACT FACTOR 1.174 (Q2).***

[2] **Nareerut Jariyapunya** and Blažena Musilová, Analysis of Stress and Strain to Determine the Pressure Changes for Tight-fitting Garment, *The Autex Research Journal,* DOI:10.2478/aut-2019-0006©AUTEX, ***IMPACT FACTOR 0.957 (Q2).***

[3] **Nareerut Jariyapunya**, Blažena Musilová, J. Geršak and S. Baheti, The Influence of Stretch Fabric Mechanical Properties on Clothing Pressure, *Vlákna a textil (Fibres and Textiles)*, Vol.24, Issue 2, ISSN 1335-0617, p. 43 – 48, 2017. **SCOPUS**

[4] **Nareerut Jariyapunya** and Jantana Sutdaen, Construction Simulation 3D of Tight-Fitting Sportswear to Evaluate Tension Distribution of Elastic Fabric, *Journal of Engineering,* RMUTT, Vol.15, Issue 2, ISSN 1685-5280, p. 69 – 76, 2017.

[5] **Nareerut Jariyapunya,** Blažena Musilová and Marie Koldinská, Evaluating the Influence of Fiber Composition Structure of Knitting Fabrics on Total Hand Value (THV), *Applied Mechanics and Materials, ISSN* 1662-7482, Vol. 848, p. 211-215, 2016. doi:10.4028/www.scientific.net/AMM.848. 211 © 2016, ***(Q4)***

[6] Smita Baheti, **Nareerut Jariyapunya** and Maroš Tunák, Image Analysis for Characterizing Tensile Deformation of Knitted Fabric, *Vlákna a textil (Fibres and Textiles)*, Vol.24, Issue 2, ISSN 1335-0617, p. 54 – 58, 2017. **SCOPUS**

[7] **Nareerut Jariyapunya** and Smita Baheti, Application of Image Analysis Method for Measurement of Fabric Stretch Deformation, *IOP Conference Series: Materials Science and Engineering,* 2017. **SCOPUS**

8.2 Conference Publications

[1] **Nareerut Jariyapunya**, Blažena Musilová and Antonín Havelka, Prediction of Pattern Dimensions for Pressure Garment, *22nd International Conference Structure and Structural Mechanics of Textile*, TUL Liberec, Czech Republic, p. 287-293, 5th-7th December 2018. ISBN: 978-80-7494-430-7

[2] Blažena Musilová, Alžbeta Hôrecká and **Nareerut Jariyapunya**, Method of Generation Zoning Areas in Pattern Construction Net of Seamless Underwear, *22nd*

International Conference Structure and Structural Mechanics of Textile, TUL Liberec, Czech Republic, p. 83-89, 5th - 7thDecember 2018.ISBN:978-80-7494-430-7

[3] **Nareerut Jariyapunya,** Nadiia Kholiavko and Blažena Musilová, Designing Method for 3D Modelling for Garment Compression Values of Elastic Fabric Extension, *the 9th Central European Conference*, ISBN 978-80-7494-355-3, p. 44 – 48, 2017

[4] **Nareerut Jariyapunya** and Smita Baheti, Application of Image Analysis Method for Measurement of Fabric Stretch Deformation, *17th World Textile Conference AUTEX*, 29th–31st May 2017.

[5] **Nareerut Jariyapunya,** Blažena Musilová and Smita Baheti, Study on Stretch Deformation and Mechanical Properties of Knitted Fabrics for Tight-Fitting of Clothing, *44th Textile Research Symposium, IIT Delhi, India*, 14th - 16th December 2016.

[6] **Nareerut Jariyapunya**, Jelka Geršak, Blažena Musilová and Smita Baheti, Designing and Patternmaking with Stretch Fabrics, *21st International Conference Structure and Structural Mechanics of Textile,* Liberec, Czech Republic, 1st-2nd December, ISBN 978-80-7494-269-3, p.239 - 244, 2016

[7] Smita Baheti and **Nareerut Jariyapunya**, Characterization of Knitted Fabric Tensile Deformation by Image Analysis, *Workshop for Ph.D. Students of Faculty of Textile Engineering and Faculty of Mechanical Engineering TUL*, Bílá voda, 20th - 23rd September, ISBN 978-80-7494-293-8, p. 32 - 38, 2016.

[8] **Nareerut Jariyapunya**, Blažena Musilová, Jelka Geršak and Smita Baheti, A Study of Mechanical Properties of Stretch Fabric and Pattern Construction to Evaluate Clothing Pressure, *Workshop for Ph.D. Students of Faculty of Textile Engineering and Faculty of Mechanical Engineering TUL,* 20th - 23rd September, ISBN 978-80-7494-293-8, p. 62-67, 2016.

[9] **Nareerut Jariyapunya**, Blažena Musilov*á*, Smita Baheti and Jantana Sutdaen, "Construction Simulation 3D of Sportswear to Evaluate Tension Distribution of Elastic Fabric for Tight-Fitting Garment," *Rajamangala University of Technology International Conference (7th RMUTIC),* Bangkok, Thailand, 24th – 26th August 2016.

[10] **Nareerut Jariyapunya** and Blažena Musilová, A Study of the Elastic Flat Textile Properties Which Influence a Shape of Clothing Cut and Style, *Workshop for Ph.D. Students of Faculty of Textile Engineering and Faculty of Mechanical Engineering TUL, Světlanka,* Rokytnice nad Jizerou, 22nd-25th September, ISBN978-80-7494-229-7, p. 67 – 72, 2015.

[11] **Nareerut Jariyapunya,** Blažena Musilová and Marie Koldinská, Evaluating the Influence of Fiber Composition Structure of Knitting Fabrics on Total Hand Value (THV), *The 6th RMUTP International Conference on Science*, Bangkok, Thailand, 15th-16th July 2015.

[12] **Nareerut Jariyapunya**, Blažena Musilov*á,* Analysis of Female Body Measurements in Comparison with International Standard Sizing System, *20th International Conference Structure and Structural Mechanics of Textile,* Liberec, Czech Republic, 1st-2nd December, p.155-158, 2014.

9 Curriculum vitae

PERSONAL INFORMATION

Nareerut JARIYAPUNYA M.Eng.,

17 Listopadu 584/2, 46015 Liberec, Czech Republic

+420 48 535 3241 +420 77 359 1414

nareerut.j@en.rmutt.ac.th

Date of birth: 16 December 1981
Nationality: Thai

EDUCATION

(January 2014 – until now)

Doctoral student

Clothing Technology Department, Faculty of Textile Engineering,
Technical University of Liberec, Czech Republic.
Topic: Clothing Patternmaking Method for Stretch Fabrics.

June 2008 – May 2010

Master's Degree of Engineering (Industrial Development),

Industrial Engineering Department, Faculty of Engineering,
Thammasat University, Thailand.
Topic: Analysis of customer Requirement with the Quality Function Deployment Techniques in the Development of New Trekking Products.

June 2001 – March 2005

Bachelor's Degree of Engineering (Garment Engineering),
Textile Engineering Department, Faculty of Engineering,
Rajamangala University of Technology Thanyaburi, Thailand.

WORK EXPERIENCE

(July 2006 – 2013)

Lecturer of Textile Engineering Department, Faculty of Engineering,
Rajamangala University of Technology Thanyaburi (RMUTT), Thailand.
http://www.engineer.rmutt.ac.th/english/

(2005 – June 2006)

Merchandiser, the Thai Silk Company Limited (Jim Thompson), Thailand.

http://www.jimthompson.com/index.asp

TRAINING

January - February 2017

Internship for PhD.
Faculty of Mechanical Engineering, University of Maribor, Slovenia.
Supporting by CEEPUS Mobility CIII-SI-0217-10-1617-M-97968.
Mentor: Prof. Dr. sc. Jelka Geršak.

16th - 22nd October 2016

CEEPUS Winter School DESIGN WEEK 2016.
Faculty of Mechanical Engineering, University of Maribor, Slovenia.

April 2016 – June 2016

Internship for PhD.
Faculty of Mechanical Engineering, University of Maribor, Slovenia.
Supporting by ERASMUS Mobility
Mentor: Prof. Dr. sc. Jelka Geršak.

10 Record of the state doctoral exam

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

ZÁPIS O VYKONÁNÍ STÁTNÍ DOKTORSKÉ ZKOUŠKY (SDZ)

Jméno a příjmení doktorandky: **Nareerut Jariyapunya, M.Eng.**

Datum narození: **16. 12. 1981**

Doktorský studijní program: **Textilní inženýrství**

Studijní obor: **Textile Technics and Materials Engineering**

Termín konání SDZ: **26. 6. 2018**

prospěla ~~**neprospěla**~~

Komise pro SDZ:

Podpis

Předseda:	prof. Dr. Ing. Zdeněk Kůs
Místopředseda:	doc. Ing. Lukáš Čapek, Ph.D.
Členové:	prof. Ing. Karel Adámek, CSc.
	prof. Ing. Jiří Militký, CSc.
	doc. Dr. Ing. Dana Křemenáková
	Ing. Petra Komárková, Ph.D.
	Ing. Irena Lenfeldová, Ph.D.

V Liberci dne 26. 6. 2018

O průběhu SDZ je veden protokol.

TECHNICKÁ UNIVERZITA V LIBERCI | Fakulta textilní | Studentská 1402/2 | 461 17 Liberec 1
tel.: +420 485 353452 | jmeno.prijmeni@tul.cz | www.ft.tul.cz | IČ: 467 47 885 | DIČ: CZ 467 47 885

11 Recommendation of the supervisor

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

Supervisor´s opinion of PhD thesis

Thesis title:	Clothing Patternmaking Method for Stretch Fabrics
Study programme:	P3106 – Textile Engineering
Study branch:	3106V015 – Textile Technics and Materials Engineering
Author´s name:	Nareerut Jariyapunya, M.Eng.
Supervisor:	Ing. Blažena Musilová, Ph.D.
Department:	Department of Clothing Technology

The thesis addresses the specific problems of understanding how to optimize a clothing pattern making method to generate a cut of a specific tight fit garment which is made from stretch fabric. Due to its highly speculative nature, that research project was challenging.

Referring to this work, Ms. Nareerut Jariyapunya has proposed and developed a novel method to define pattern construction parameters of garment to achieve its accurate size and a required specific pressure.

She was able to meet very well all the main objectives.

The experimental investigation was divided into two steps:

1. To define the method for determining the dimension of a particular structural segment of the pattern construction net that is capable of calculating the size of that pattern construction segment according to the dimension of human body thereof.
2. To define the method for calculating the extensibility of fabric from elastic coefficients of clothing that expresses the capability of its specific pressure required for correction of the dimension of a particular structural segment of the pattern construction net.

The main key parameter of her research was to define elastic coefficients in two dimensions of width (ECW) and length (ECL) of patternmaking by multiplying construction abscissa formula at the important points of particular structural segment.

The elastic coefficient in width dimension (ECW) was obtained from the result of stress - strain curve while elastic coefficient in length dimension (ECL) was detected by observing the deformation of fabric stretched behaviour by uniaxial loading and evaluated by digital image analysis using the MATLAB and NIS-Element software.

The prediction of the strain value from the mathematical modelling was related to the geometric model of the cylindrical shape as well as the human body shape. This modelling confirmed the correctness of the strain results by mathematical modelling to calculate the elastic coefficient from the stress-strain curve.

The formulas of the 2D patternmaking of blouse were derived from elastic coefficient which were applied to the human body under a certain pressure that is necessary to ensure the amount of pressure required for compression garment applications. A default algorithm has been developed in order to calculate the size of pattern construction net only in particular part as a cylindrical shape of body including fuselage, arms, thighs etc. This construction algorithm has successfully been tested to create an automated the block pattern by CAD system which allows the structural segment lines to be modified by inputting the parameter of elasticity coefficients in both ECW and ECL.

The research methods used within this work are appropriately chosen and appropriate to the topic of it. The implementation of experimental results achieved during internship can also be positively evaluated.
Ms. Jariyapunya´s activity when she writing her thesis was excellent. We only discussed the general content in the thesis, and she was able to produce a good draft of experimental research steps. Likewise, while we discussed a few times the experimental design and result, everything else, including the details of the experiment and implementation of special software, were entirely done by herself without further input.

TECHNICKÁ UNIVERZITA V LIBERCI | Fakulta textilní | Studentská 1402/2 | 461 17 Liberec 1
tel.: +420 485 353452 | jmeno.prijmeni@tul.cz | www.ft.tul.cz | IČ: 467 47 885 | DIČ: CZ 467 47 885

Formal level, language level and the scope of work is excellent. Although the work contains several formal mistakes, they did not affect the good quality of the work.

The publication quality is excellent also. The total number of publications is 19, 2 of them are published in IF magazines with Q2, 3 publications are published in SCOPUS and 16 publications are listed as the first author. Some more are submitted and under a review and expected to be published soon.

Checking of plagiarism provided within the IS STAG system on 30.04.2019 showed no relevant similarity to other work. The result is 0%.

I therefore recommended the thesis for defense.

Ing. Blažena Musilová, Ph.D.
Supervisor

12 Opponents' reviews

Review of doctoral thesis

Student: Nareerut Jariyapunya, M.Eng.
Supervisor: M.Sc., Blažena Musilová, Ph.D.
Title of the thesis: **Clothing Patternmaking Method for Stretch Fabrics**
Study programme: Textile Engineering
Study branch: Textile Technics and Materials Engineering, Faculty of Textile Engineering, Technical University of Liberec

This submitted doctoral thesis is devoted to study of patternmaking method for stretch fabrics, which are suitable for compression garments. Significant characteristics of compression textiles and their properties were also studied.
The composition of thesis conforms to principles and requests to the structure of scientific thesis. The topic of thesis is current and relevant in the context of up-to-date research in the area of compression garment and systems of patternmaking construction.

It is evident that the author has plunged into the subject and has gradually found and addressed the necessary attributes and contexts that are related to the patternmaking construction of the knitted products. Chapters 1-2 are theoretical background of the research.

Chapter 3 performed the knitted fabrics suitable for compression garment. In the Figure 4.1, p.61 the dependences of the force-elongation of sample S3 and S6 with biggest size of elastane yarn count show high values of force, but different values of elongation. How do you explain this phenomenon?

How do you interpret the high elongation values of your samples (e.g. up to 300% - 500%)? What does interlock knitted structure with 30% elastane look like? Elongation of the warp knitted structure - locknit (charmeuse) can be expected due to the used elastane in back guide bar and polyamide in front guide bar (long underlaps).

Explanation of the significant influence on the stress value when yarn count number of elastane is higher (p. 63, Figure 4.2 same structure – sample S3 and S6 (elastane 78 dtex) is insufficient. Those curves are not similar and values too.

When we compare the results from dynamic work recovery (p.68) not only percentage of elastane might be helping for adjustment to improve the performance of the fabric recovery but together with the relation of the ground yarn count (polyamide). Small recovery is caused with the increasing the ground yarn count and the similar value of wale and course densities of all samples.

In chapter "4.4.1 Measurement of fabric properties by novel tensile measurement device" the results (loading – elongation) which are displayed on curves in Figure 4.22, p. 89, especially in the 1 st cycle were calculated? The curves are not exponential. Why?

When stretching knitted structures large shrinkage in perpendicular direction are occurred. Was that effect included in new patternmaking method?

Now, with the technical improvement of knitted machines, their possibilities and new technics of patterning of the weft/warp knitted structures with the methods of closing/linking, the modern approach will connect the knitted products and patternmaking system together to design so called “seamless” product and eliminate cutting the each product parts and joining together with the sewing process. Both technology warp/weft can produce that sort of product. In the area of weft knitted technology, modern V-bed flat knitted machines can produce the whole-garment product. In the case of circular knitted machines it is necessary the “seamless” product finished with sewing process (shoulders, sleeves), but body/torso with the welt can be designed directly to the machine.

With respect to the above mentioned comments, the author of the thesis proved her ability to perform research and to achieve scientific results.

I recommend the thesis for presentation with the aim of receiving the Degree of Ph.D.

Liberec, July 16, 2019

Irena Lenfeldová, M. Sc., Ph.D.
Department of Technologies and Structures
Faculty of Textile Engineering, Technical University of Liberec

OPONENT - doc. Ing. Jan Krmela, Ph.D.
Alexander Dubček University of Trenčín, Faculty of Industrial Technologies in Púchov
Slovak Republic

Opponent Assessment Report on Dissertation Thesis

Title of Thesis: **Clothing Patternmaking Method for Stretch Fabrics**

Author (candidate): **M.Eng. Nareerut JARIYAPUNYA**

The submitted or presented dissertation thesis, which is written in English language, is closely connected with the current topic in the terms of method design for determination of the optimum geometry of the garment pattern construction in order to obtain the pressure required capability. The given dissertation thesis consists of 106 pages, which are clearly divided into 5 logically related or connected and content-balanced chapters, which are followed by a list of used references and a list of own publishing activities. The two objectives of the dissertation thesis are clearly and specifically defined. Perhaps, the definition of objectives should be presented in a separated chapter after the introduction. From the aspect of content topic as well as clarity, the sub-chapters should be presented and introduced maximally at the third level. There are the 116 quotations of foreign publications predominantly but the citations of candidate's publications are also included here. The dissertation is supplemented by two pages of annexes. It should be noted that the structure of the dissertation thesis was selected deliberately, carefully and accurately in relation to the defined objectives of the given work. In my opinion, the most important part of the dissertation thesis is represented by the *"Results and Discussion"* chapter, in which the measured or obtained data are evaluated at a high professional technical level due to the utilisation of ANOVA statistical processing and graphical interpretation in the form of various graphs.

Assessment or Evaluation of the Proposed Dissertation Thesis

- **<u>from the aspect of the dissertation thesis contribution for the scientific field</u>**

  the submitted dissertation thesis represents an innovative approach to the solved issue and new knowledge for the given scientific field with a focus on garment pattern construction, because the obtained results are original, applicable in practice and they can be also applied in the pedagogical process. Perhaps, it would be a good idea to make the demonstrative videos for students from experimental procedures, but it can be a topic

Alexander Dubček University of Trenčín, Faculty of Industrial Technologies in Púchov, Department of Numerical Methods and Computational Modelling, I.Krasku 491/30, 020 01 Púchov, Slovak Republic
e-mails: jan.krmela@fpt.tnuni.sk , jan2.krmela@post.cz

for the following continuation in the research work. The dissertation can be also considered as a benefit or contribution for the other scientific fields or disciplines, such as material engineering, textile materials and biomechanics, because the given work can be used in a multidisciplinary way;

- **from the aspect of <u>the problem solving process, the usage of methods used and fulfilment of the predetermined objectives</u>**
  the methods are selected and used appropriately and they are adequate to the topic of the work. I appreciate and I assign high value to the inclusion of acquired knowledge from candidate's internships, because owing to the given internships, the instrumentation for the necessary experiments was appropriately used for creation of the dissertation work. I consider the process of problem solving by the selected methods, the results obtained from the experiments and the way of their presentation as an original. I agree with the statement in the conclusions of the given work. I can conclude that the objectives of the dissertation thesis have been fulfilled in the entirety or full extent;

- **from the aspect of <u>the results of the dissertation work and the significance of the candidate's original contribution</u>**
  the dissertation thesis shows the complex approach of the candidate to solve the given system of problems, because the work represents the linkage between the theoretical knowledge and the experimental data with the result of practical outputs in the form of space graphs, which were created in the ORIGIN program and have shown the noticeable dependencies of important parameters, while the given important parameters can be applied for prediction of values relating to "input parameters" for a particular material. Although it was very difficult and demanding task, the candidate showed the adequate and sufficient skills for preparation of these mentioned dependencies in order to be used and generalised for further processing of results. In her work, she used image analysis which was based on NIS-Elements and MATLAB programs. The discussion of the results is done consistently, carefully, precisely and in a comprehensive way. The dissertation shows new findings and knowledge that can complete or amend the missing information in the publications with the same or similar issue;

- **from the aspect of <u>the formal overview in relation to the text editing of the dissertation thesis</u>**
  the work contains minor typing or formal errors, such as presenting units in the round brackets – the units should be given in square brackets, non-uniform style of displaying the ranges of variables, a space has to be inserted between the value and the unit as such as %, or mathematical relationships are without indicating units and the full words are used instead of the abbreviated SI symbols – e.g.: 60 s should be used instead of 60 seconds. Furthermore, for the pressure values, the kPa unit should be used instead of Pa unit in Tab. 4.6 (page 67) to make the results more transparent or clear without any values of

Alexander Dubček University of Trenčín, Faculty of Industrial Technologies in Púchov, Department of Numerical Methods and Computational Modelling, I.Krasku 491/30, 020 01 Púchov, Slovak Republic
e-mails: jan.krmela@fpt.tnuni.sk , jan2.krmela@post.cz

thousands. On the other side, the graphical processing of the dissertation work is very good or at really high level – perhaps, the graphs could be larger or included into the annexes because they are well and intelligible processed;

- **from the aspect of the overall level of the dissertation thesis**
  the dissertation thesis has a comprehensive and intelligible concept and gives the evidence that the candidate has coped with the given difficult task or issue on the basis of the adequate, appropriate careful approach to the solution of the whole complex of problems. From a technical and scientific aspect, the dissertation work is processed at a high or professional quality level. The overall level of work is not significantly influenced by the mentioned formal errors, and in my opinion, the work is effective and valuable. The dissertation thesis is the demonstration of the candidate's ability to have scientific approach in relation to the solution of the technical problem;

The evaluation of candidate's publications in relation to the topic of work
I consider the candidate's publication activity as extraordinary, because she has 19 publications, while 2 of these publications are published in journals with IF with Q2, 3 publications are in SCOPUS and she is listed as the first author in 16 publications. The titles of publications and the year of their publication indicate that the results of the dissertation work were continuously published at conferences and in journals and the candidate sufficiently informed the professional community about the continuous results.

From the above mentioned facts, I state that the submitted dissertation thesis of candidate, M.Eng. Nareerut Jariyapunya, with the title "Clothing Patternmaking Method for Stretch Fabrics", meets all the requirements given in the official documents on doctoral or dissertation thesis.

I would like to ask candidate to answer the following questions briefly:

1) What was the reason of the difference between the results of a standard and manual experiment (page 89, Fig. 4.22 a)?
2) How were the values of Young's modulus of elasticity obtained?
3) What was the main reason for selection of 60 s as a relaxation time (e.g.: page 66 and Fig. 4.5)?
4) Could you define the term "neural network"? What is your opinion on application of neural networks for further research in relation to the solution of the given issue?

Alexander Dubček University of Trenčín, Faculty of Industrial Technologies in Púchov, Department of Numerical Methods and Computational Modelling, I.Krasku 491/30, 020 01 Púchov, Slovak Republic
e-mails: jan.krmela@fpt.tnuni.sk , jan2.krmela@post.cz

I evaluate or asses the submitted **dissertation thesis in a positive way**

and

I propose to accept this thesis for defence

and

after successful defence,

I recommend to confer a scientific degree of Ph.D. (doctor)

to M.Eng. Nareerut Jariyapunya

in 3106V015 study field – Textile Technics and Materials Engineering,

study programme P3106 – Textile Engineering

In Púchov, June 24, 2019 **doc. Ing. Jan Krmela, Ph.D.**

Alexander Dubček University of Trenčín, Faculty of Industrial Technologies in Púchov, Department of Numerical Methods and Computational Modelling, I.Krasku 491/30, 020 01 Púchov, Slovak Republic
e-mails: jan.krmela@fpt.tnuni.sk , jan2.krmela@post.cz