FACULTY OF TEXTILE ENGINEERING TUL

Tensile Characterization of Compression Socks's Ankle Cut-Strips and Development of Models to Approximate Laplace's Law

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SUMMARY OF THE THESIS

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ABSTRACT

Tensile properties of compression socks play a vital role to exert the adequate radial pressure, directly linked to their work performance, and working life. These properties are deployed using various type of materials and machine adjustments. In this scientific research work, socks samples were commercially bought and cut to evaluate their physical, structural, tensile properties and theory of exertion of compression pressure. So, current research work is comprised of two parts. Part 1 presents a scientific tensile characterization of the sock's cut-strip hauled to analyze; force at practical extension compared to experimental pressure (Ps), comparison between tensile indices, experimental pressure (Ps) and force at practical extension. These tensile indices include; loading energy (W), unloading energy (W′), hysteresis (H), and tensile linearity (TL). Results showed that the force value at practical extension (F_L) impart the significant influence to explain experimental pressure (Ps). It was also concluded that the tensile indices (W, W′, H, and TL) statistically shows significancy (R^2- value = moderate-strong) to force at practical and experimental pressure. Part 2 is comprised of a theoretical investigation of compression pressure using the modelization technique and transformation of the Laplace's law. This technique helped to explore some unknown parameters especially, deformed width (w_f), true stress (σ_T)/ logarithmic strain (ε_T)/true modulus (E_T). Using these unknown parameters; Laplace's law was transformed to two new mathematical models; Model 1 (T.Y.M); based on true Young's modulus and Model 2 (E.Y.M); based on engineering Young's modulus and deformed width (w_f). Furthermore, the results revealed that the transformed models; model 1 and model 2 and basic Laplace's law have well approximation to experimental pressure (Ps). Existing models were also compared to experimental pressure to analyze their efficacy. Newly transformed models were also statistically compared to original Laplace's law revealed that newly developed models have strong significant approximation to basic Laplace's law.

KEYWORDS: *Tensile characterization, ankle cut-strips, modelization technique, transformed Laplace's laws, experimental pressure, approximation to Laplace's law*

ABSTRAKT

Tahové vlastnosti kompresních ponožek hrají zásadní roli při vyvíjení přiměřeného radiálního tlaku, přímo spojeného s jejich pracovním výkonem a životností. Tyto vlastnosti jsou nasazovány pomocí různých druhů materiálů a strojních úprav. V této vědecko-výzkumné práci byly komerčně zakoupeny a nařezány vzorky ponožek, aby se vyhodnotily jejich fyzikální, strukturální a tahové vlastnosti a teorie vyvíjení kompresního tlaku. Současná výzkumná práce se tedy skládá ze dvou částí. Část 1 představuje vědeckou charakteristiku tahu proužku ponožky taženého k analýze, sílu při praktickém vytažení ve srovnání s experimentálním tlakem (Ps), srovnání mezi indexy tahu, experimentálním tlakem (Ps) a silou při praktickém vytažení. Tyto indexy tahu zahrnují zatěžovací energii (W), odlehčovací energii (W´), hysterezi (H) a tahovou linearitu (TL). Výsledky ukázaly, že hodnota síly při praktickém prodloužení (F_L) má významný vliv na vysvětlení experimentálního tlaku (Ps). Rovněž se dospělo k závěru, že indexy tahu (W, W´, H a TL) statisticky vykazují významnost (hodnota R^2 = střední až silná) pro sílu při praktickém a experimentálním tlaku. Část 2 se skládá z teoretického zkoumání kompresního tlaku pomocí techniky modelování a transformace Laplaceova zákona. Tato technika pomohla prozkoumat některé neznámé parametry, zejména deformovanou šířku (w_f), skutečné napětí (σ_T) / logaritmickou deformaci (ε_T) / skutečný modul (E_T). Pomocí těchto neznámých parametrů byl Laplaceův zákon přeměněn na dva nové matematické modely. Model 1 (T.Y.M) je založen na skutečném Youngově modulu a Model 2 (E.Y.M) je založen na inženýrském Youngově modulu a deformované šířce (w_f). Kromě toho výsledky odhalily, že transformované modely model 1 a model 2 a základní Laplaceův zákon se dobře přibližují experimentálnímu tlaku (Ps). Stávající modely byly také porovnány s experimentálním tlakem za účelem analýzy jejich účinnosti. Nově transformované modely byly také statisticky porovnány s původním Laplaceovým zákonem a ukázalo se, že nově vyvinuté modely mají silnou významnou aproximaci k základnímu Laplaceovu zákonu.

KLÍČOVÁ SLOVA*: Charakterizace tahu, kotníkové střihy, modelační technika, transformované Laplaceovy zákony, experimentální tlak, přiblížení k Laplaceovu zákonu*

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Nomenclature

List of Symbols

A_o	Original cross-sectional area [mm^2]
A	Actual cross-sectional area [mm^2]
C_L	Circumference of the leg [mm]
C_S	Circumference of socks [mm]
d	Diameter of the leg [mm]
d_L	Arc length of circular strip [mm]
E_E	Engineering modulus [N/mm^2]
E_T	True modulus [N/mm^2]
F_L	Radial force /Practical force of extension [N]
ℓ	Final length [mm]
ℓ_o	Original length [mm]
ln	Natural log
L	The total length of the circular strip [mm]
$\Delta\ell$	Extended length/change in length [mm]
P	Pressure exerted per unit area [kPa]
Ps	Experimental pressure [kPa]
P_E	Pressure concerning engineering modulus [kPa]
P_T	Pressure concerning true modulus [kPa]
R	Radius of the leg [mm]
T	Tension on the cylindrical wall [N/mm]
t	Thickness of compression socks [mm]
w_i	Initial/un-stretched width of circular strip [mm]
w_f	Deformed width of circular strip [mm]
W	Loading energy [mJ]
W'	Unloading energy [mJ]
ε_E	Engineering strain
θ	Degree angle
ε_T	True strain
σ_E	Engineering stress [kPa]
σ_T	True stress [kPa]
λ	Draw ratio

List of Abbreviations

CEN	Committee of European Standardization
CCL	Compression class level
E.Y.M	Engineering Young’s modulus [kPa]
ECE	European colorfastness establishment
FEA	Finite element analysis
ISO	International standard organization
ICC	International compression committee
MST	Medical stocking tester
Model 2 (E.Y.M)	Model 2 based on engineering Young’\s modulus
Model 1 (T.Y.M)	Model 1 based on true Young’s modulus
PA	Polyamide
PU	Polyurethane
RH%	Relative humidity percentage [%]
T.Y.M	True Young’s modulus [kPa]
H	Hysteresis
LE	Loading energy
UE	Unloading energy
TL	Tensile linearity

1. Introduction

Medical compression socks with the gradual decrease in compression pressure are utilized to conduct the compression therapy. There are two main principles i.e. Laplace's law and Pascal's law, involved in explaining how the compression therapy system delivers the pressure around the leg. The first principle involves the application of Pascal's law, which demands muscle movement to generate a pressure pulse that is distributed evenly in lower limbs during active and passive exercise. Pascal's law is also used to explain the compression pressure during dynamic conditions [1]. The second principle involves the application of Laplace's law to create a varied interface pressure based on limb shape and tension of the stocking applied. This law is used to evaluate the compression pressure in static conditions [2].

Based on the theory of Laplace's law that was developed to relate the wall tension and radius of cylinders (e.g. blood vessels) to the pressure difference due to inflation and deflation of two halves of cylindrical vessels [3],[4],[5]. The equation can be expressed as

$$P = \frac{T}{r} \tag{1}$$

where; P denotes pressure [Pa], T is cylinder wall tension [N/mm] and r is cylinder radius [mm]. Ancutiene *et. al* (2017) investigated the tensile properties using the KES-F system. The graphical representations (figure 1) of the stretch (1st cycle) and recovery (5th cycle) results portray the various tensile properties of compression sock strips.

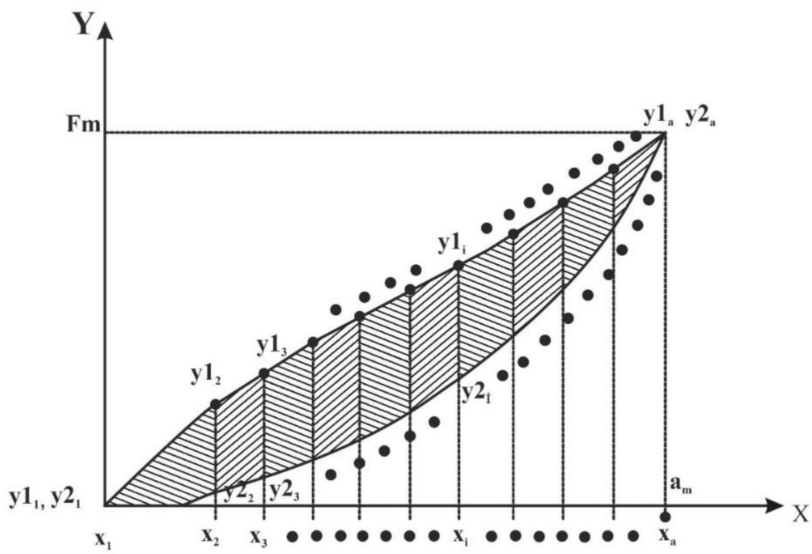


Figure 1. Load-extension curve [6]

To obtain the areas bordered by the tensile and resilience curves, the trapezoidal rule was a simple and operative quadrature rule. According to the trapezoid rule, the partial sum of individual trapezoid areas could quantitatively present the hysteresis (H) when the fabric is stretched as shown in figure 1.

$$H \approx \sum_{i=1}^{n-1} \frac{(y1_i - y2_i) + (y1_{i+1} - y2_{i+1})}{2}.\ (x_{i+1} - x_i) \tag{2}$$

where H is the hysteresis, , $y1_i$ is the tensile curve and $y2_i$ is the resilience curve [6].

The tensile energy W can be quantitatively estimated by equation 3.

$$W = \int_0^x F(x).d(x) \quad (3)$$

With the decreasing of the stretch loading, the return curve formed reflects the tensile resilience energy W' of the fabric, which can be calculated by equation 4.

$$W' = \int_0^x F(x)'.d(x) \quad (4)$$

where; x is the displacement of stretched fabric; F(x) is the tensile force needed in response to the stretched displacement [6].

Tensile linearity indicates the wearing comfort. Lower values of the TL give higher fabric extensibility in an initial strain range indicating better comfort but the fabric dimensional stability decreases. Tensile linearity can be calculated using below equation

$$TL = \frac{2.W}{F_m.a_m} \quad (5)$$

where; F_m is the force at maximum deformation, a_m is maximum displacement, W is loading energy [6]

Stretch ratio is the ratio of the circumferential difference between the leg and socks to the sock's circumference while reduction percentage is the ratio of the circumferential difference between the leg and socks to the leg's circumference calculated using equation 6 and equation 7 [7].

$$\text{Stretch ratio } (S_e) = \frac{L_c - S_c}{S_c} \quad (6)$$

$$\text{Reduction ratio } (R_e) = \frac{L_c - S_c}{L_c} \quad (7)$$

where; L_c is leg circumference, S_c is socks circumference

Hui and Ng (2001) [8] and Halfaoui *et al.* (2016) [9] developed a model to predict interfacial pressure exerted on a fabric tube. In this study, they formulate a theoretical model to predict interfacial pressure is generalized as

$$P = \frac{2\,\pi\,\varepsilon\,E_i\,h_i}{C} \quad (8)$$

where; E_i is the modulus of elasticity [N/mm^2], h_i is fabric thickness [mm], C is the circumference of cylindrical fabric [mm], ε is engineering strain.

Ng and Hui (2001) [10] proposed objective method to predict interfacial pressure as given below

$$P = \frac{2\,\pi\,R_e\,EI\,t}{C_{tube}\,(1 - R_e)} \quad (9)$$

where; EI is the modulus of elasticity [N/mm^2], R_e is the reduction ratio, C_{tube} is the circumference of the cylindrical tube and t is the thickness

Maklewska *et al.* (2006) [11] designed and modeled warp fabrics used for compression therapy based on the pre-set value of unit pressure. The model is based on the theory of Laplace's law.

$$P_i = \frac{2\,\pi\,F}{W\,G_1} \quad (10)$$

where; F is force [N] of strip, G_1 is circumference [cm] of leg, W is cut-strip width [cm] and P_i = pressure exerted by the knitted fabric

Dubuis *et. al.* (2014) [12] studied the patient-specific FE model leg under elastic compression and design a model to evaluate compression pressure. They established model is given below

$$P = \frac{stiff\ \varepsilon}{r} \tag{11}$$

where; *stiff* is the sock's stiffness [N/mm], r is the radius of leg curvature [mm], and ε is the strain

Leung *et. al* (2010) [13] designed a mathematical model based on the theory of Laplace's law

$$P = \frac{2\, \pi\, E\, A_o\, \varepsilon}{\ell_o (1 + \varepsilon)\, C} \tag{12}$$

where; E is the modulus of elasticity [N/mm^2], C is the body circumference [mm], A_o is the original cross-sectional area of fabric [mm^2], and ε applied strain

Jariyapunya *et al.* (2018) developed knitted fabrics for the estimation of strain value [14].

$$P = \frac{2\, \pi\, \sigma_E\, d}{C} \tag{13}$$

where; σ_E is fabric circumferential stress [Pa], d is the thickness, C is the cylinder circumference

Zhang's *et al.* (2019) [15] used the concept of cylinder stress law with thin-walled assumption to design mathematical models for the prediction of compression expressed as below

$$P = \frac{D_i\, E_i\ \ t}{r_{w.i}} \tag{14}$$

where; t is the thickness of cylinder, $r_{w.i}$ is the radius of part i of the cylinder, E is the tensile modulus, D_i is the axial length of the cylinder

Teyeme *et al.* (2021) modified the Laplace's law based on the theory of modelization by incorporating the parameters of engineering stress and strain values mentioned below.

$$P = \frac{E\, \varepsilon\, s\, 2\pi}{C} \tag{15}$$

where P is pressure, E is elastic modulus, ε is strain, C is leg circumference and s is thickness [16].

2. Purpose and the Aim of Study

The main purpose of current research was to investigate how well the tensile indices values explain the pressure results. It was also claimed to re-establish the pressure predicting mathematical models. For this modelization technique, there were introduced some new parameters to transform basic Laplace's law. The main objectives of the current research are tabulated as follows;

Tensile characterization of compression sock's ankle cut-strips

- Force at practical extension compared to experimental pressure
- Comparison of hysteresis, force at practical extension and experimental pressure
- Comparison of loading energy, force at practical extension and experimental pressure
- Comparison of unloading energy, force at practical extension and experimental pressure
- Comparison of tensile linearity, force at practical extension and experimental pressure

Theoretical investigation to modify Laplace's law

- Development of model 1 considering true Young's modulus and deformed width (w_f); model 1 (T.Y.M)
- Development of model 2 considering engineering Young's modulus; model 2 (E.Y.M)

Statistical comparison of modified and existing models

- Experimental pressure compared to model 1 (T.Y.M) and Laplace's law
- Experimental pressure compared to model 2 (E.Y.M) and Laplace's law
- Experimental pressure compared to existing models
- Comparison of developed models and Laplace's law

3. Overview of the Current State of the Problem

a) The tensile properties of compression socks play a vital role defining periodical efficacy and targeted compression pressure. In the scientific literature, no research was found in which the combined influence of tensile indices (W, W′, H, TL), force at practical extension (F_L) and experimental pressure (Ps) had measured. Literaturely, a few studies exist in which tensile indices are related to experimental pressure. These tensile indices values are measured using Kawabata evaluation system (biaxial extension) [6],[17], [18], [19], [20], [21] instead of uniaxial tensile tester (followed in this study).

b) Many studies exist in which the theoretical prediction of compression pressure is done using a numerical approach; Finite-Element method (FE method) [22–31] and mathematical approaches by approximating/modifying the basic Laplace's law [9-16], [32–38]. European Committee for Standardization (CEN) declared that the pressure values of compression garments are calculated by Laplace's law, where the tensile force is measured under semi-static conditions [32]. Equation of Laplace's law was applied on various objects; wooden leg, [7],[8],[11], [33-35], PVC cylinder [14-16],[39] biological vessels [36], wooden leg wrapped with neoprene fabric simulating the human skin morphology and then installed the socks [26], leg mannequin of varying anatomy of the leg and together on human leg as well wooden leg [6],[8-10],[12-13], [37], to validate experimental compression pressure. Most of the researchers concluded that Laplace's law well explained the experimental pressure when worn onto wooden legs but there are a few researchers who disagree to this concept. Macintyre *et al.* (2004) concluded that Laplace's law predicted the pressure exerted by compression garments on a cylinder model with different curvature radii and Laplace's law significantly overestimated the compression pressure in some cases [3]. Costanzo and Brasseur (2013) proved the inadequacy of Laplace's law when applied to the biological vessel. This has a non-linear response to deformation that is difficult to measure because of the nonlinear hydrostatic response. To overcome this flaw of Laplace's law shear stress concept was introduced instead of hoop stress using multiple constitutive models [36],[38]. Liu *et al.* (2013) concluded that there existed considerable differences between the experimental and theoretic pressure values except for samples exhibiting more tuck stitches than others. Measured pressures in all specimens were considerably more than those predicted by Laplace's law. This difference may be considered due to geometric and morphologic deformation in loops and stitches. [6]. In most of the above scientific research, the basic Laplace's law is used for the prediction of compression pressure but some of the researchers had claimed to modify it without any additional parameter except the notational changes which was the gap in this part of the research work. In this research work, there were introduced some missing parameters that can be incorporated for the modification of Laplace's law using the modelization technique. These unknown parameters include; true stress (σ_T), true/logarithm strain (ε_T), true modulus (E_T), engineering stress (σ_E)/ strain (ε_E) / engineering modulus (E_E) and deformed width (w_f). Using these mentioned parameters, two new models based on engineering Young's modulus and true Young's modulus abbreviated as Model 1 (E.Y.M) and Model 2 (T.Y.M) were developed. As per the literature review, none of the researchers has considered the viscoelastic behavior of the compression socks only justifying the theoretical and experimental difference that is due to surface friction, stitches uneven deformation and slippage factor, etc. In real, compression socks being super-elastic when donned on the leg undergoes axial shrinkage after circumferential expansion causing the ultimate circumferential compression pressure.

4. Experimental Work

4.1. Procurement of compression socks

A total of 13 commercially available sock‘s samples were purchased exhibiting three different compression class levels (Class I, 2.40~2.80 kPa; class II, 3.06~ 4.27 kPa and class III, 4.53~ 6.13 kPa; where (1 kPa =7.500 mmHg) [7]. Class 1 socks samples are coded as A1, A2, and A3; Class II as B1, B2, and B3 while class III as C1, C2, C3, C4, C5, C6, and C7. Most of the socks (about 11 samples) exhibited (1×1 laid-in plain Knit) structure shown in figure 2(b). While only 2 samples belonging to class I exhibit (1×1 laid-in- mesh knit) portrayed in figure 2(a) were confirmed during visual as well as unravelling analysis of compression socks. Compression socks were tested on fix-sized standard wooden leg exhibiting 240 mm circumference around the ankle.

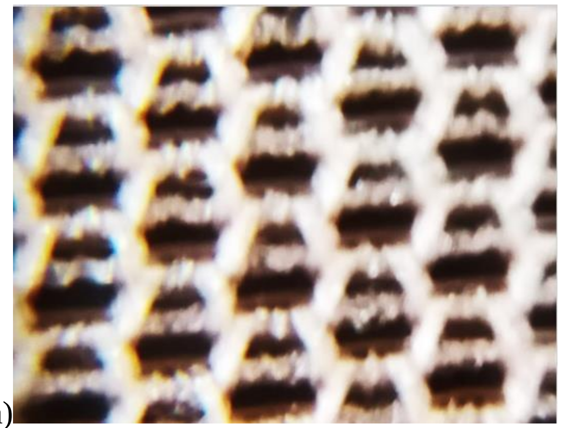
(a)  (b) 

Figure 2. (a) 1×1 laid-in- mesh knit (b) 1×1 laid-in plain knit

All of the samples were evaluated for their built-in physical and technical specifications as shown in table 1 and table 2 with great precision and accuracy under standard atmospheric conditions RH%, 65±5%, temperature, 20±2°C as per CEN 15831:2009 [32], and RAL-GZ 387/1 (Medical compression hosiery quality assurance) [7].

4.2. Preliminary testing of compression socks under study

Preliminary data of all 13 samples were evaluated at the ankle portion includes; fabric weight [g/m^2], fabric thickness [mm], quantitative analysis for polyurethane composition [%], type of yarns transformed to knit, stitch density, and circumference/width of the compression socks at ankle portion. All samples were categorized grounded on the 3-levels of compression classes (Class I, class II and class III) based on the intensity of compression pressure at the ankle mentioned in CEN 15831:2009 [32] and RAL-GZ 387/1 [7]. The class level is defined concerning pressure at the ankle portion because of being a complex part of the leg (contour surfaces and bony).

4.2.1. Determination of fiber content of the fabrics

Fiber analysis of all samples was done using the standard procedure mentioned in AATCC-20A-2013 and results are shown in table 1. To confirm the contents (Polyamide /Polyurethane) at the ankle portion, there was marked a square of 50×50 mm (250 mm^2) on both faces of compression socks as shown in figure 3(b), unraveled the weft knitted threads to understand the yarn and knit type, as well as contents, etc. Unraveled threads were weighed, and treated with an 95% solution of formic acid to dissolve the polyamide filaments per the procedure mentioned in AATCC-20A method (Quantitative analysis of fiber composition). The weight of the undissolved polyurethaneextracted from all samples was done to find the percentage of polyurethane through the solubility test given in table 1 using the following equation.

$$\text{Polyurethane percentage }[\%] = \frac{\text{Weight of polyurethane threads}}{\text{Total weight of the threads}}.100 \qquad (16)$$

Table 1**.** Physical specifications of compression socks

Sr. no.	Code	Circumference at ankle [mm]	Fiber analysis [%] *PU/*PA	Classification
1	A1	190	30/70	*CCLI (2.40–2.80 kPa)
2	A2	186	31/69	
3	A3	144	28/72	
4	B1	156	33/67	*CCLII (3.06–4.27 kPa)
5	B2	178	30/70	
6	B3	164	25/75	
7	C1	162	50/50	*CCLIII (4.53–6.13 kPa)
8	C2	156	45/55	
9	C3	146	38/62	
10	C4	178	28/72	
11	C5	156	40/60	
12	C6	146	32/68	
13	C7	162	45/55	

*PA=polyamide, *PU= polyurethane*CCL= Compression class level [7].

4.2.2. Determination of thread count of fabrics

The number of wales and courses per centimeter and stitch density per centimeter square were measured using the pick glass advised by the RAL GZ-387/1 standard of quality assurance [7]. Results of measured parameters; wales density (number of wales per cm), course density (number of courses per cm), and stitch density (stitches per centimeter square) are given in table 2.

4.2.3. Determination of thickness of the fabrics

Digital thickness tester of model M034A, SDL (Atlas) device was used to determine the thickness of the material according to standard test method ISO 5084:1996. The material is measured as the perpendicular distance between the base plate on which the fabric sample is positioned, and a circular pressing disc that develops on the surface of the fabric. The measurement progress is recorded by a computer program. The area of the pressing leg was 20 cm^2 while the load of 200gram was applied. Thickness testing results are given in table 2.

4.2.4. Determination of weight per unit area of fabrics

Sample cut-strips; 250 mm^2 obtained from each sock were relaxed for 24 hours under controlled standard atmospheric conditions and were weighed using an electronic weighing balance. Given results in table 2 were calculated using the formula given below

$$\text{Fabric weight }\left[\frac{g}{m^2}\right] = \frac{\text{Average fabric weight }[g]}{\text{Area of fabric }[cm^2]}.400 \qquad (17)$$

Table 2**.** Technical specifications of compression socks

Code					Stitch density

	Thickness [mm]	Fabric Weight [g/m^2]	Course density [per cm]	Wales density [per cm]	[stitches/ cm^2]
A1	0.40	139.44	22.4	19.21	430.43
A2	0.46	134.00	24.6	16.20	398.52
A3	0.54	149.28	18.20	20.00	360.00
B1	0.90	291.60	22.00	18.00	396.00
B2	0.75	298.00	22.60	18.27	412.90
B3	0.64	306.08	23.20	22.06	511.79
C1	0.69	281.60	20.80	22.41	466.12
C2	0.68	265.20	21.80	20.34	443.41
C3	0.65	296.00	21.00	23.44	492.24
C4	0.86	360.56	19.20	19.00	364.80
C5	0.70	298.44	24.00	22.00	528.00
C6	0.87	312.80	16.80	24.48	411.26
C7	0.72	384.88	22.60	26.00	587.60

4.3. Hand washing

Hand washing and rinsing of pair of each sock's samples was preceded before testing the physical and technical specification under slightly hot water for washing at a temperature of about 37±3 ^{o}C as per detailed specifications given below in table 3. The procedure comprised of dipping socks in a bucket for 10-15 minutes then were dehydrated (Hydro-extraction) by placing them flatly between two layers of towels for 24 hours under standard atmospheric conditions (RH%, 65±5%, temperature, 20±2 ^{o}C) for fully drying purpose proposed by socks manufacturing brands.

Table 3. Hand washing parameters

Parameters	Dipping time	Water temperature	Samples weight	Water quantity
Hand washed	10-15 minutes	37±3 ^{o}C	250 g	5 liters

4.4. Marking and slicing of cut-strips (ankle portion)

Initially, a dried sock sample was put onto a wooden leg in such a way that socks samples are not fully stretched to wales direction (longitudinal direction), considering no creases on the surface/face of fabric drawn a mark of mean-dashed-line (-); figure 3(a) corresponding to main-grooved-line engraved on the face of the wooden leg; figure 3(e). After marking the mean-dashed line (-), socks were put-off and allowed to be relaxed for 24 hours. After 24 hours, a square of 50×50 mm (250 mm^2) was marked keeping the drawn dashed line (-) as the mean line of the square marked on the face of the fabric. This was done to overcome variation due to repeated measurement of compression pressure and to keep the wales and courses smooth and straight.

Putting on and off all the hand-washed socks samples was done 5 times keeping the mean of the marked square, figure 3(c), at the main grooved line around the leg, and pressure was measured using the Salzmann MST MKIV model. Such a method of marking can be proposed to avoid the variability and reliability of compression pressure results. After marking and pressure measurement, a circular strip having widths of almost 50 mm was sliced into loop-strips as shown in figure 3(d). The slicing can be made at any position of leg up to thighs and arms in un-stretched form. The sliced loop strips of all 13 socks samples were donned to the leg to measure deformed width (w_f) as shown in figure 3(d).

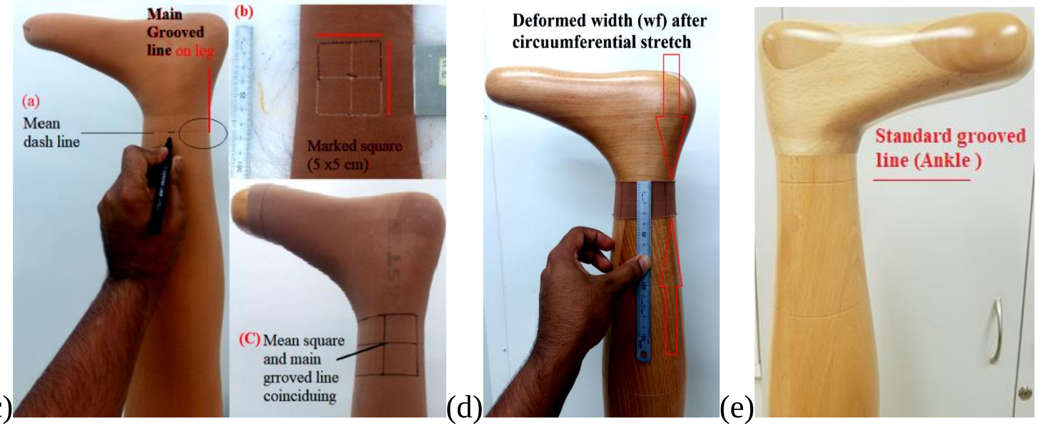
(a, b,c)


Figure 3. Marking (a) Locating exact grooved line on leg on the face of socks (b) Square marking 50×50 mm (250 mm2) (c) Coinciding mean line and main line over the sensor at the ankle on leg surface (d) Deformed width (e) Grooved line (ankle portion)

4.5. Wooden leg model

The compression pressure of each sock sample was measured on a standard-sized wooden leg arranged by Swisslastic standard leg producing company, located in Switzerland recommended by RAL-GZ 387/1 and CEN 15831. The circumference of the leg at ankle; cB = 240 mm while the length of the ankle from the sole of foot along the leg; ℓB = 120 mm (the height from the sole to grooved line on the face of leg at ankle portion).

4.6. Measurement of experimental pressure

Currently, there are two major methods used for the determination of compression performance- the direct in vivo method and the indirect in vitro method using different tools. In this research work, we performed in vitro method for indirect evaluation of compression pressure using the Salzmann pressure measuring device MST MKIV (Salzmann AG, St Gallen, Switzerland). as shown in figure 4.

Figure 4. MST MKIV pressure measuring device

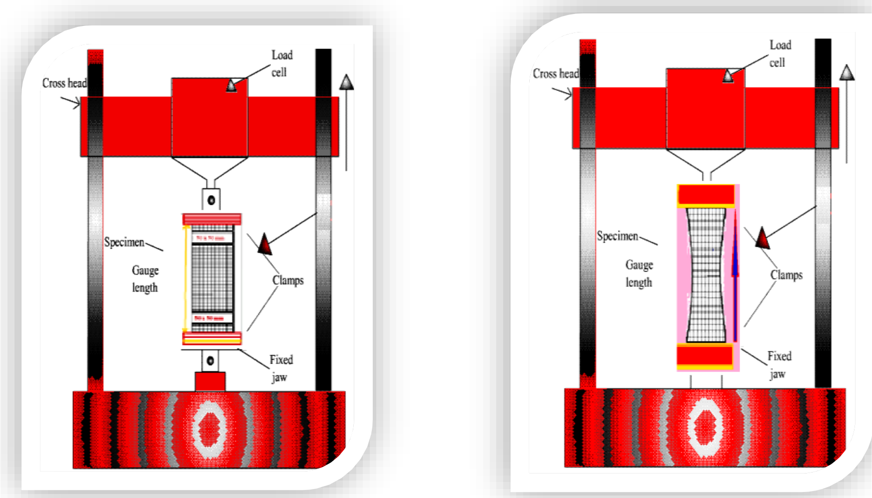
Two lengths of the probe are available. Only the shorter one (34cm long) with four contact points was used in this study. Such evaluation of compression measurement was performed under the standard test method RAL-GZ-387/1.

4.7. Force-extension curve analysis using the cut-strip method

In this scientific research, all the detached cut-strips were investigated for their tensile behavior. For this CRE (constant rate of extension) based Testometric tensile testing machine was selected and used.

4.7.1. Sample preparation

To investigate the tension behavior, all the circular cut-strips from the ankle part of compression socks were linearized into rectangular strips keeping the vertical edges of square mark of area 250 mm^2 between inner edges of clamps, alternatively as shown in figure 5(a). All 13 sample strips were allowed to be relaxed under controlled atmospheric conditions for 24 hours. Tensile testing along the wale direction is not tested here because there is no impact of the force of axial extension (longitudinal extension) on compression pressure. So decided to extend the cut-strips transversally to characterize the radial forces and measurement of tensile indices. Relaxed samples were cleaned by removing edging threads along the course direction to ensure inlaid threads must be griped to both clamping jaws to get an accurate and precise measurement of the force compared to extension data as publicized in figures 5(a) and 5(b).



(a) (b)

Figure 5. (a) Clamped strip without extension, (b) Clamped strip after extension

The testing parameters and machine specifications were followed as per BS EN 14704-1 standard test method. Test specifications include: tensile rate, 100 mm/minute; specimen dimensions were 144~190mm×40~55mm (*lengthwise range of all cut-strips* × *widthwise range of all cut-strips*), gauge length adjusted was 50 mm. *Lengthwise range* means the strip lengths along the width of compression socks or in the course direction. While the *widthwise range* means the strip width along the length or the wales direction of compression socks.

Most of studies in which the strips are extended to fix extensions depending on the size of the object or requisite intensity of compression pressure. Ng and Hui (2001) [10] mentioned that elastic fabric is stretched in making up a pressure garment for clinical treatment generally ranges from 5-50%. While RAL-GZ 387/1 defines this range by mentioning that standard size hosiery can be a maximum of 50% of the extensibility transversely at all measuring points. Dongsheng *et al.* [40] proposed that clothing pressure increases linearly by increasing fabric elongation when it is within the 60% range. A person while wearing a tight garment transversal extension is not more than 60% the of initial length. Chattopadhyay *et al.* [41] mentioned during preliminary studies of pressure garments on several subjects that the maximum extension at which the samples were subjected during wear is about 60%. Therefore, it was decided to study the load elongation behaviour of the test samples only up to 65% extension.

Table 4. Specifications of cut strips/compression socks/wooden leg

Code	Force at practical extension	Extended length	Initial width	Thickness	Deformed width	Original area	Final length	Socks circumference	Experimental pressure
	[N]	[mm]	[mm]	[mm]	[mm]	[mm^2]	[mm]	[mm]	[kPa]
	F_L	$\Delta\ell$	w_i	t	w_f	A_o	ℓ	S_c	Ps
A1	2.978	13.16	50.0	0.40	44.3	20.00	63.15	190	2.24
A2	3.416	14.52	46.5	0.46	43.0	21.39	64.51	186	2.4
A3	4.54	33.33	40.0	0.54	36.0	21.44	83.33	144	3.07
B1	7.872	26.92	54.0	0.90	48.0	48.65	76.92	156	3.65
B2	5.148	17.42	50.0	0.75	44.0	37.50	67.42	178	3.75
B3	7.72	23.17	54.0	0.64	48.0	34.56	73.17	164	4.34
C1	8.304	24.07	54.0	0.69	49.0	37.26	74.07	162	4.71
C2	8.238	26.92	48.0	0.68	42.0	32.64	76.92	156	4.83
C3	9.338	32.19	52.0	0.66	46.5	34.32	82.19	146	5.29
C4	7.928	17.42	50.0	0.86	45.0	43.00	67.42	178	5.33
C5	9.332	26.92	51.3	0.68	47.8	34.88	76.92	156	5.46
C6	10.972	32.19	50.0	0.87	45.0	43.50	82.19	146	6.26
C7	11.996	24.07	55.0	0.72	51.5	39.60	74.07	162	6.46

Table 5. Tensile indices values of compression socks' cut-strips

Code	Hysteresis	Loading energy [mJ]	Unloading energy [mJ]	Tensile linearity	Force at practical extension [N]
	H	W	W'	TL	F_L
A1	3.54	14.26	10.72	0.728	2.978
A2	4.36	16.16	11.8	0.652	3.416
A3	6.41	75.12	68.71	0.993	4.54
B1	12.96	103.78	90.82	0.979	7.872
B2	8.84	45.92	37.08	1.024	5.148
B3	19.77	107.24	87.47	1.199	7.72
C1	13.02	115.78	102.76	1.159	8.304
C2	13.42	116.29	102.87	1.049	8.238
C3	15.35	155.6	140.25	1.035	9.338

C4	11.78	71.96	60.18	1.042	7.928
C5	18.12	144.33	126.21	1.149	9.332
C6	14.671	199.421	184.75	1.129	10.972
C7	19.075	160.44	141.365	1.111	11.996

4.7.2. Loading curve at practical extension

Force at practical extension was extracted from the 5th cycle loading curve as shown below in figure 6. The practical elongation is calculated by considering the circumferences of the leg as well as of socks at the ankle portion. Here the circumference of the leg is fixed to 240 mm but each socks sample exhibit different circumferences at the ankle so the force of extension at specific practical elongation (extension level) is different. Figure 6 revealed the intensity of force of practical extension for all socks samples is different because of the varying parametrical and dimensional specifications.

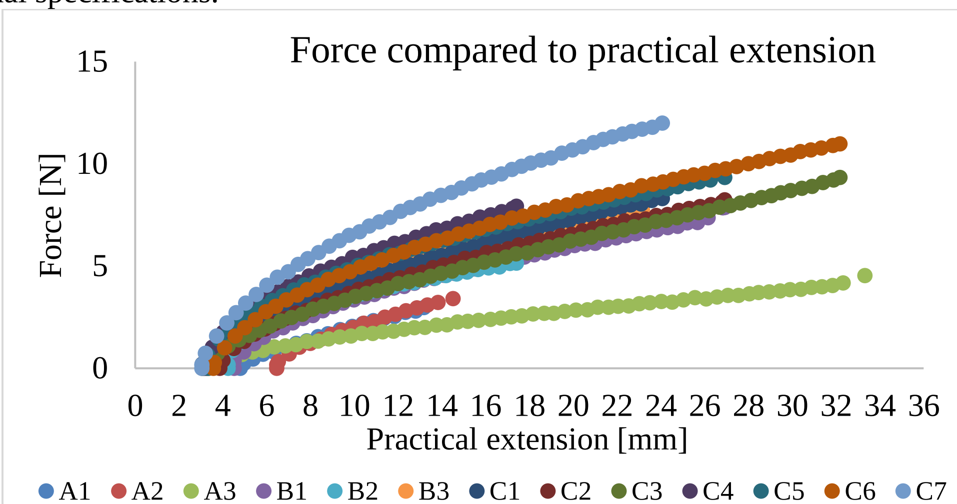


Figure 6. Force extension diagram at practical extension

4.8. Statistical analysis

All of the testing results were statistically analyzed using simple regression analysis. Regression analysis is the statistical tool used to define the data point's distribution by using the least-squares estimation method which derives the regression equation by minimizing the sum of the square of errors. The best-fit line is actually the regression model line. This regression line passing through data points gives us a regression model that helps to determine how well the independent variable explains the dependent variable. Regression results help to identify the direction, size, and statistical significance of the relationship between a predictors and responses. Regression equation provides 'best' fit line to examine how the response variable is changed by changing the predictor value as well as to predict the value of the response variable for any predictor value. The tools used in this research are coefficient of determination value (R^2-value) and Pearson correlation coefficient.

5. Modelling part

5.1. Modelization technique to analyze Laplace's law

The compression pressure (P) is defined by the force (F) which is exerted on an area of 1 m^2. From figure 7(a), the curvature of the leg plays a deciding role to quantify the extent of pressure on the surface of the human leg. This is described by Laplace's law stating that the pressure (P) is directly proportional to the tension (T) of compression socks but inversely proportional to the radius (R) of the curvature to which it is applied (see equation 1). Costanzo *et al.* [36] estimated the hoop stress in biological vessels using Laplace's law mentioning that commonly wall stiffness is measured by interpreting the slope of total hoop stress against strain as an elastic modulus but he used the mathematical Laplace's law model to estimate the hoop stress.

For prediction of compression pressure exerted by the circular strip, the circular strip was worn to the ankle portion of the wooden leg as shown in figure 7(a). To evaluate the intensity of compression pressure on the surface of the wooden leg at the ankle portion, it was divided the circular wooden leg into two halves along with a deformed circular-cut strip as shown in figure 7(b). Each half portion of the circular cut strip when stretched and deformed width was analyzed and assigned the different notations describing the suppression of the cut-strip from the inner side.

Figure 8 is describing the mechanism of the force of exertion from the internal side of circular stretched cut strips per unit area of small arc length ($dL= R.\ d\theta$) by the leg and the reversal force of exertion assumed to be interface compression pressure (P). To calculate the interface pressure (P) it was assumed the following limitations of the current model.

- Geometry of cylinder is axisymmetric
- Material is isotropic
- An axial force is assumed to be zero
- Friction between socks and leg is neglected
- Practical force (F_L) is assumed to be acting radially to exert interface pressure (P).
- The thickness of the circular cut strip after stretching is very small so assumed to be unchanged.
- Different stretch ratio as causing a decrease in the width of the circular cut strip as shown in figure 7(a) is considered as deformed width (w_f)

Laplace's law is the basic principle that attributes to characterize the graduated nature of compression hosiery. It describes the tension produced by a pressure gradient acting across the wall of an elastic cylinder. Laplace's law can be easily derived by considering the case for a static equilibrium where the force caused by the internal pressure (P) induced by a medium of width (w_i) stretched on a cylinder by a force (F_L) as shown in figure 8. It was found that pressure exerted by a strip on the surface of the human leg has compatibility with Laplace's law.

F_L= Radial practical force [N]
d= Diameter of stretched socks/wooden leg [mm]
w_f= Deformed width of circular strip [mm]
L= Total length of strip [mm]
t= Thickness of compression socks [mm]
R= Radius of wooden leg [mm]
X= X-axis
Y= Y-axis/direction of pressure
d_L= Arc length of the circular strip [mm]
θ = Degree angle
P= Pressure exerted per unit area [kPa]
Due to static equilibrium condition

$$\sum \overrightarrow{F_y} = \vec{0}$$

The total sum of forces will become

$$2\vec{F} = \int_0^{\pi} \vec{P}\, w_f\, R\, d\theta$$

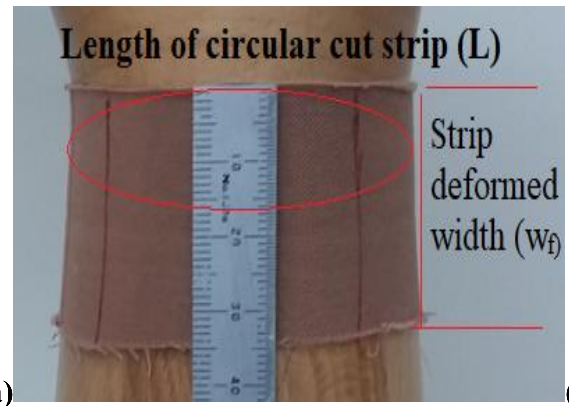
Where $\vec{P}$ can be replaced by $P.\sin\theta$ so the above equation will become

$$2F_L = P\, R\, w_f \int_0^{\pi} \mathrm{Sin}\theta.\, d\theta = \; P\, R\, w_f\, .(-1)[\cos 180° - \cos 0°]$$

$$2F_L = P\, R\, w_f\, [1 + 1] = 2\, P\, R\, w_f$$

$$F_L = P\, R\, w_f \tag{18}$$

where; F_L is the radial practical force of cut-strip around the leg [N], P is radial pressure [kPa], R is radius of wooden leg [mm], w_f= deformed width [mm] of socks strip around the leg [9],[13], [16], [42-45].

(a) 

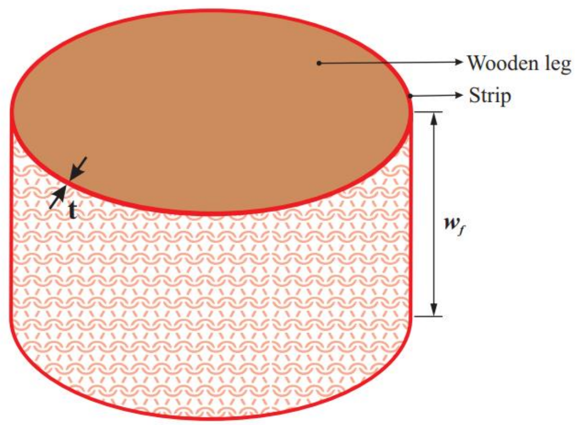
(b) 

Figure 7. (a) Front view of the leg and cut-strip (b) Top view of cut strip worn to wooden leg

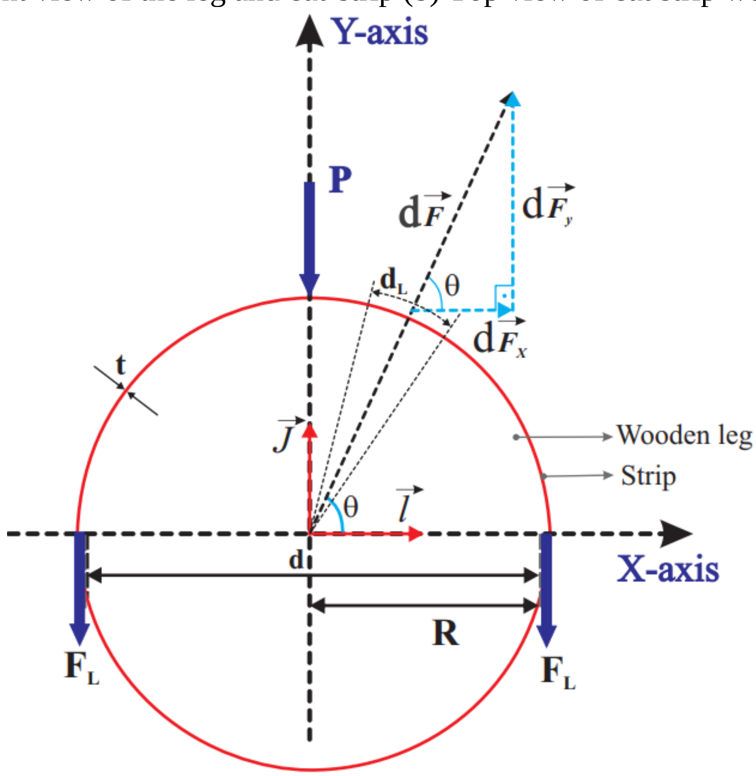


Figure 8. Mechanism of suppression of circular cut-strip due to the wooden leg

5.2. Development of model 2 (E.Y.M) in view of engineering Young's modulus

5.2.1. Engineering stress

The engineering measures of stress and strain notated in this research as σ_E are determined using the original specimen cross-sectional area A_0. Force and extension data were obtained using a Testometric tensile testing device. The corresponding engineering stress and strain were calculated using equations 19 and 20.
Stress (σ) is defined as the force per unit area of a material so engineering stress can be calculated as

$$\sigma_E = \frac{F_L}{A_0} = \frac{F_L}{t\, w_i} \tag{19}$$

F_L= Tensile force applied to fabric [N], A_0 =Original cross-sectional area of the fabric [mm^2], t = Thickness of fabric [mm], wi = Width of fabric [mm] [46].

5.2.2. Engineering strain

In terms of cut strips, strain (ε_E) is defined as extension per unit length so engineering strain can be defined and calculated using

$$\varepsilon_E = \frac{\text{Extended length}}{\text{Original length}} = \frac{\ell}{\ell_o} - 1 \tag{20}$$

Equation 20 can be used to measure stretch ratio/draw ratio (λ) which is the reciprocal of elastic coefficients

$$\text{Draw Ratio} = \frac{\ell}{\ell_o} = 1 + \varepsilon_E = \lambda \tag{21}$$

where; ε_E is engineering strain, ℓ is final length, ℓ_o is original length
In case of circular loop-strip and cylindrical wooden leg, the circumferential/longitudinal/practical strain is the ratio of circumferential difference between leg and socks to circumference of the socks. Equation 20 and 22 shows the analogy between them.

$$\varepsilon_E = \frac{C_L - C_S}{C_S} = \frac{C_L}{C_S} - 1 \tag{22}$$

where; ε_E; engineering strain, C_L; leg circumference, $C_{S;}$ circular strip circumference [7],[46].

5.2.3. Measurement of deformed width

When the sock's circular-cut strips detached from the ankle portion were donned to the wooden leg at the ankle portion as shown in figure 7(a) at practical elongation, the deformations in the strip's widths (w_f) were measured given in table 4.

5.2.4. Engineering modulus

Young's modulus, or the modulus of elasticity, is one of the most important measures of the mechanical properties of a material. However, it is difficult to obtain an exact stress-strain diagram on textile fibers even if we use the load-extension diagram as a substitute for the stress-strain diagram. This is because the load-extension diagram does not make a straight line and because the percentage of extension is so high that many difficulties occur in determining Young's modulus. Generally, his modulus is measured while elongation is kept very small.
Here, ideally, elastic material (compression socks) satisfies Hook's law so, let σ_E be the engineering stress and ε_E be an engineering strain at any point in the straight-line region of the

stress-strain diagram. Then, Young's modulus E is defined as the ratio of engineering stress to engineering strain so we can write

$$E_E = \frac{\text{Engineering stress}}{\text{Engineering strain}}$$

$$E_E = \frac{\sigma_E}{\varepsilon_E} = \frac{F_L}{A_0\ \varepsilon_E} \tag{23}$$

Here σ_E is engineering stress; ε_E is engineering strain while E_E is the modulus of elasticity [36],[38],[48],[49], [50],[51].

Comparing equation 18 and equation 23, we can get

$$F_L = F_L$$

$$P\ R\ w_f = E_E\ A_0\ \varepsilon_E$$

$$P_E = \frac{E_E\ A_0\ \varepsilon_E}{R\ w_i}$$

$$P_E = \frac{2\ \pi\ E_E\ A_0\ \varepsilon_E\ 1000}{C\ w_i} \tag{24}$$

where; E_E is engineering elastic modulus [N/mm^2], w_i is initial width of strip [mm], t is thickness [mm], ε_E is engineering strain, C is circumference [mm] and P_E is circumferential pressure exerted around the wooden leg [kPa]. Equation 24 is denoted as model 2 based on engineering Young's modulus (E.Y.M); model 2 (E.Y.M).

5.3. Development of model 1 (T.Y.M) in view of true Young's modulus

5.3.1. True stress

The stress is calculated based on the instantaneous area at any instant of load, and then it is the true stress. There could exist a relationship between the true stress and engineering stress once no volume change is assumed in the specimen. Under this assumption;

$$\text{True stress} = \frac{\text{Instantaneous load}}{\text{Instantaneous cross} - \text{sectional area}}$$

$$\sigma_T = \frac{F_L}{A} \tag{25}$$

where; A is the actual area of the cross-section corresponding to load F_L

Assuming material volume remains constant

$$A\ \ell = A_0 \ell_o$$

Based on the assumption of the above equation, equation 25 can be written as

$$\sigma_T = \frac{F_L\ A_o}{A\ A_0} = \frac{F_L\ \ell}{A_o\ \ell_o}$$

Using equations 19 and 21 in the above equation

$$\sigma_T = \sigma_E(1 + \varepsilon_E) \tag{26}$$

5.3.2. True/logarithm strain

True strain is defined as the instantaneous increase rate in the instantaneous gauge length defined as true strain [46],[51].

$$\varepsilon_T = \int_{\ell o}^{\ell} \frac{d\ell}{\ell}$$

$$\varepsilon_T = \ln(1 + \varepsilon_E) \tag{27}$$

5.3.3. True elastic modulus/Young's logarithm modulus

Using equations 26 and 27

$$E_T = \frac{\text{True stress}}{\text{True strain}} = \frac{\sigma_T}{\varepsilon_T}$$

$$E_T = \frac{\sigma_E(1+\varepsilon_E)}{\ln(1+\varepsilon_E)} \tag{28}$$

Using equations 19, equation 28 can be modified to

$$E_T \ln(1+\varepsilon_E) = \frac{F_L(1+\varepsilon_E)}{A_0}$$

$$F_L = \frac{E_T A_0 \ln(1+\varepsilon_E)}{(1+\varepsilon_E)} \tag{29}$$

Equating equations 18 and equation 29, relation will become

$$F_L = F_L$$

$$\frac{E_T\, A_0 \ln(1+\varepsilon_E)}{(1+\varepsilon_L)} = P\, R\, w_f$$

$$P_T = \frac{E_T\;\, A_0 \ln(1+\varepsilon_E)}{(1+\varepsilon_E)\, R\, w_f} \tag{30}$$

Equation 30 can be named Model 1 in view of true Young's modulus (T.Y.M)

As we know that the circumference of the leg (C) is C= 2πR so the radius can be calculated using

$$R = \frac{C}{2\pi}$$

Put the value of radius 'R' in equation 31, we can write

$$P_T = \frac{2\pi\, E_T\, A_0 \ln(1+\varepsilon_E)1000}{(1+\varepsilon_E)\, C\, w_f} \tag{31}$$

where; E_T is true engineering Young's elastic modulus [N/mm^2], w_f is deformed width of strip [mm], ε_E is engineering strain, C is circumference [mm] of the wooden leg at the ankle, w_f is deformed width [mm], P_T is circumferential pressure exerted around the wooden leg [kPa] based on the theory of true engineering Young's modulus. Equation 31 is denoted as Model 1 based on true engineering Young's modulus (T.Y.M); model 1 (T.Y.M).

Table 6 represents the theoretical measured values comprised of measurement of engineering stress (σ_E), circumferential/longitudinal/engineering strain (ε_E), engineering modulus (E_E) and deformed width (w_f), true stress (σ_T), true/logarithmic strain (ε_T), true elastic modulus (E_T) to be incorporated into modified mathematical models; model 1 (T.Y.M) mentioned as equation 31 and model 2 (E.Y.M) as equation 24. All additional supporting calculated parametrical values are also given in table 4 helped to measure the values given in table 6.

Table 6. Theoretical results of cut-strips for pressure predictions

Code	Engineering stress	Longitudinal engineering strain	Engineering modulus	Deformed width on leg	True stress	True strain	True modulus
	σ_E	ε_E	E_E	w_f	σ_T	ε_T	E_T
	[N/mm^2]	No unit	[N/mm^2]	[mm]	[N/mm^2]	No unit	[N/mm^2]
A1	0.149	0.263	0.566	44.3	0.188	0.234	0.805
A2	0.160	0.290	0.550	43.0	0.206	0.255	0.808

A3	0.210	0.667	0.315	36.0	0.350	0.511	0.686
B1	0.162	0.538	0.301	48.0	0.249	0.431	0.578
B2	0.137	0.348	0.394	44.0	0.185	0.299	0.619
B3	0.223	0.463	0.482	48.0	0.327	0.381	0.859
C1	0.223	0.481	0.463	49.0	0.330	0.393	0.840
C2	0.252	0.538	0.469	42.0	0.388	0.431	0.901
C3	0.272	0.644	0.423	46.5	0.447	0.497	0.900
C4	0.184	0.348	0.529	45.0	0.249	0.299	0.832
C5	0.268	0.538	0.497	47.8	0.412	0.431	0.955
C6	0.252	0.644	0.392	45.0	0.415	0.497	0.834
C7	0.303	0.481	0.629	51.5	0.449	0.393	1.142

6. Results and Discussion

In this scientific research work, the tensile properties of socks's cut strips were statistically compared with experimental pressure and force at practical extension. These tensile properties include; hysteresis (H), loading energy [mJ], unloading energy [mJ], and tensile linearity (TL). Secondly, theoretically developed models for the prediction of compression were also statistically equated with experimental pressure, existing models, and Laplace's law to estimate their mutual significance. To determine a relationship between any of two variables, Pearson correlations (r) and coefficient of determination values (R^2-value) were computed with a significant threshold set at $p < 0.05$.

6.1. Force at practical extension compared to experimental pressure

Figure 9 portrays the effect of force at practical extension on experimental pressure (Ps). The practical force of extension is the function of compression pressure exerted by the cut-strips. This function of exertion is defined mainly by Laplace's law and various researchers. The contribution of the force of the practical extension to compression pressure was statistically analyzed using simple linear regression analysis.

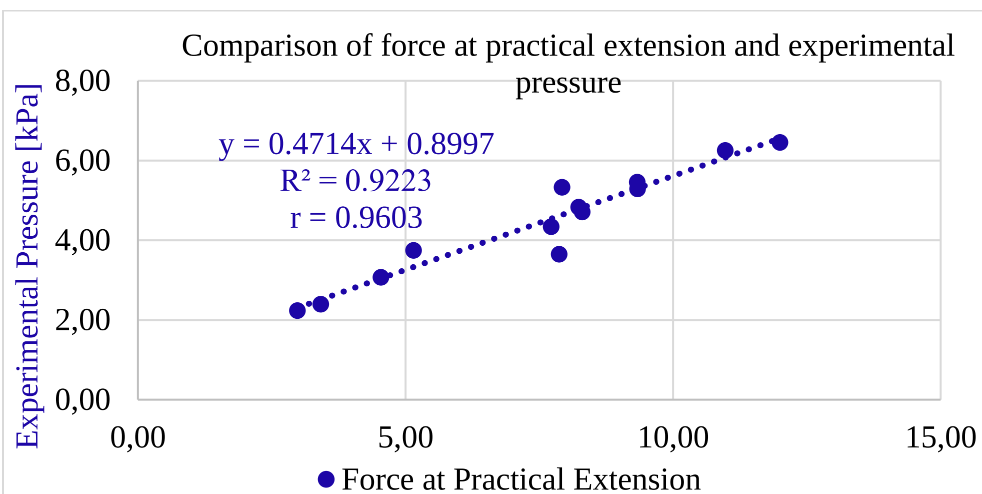


Figure 9. Force at practical extension compared to experimental pressure

Statistical results shown in figure 9 has revealed that force at practical extension imparts a significant influence on the intensity of compression pressure. It was quantified based on the coefficient of determination values (R^2 -value =0.9223). This R^2 -value depicts that the intensity of pressure exertion depends about 92.23% to the practical force of extension [N]. The regression model (figure 9) also comprised of the two more important coefficients explaining the nature and trend of the regression line. These regression coefficients are named y-intercept (0.8997) and slope value (0.4714). Here y-intercept value (0.8997) means the regression line intercepts the y-axis at 0.8997 which is very closer to the origin of axes while the slope gives the rate at which the dependent variable can be explained by the independent variable. The slope values (0.4714) also indicated that experimental pressure will increase by 0.4714 kPa for every increase in 1 unit of force at practical extension. The correlation value between the force of practical extension and experimental pressure was also measured (r= 0.9603) which also shows a direct positive relationship between the two mentioned parameters.

6.2. Hysteresis

Figure 10 illustrates the statistical relationship between force at practical extension (F_L), hysteresis (H) and experimental pressure (P_S). But it was necessary to relate how hysteresis (H) values of the all the socks samples explains the experimental pressure (Ps) and force at practical extension. Figure 10 portrayed that hysteresis value of all the samples explain 74.7% to the experimental pressure values. The strength of the significance was measured on the basis of the coefficient of the determination values (R^2 -value = 0.747) and correlation coefficient (r=0.864; strong positive Pearson correlation coefficient) using second order polynomial fitting line in regression analysis. It also portrayed that hysteresis has a very strong relationship with force at practical extension values. The extent of dependency was computed based on the coefficient of the determination value (R^2 -value = 0.8297) and direction of the relationship using Pearson correlation coefficient (r=0.910; strong positive correlation). This shows that hysteresis values of all samples explain the 82.97% to force at practical extension.

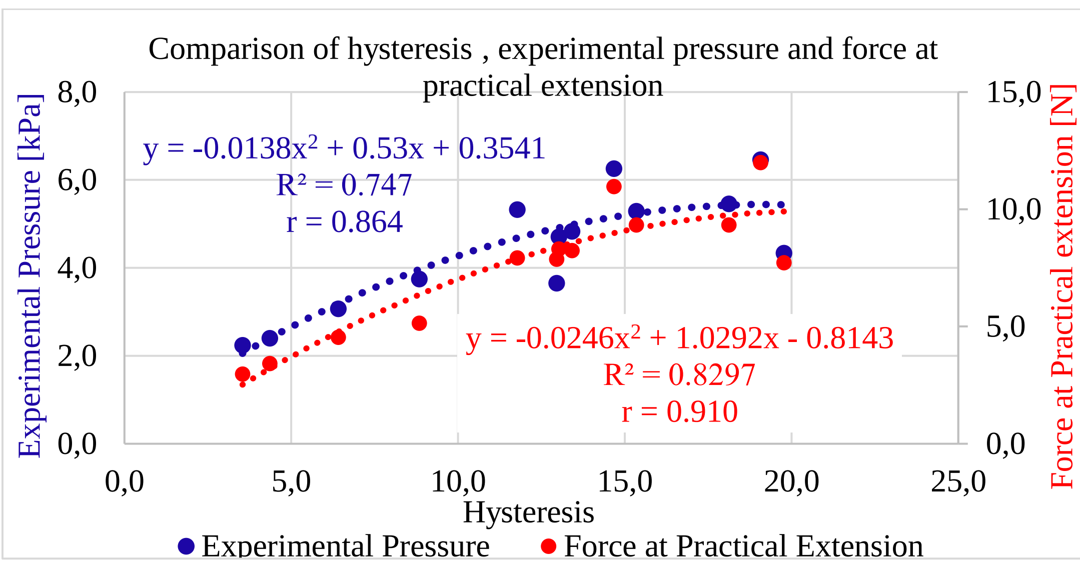


Figure 10. Hysteresis and force at practical extension compared to experimental pressure

6.3. Loading energy

Figure 11 represents the relationship between the force of practical extension (F_L), loading energy (LE), and experimental pressure (P_S). The extent of the dependency was measured on the basis of the coefficient of the determination values (R^2 -value) and Pearson correlation coefficient (r).

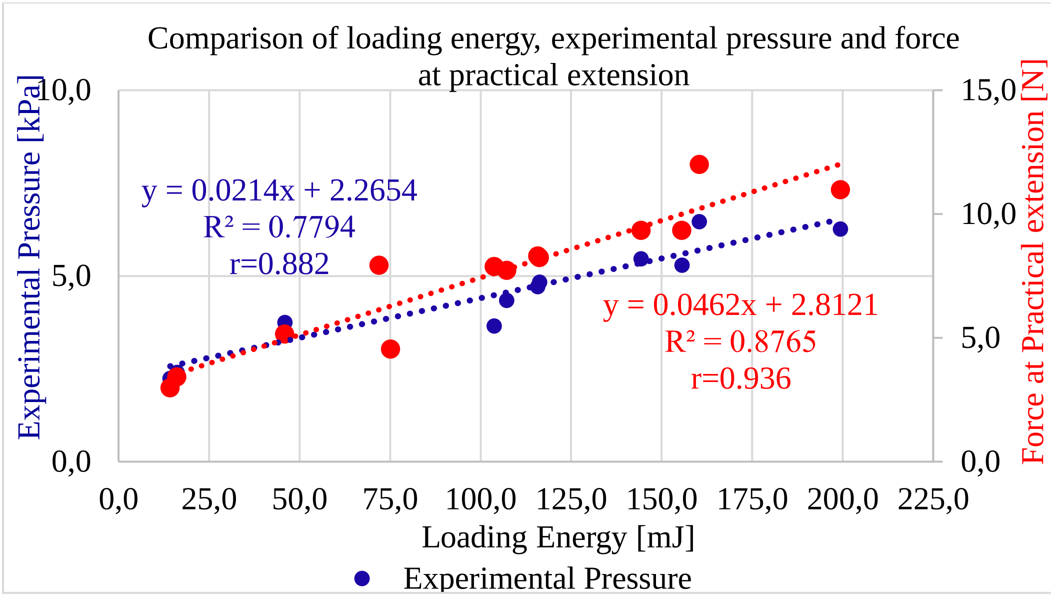


Figure 11. Loading energy and force at practical extension compared to experimental pressure

Higher deformation causes higher recovery of fabric to return to its original position ultimately increasing the intensity of compression pressure. The strength and direction of the relationship between loading energy (as predictor) and experimental pressure (response variable) was R^2=0.7794 and r=0.882. While extent of the relationship between loading energy and force at practical extension was R^2=0.8765 and r= 0.936. These R^2 -value and r values represents that loading energy explains the experimental pressure about 77.94% and correlation value r= 0.936 (strong positive relationship). While the force at practical extension explains the loading energy about 87.65%.

6.4. Unloading energy

Figure 12 reflected the relationship between unloading energy (UE), force at practical extension (F_L) and experimental pressure (Ps).

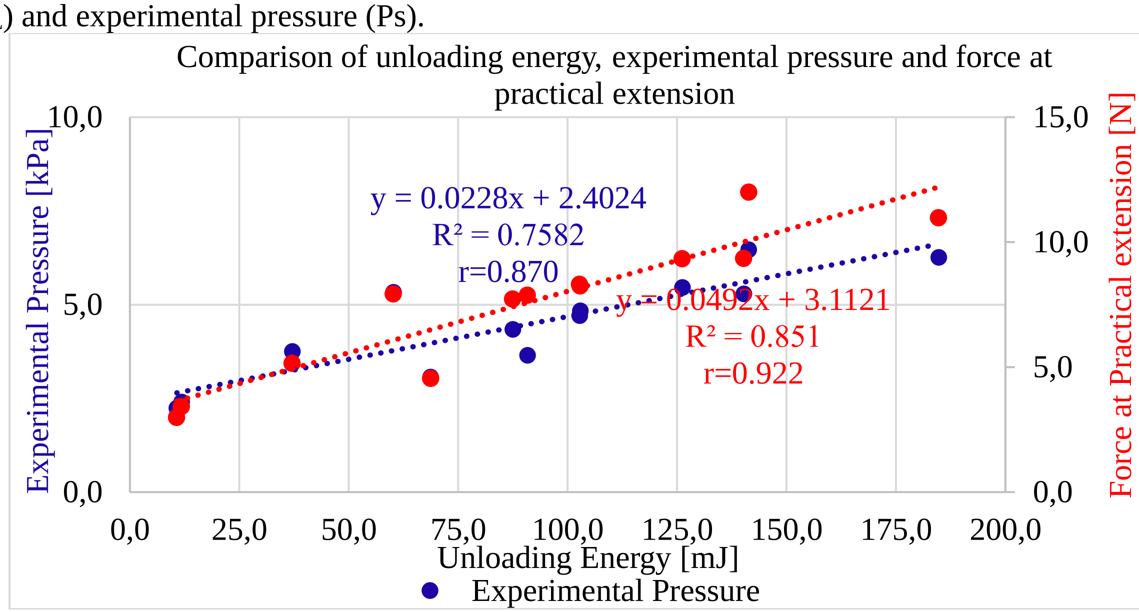


Figure 12. Unloading energy and force at practical extension compared to experimental pressure

It was replicated that unloading energy (UE) has a direct relationship with the experimental pressure (Ps) which means as the unloading energy (UE) increases the compression pressure (P_S) value increases. Simple linear regression analysis was also conducted to observe the strength of the influence of the unloading energy (UE) to force at practical extension (R^2 -value =0.851 and r= 0.922) and experimental pressure (R^2 -value =0.7582 and r=0.870) by measuring the coefficient of the determination value and correlation. These values portray that unloading energy (UE) explains experimental pressure about 75.82% and to force at practical extension 85.1% simultaneously.

6.5. Tensile linearity

Figure 13 comprised of the relationship between forces at practical extension, tensile linearity, and experimental pressure. To understand their mutual dependency, linear regression analysis was conducted to quantify it.

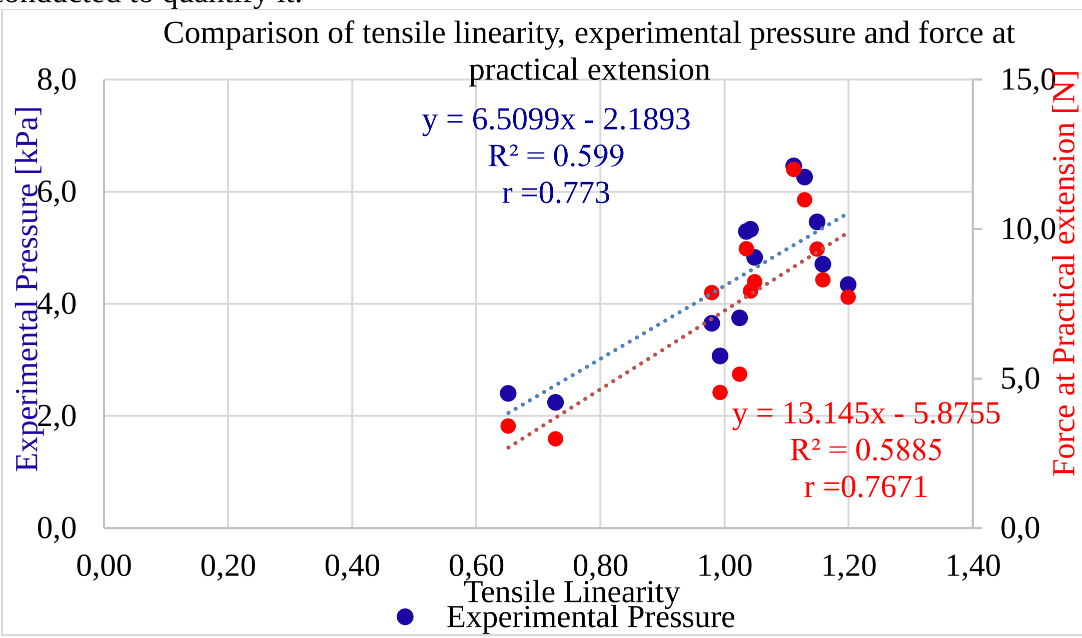


Figure 13. Tensile linearity and force at practical extension compared to experimental pressure

Figure 13 portrays that the tensile linearity explains experimental pressure to 59.92% based on the coefficient of the determination values (R^2 -value = 0.5992, r= 0.773). While it explains to force at practical extension about 58.85% based on the coefficient of the determination values (R^2 -value = 0.5885, r= 0.7671).

6.6. Statistical analysis between experimental pressure, modified models, and Laplace's law

6.6.1. Experimental pressure compared to Model 1 (T.Y.M) and Laplace's law

Figure 14 represents the relationship between experimental pressure (predictor) compared to model 1 (T.Y.M) and Laplace's law (responses). This relationship was analyzed using the least-squares estimation method which derives the regression equation by minimizing the sum of the square of errors. Regression results help to identify the direction, size, and statistical significance of the relationship between a predictors and responses. Regression equation provides 'best' fit line to examine how the response variable is changed by changing the predictor value as well as to predict the value of the response variable for any predictor value.

Figure 14 represents the strength of the relationship between predictor; experimental pressure to response variables; model 1 (T.Y.M) based on the coefficient of determination value notated as R^2-value = 0.9197). It means the newly transformed model; model 1 (T.Y.M) based on the theory of true Young's modulus explains 91.97% to experimental pressure results. In the regression model, there are two coefficients; coefficient of predictor (slope =0.9949) and constant (y-intercept = -0.137) defines the steepness of the line and the point at which the regression line connects the response variable (y-axis). Greater the magnitude of the slope, the steeper the line and the greater the rate of change.

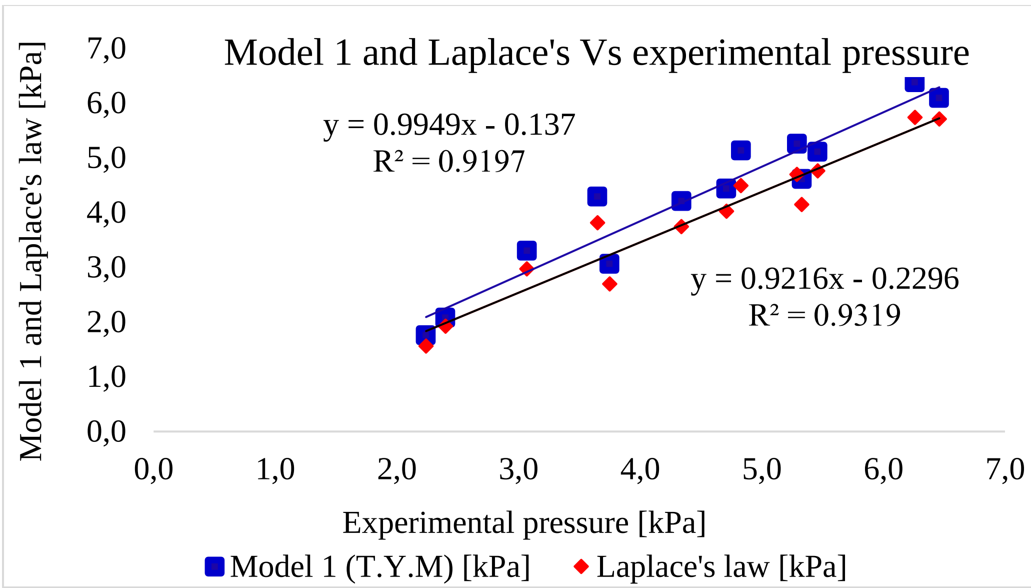


Figure 14. Experimental pressure compared to model 1 (T.Y.M) and Laplace's law

Figure 14 also shows that relationship between original Laplace's law and experimental pressure was analyzed using simple linear regression analysis. The extent of the relationship was measured based on the coefficient of determination value (R^2 = 0.9319). In the regression model, there are two coefficients; coefficient of predictor (slope =0.9216) and constant (y-intercept = -0.2296) defines the steepness of the line and the point at which the regression line connects the response variable (y-axis). Coefficient of determination values (R^2-value) of newly transformed model; model 1 (T.Y.M) is about 2% lower than original Laplace's law when was compared to experimental pressure.

6.6.2. Experimental pressure compared to Model 2 (E.Y.M) and Laplace's law

Figure 15 portrays the relationship between predictors; experimental pressure compared to response variables; Model 2 (E.Y.M) and Laplace's law. The results based on the value of the coefficients (slope and y-intercept) helped to calculate the coefficient of determination values. Coefficient of determination values calculated between Laplace's law and transformed model; model 2 (E.Y.M) compared to experimental pressure was same (R^2 = 0.9319) except the slope and y-intercept values. R^2-value represents that both Laplace's law and transformed model 2 explains the 93.19% to experimental pressure results.

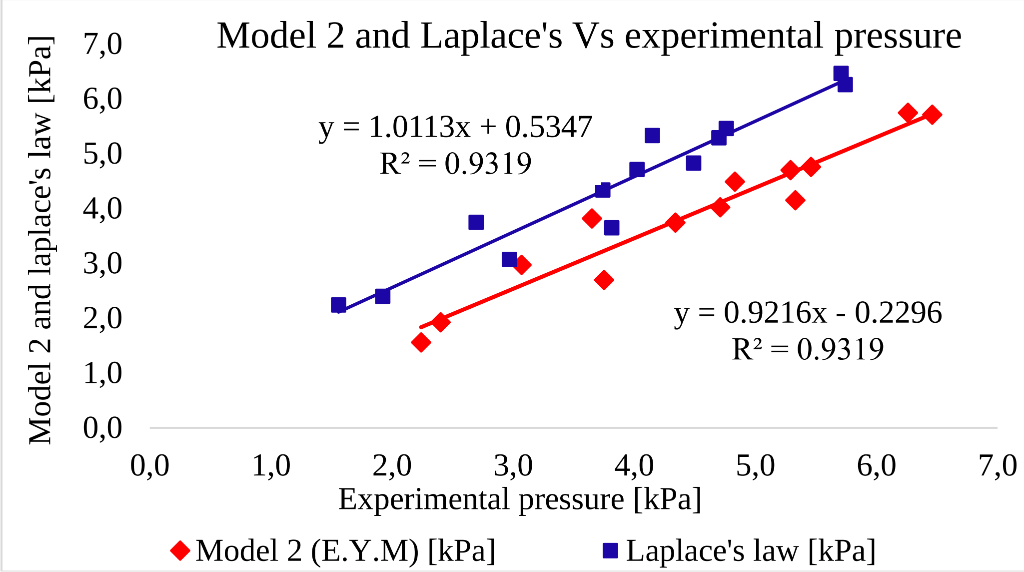


Figure 15. Experimental pressure compared to model 2 (E.Y.M) and Laplace's law

The calculated compression pressure measured using transformed model 2 and Laplace's Law are similar but in figure 15 for Laplace's law, experimental pressure is considered on y-axis to show the two different regression lines separately.

Table 7 portrays the statistical summary results of regression analysis between Model 1 (T.Y.M), Model 2 (E.Y.M), Laplace's law and experimental pressure based on coefficient of determination values showing that newly modified model's estimated results are very close to pressure predicted using Laplace's law.

Table 7. Regression analysis summary of experimental pressure results compared to modified models and Laplace's law

Experimental pressure compared to modified models and Laplace's law	Regression model Y= bX + a b; slope and a; y-intercept	Coefficient of determination (R^2-value)
Model 1 (T.Y.M)	y = **0.9949 (experimental pressure) - 0.137**	R^2 = 0.9197
Model 2 (E.Y.M)	y = **1.0113(experimental pressure) + 0.5347**	R^2 = **0.9319**
Laplace's law	y = **1.0113(experimental pressure) + 0.5347**	R^2 = **0.9319**

6.7. Comparison of existing models and experimental pressure

Table 8 is illustrating the measured values of experimental pressure (Ps) to be compared with newly modified models; model 1 (T.Y.M) and model 2 (E.Y.M). Table 8 also comprised of pressure results calculated considering existing models developed in the past. Most of these models, based on the basic theory of Laplace's law include; Hui's model (equation 8), Ng's model (equation 9), Dubuis's model (equation 11), Leung's model (equation 12), Jariyapunya's model (equation 13), Zhang's model (equation 14), Teyeme's model (equation 15); and Laplace's law (equation 1) etc.

In this research, all existing models were compared to experimental pressure (Ps) results to estimate their strength of accuracy. The measured results of all models are given in table 8.

Table 8. Comparison of theoretical and experimental pressure values

Code	Experimental pressure [kPa]	Laplace's law [kPa]	Model 1 (T.Y.M) [kPa]	Model 2 (E.Y.M) [kPa]	Hui's model [kPa]	Ng's model [kPa]	Zhang's model [kPa]	Dubuis's model [kPa]	Leung's model [kPa]	Teyeme's model [kPa]	Jariyapunya's model [kPa]
A1	2.24	1.558	1.759	1.558	1.558	1.558	1.558	1.558	1.234	1.558	1.558
A2	2.4	1.922	2.079	1.922	1.922	1.922	1.922	1.788	1.385	1.922	1.922
A3	3.07	2.970	3.300	2.970	2.970	2.970	2.970	2.376	1.426	2.970	2.970
B1	3.65	3.815	4.291	3.815	3.815	3.815	3.815	4.120	2.678	3.815	3.815
B2	3.75	2.694	3.062	2.694	2.694	2.693	2.694	2.694	1.998	2.694	2.694
B3	4.34	3.741	4.208	3.741	3.741	3.741	3.741	4.040	2.761	3.741	3.741
C1	4.71	4.024	4.434	4.024	4.024	4.025	4.024	4.346	2.934	4.024	4.024
C2	4.83	4.491	5.132	4.491	4.491	4.491	4.491	4.311	2.802	4.491	4.491
C3	5.29	4.699	5.255	4.699	4.699	4.699	4.699	4.887	2.973	4.699	4.699
C4	5.33	4.149	4.610	4.149	4.149	4.148	4.149	4.149	3.077	4.149	4.149
C5	5.46	4.760	5.109	4.760	4.760	4.761	4.760	4.884	3.175	4.760	4.760
C6	6.26	5.742	6.380	5.742	5.742	5.742	5.742	5.742	3.493	5.742	5.742
C7	6.46	5.707	6.095	5.707	5.707	5.708	5.707	6.278	4.238	5.707	5.707

The relationship between existing models; Hui's model (equation 8), Ng's model (equation 9), Dubuis's model (equation 11), Leung's model (equation 12), Jariyapunya's model (equation 13), Zhang's model (equation 14), Teyeme's model (equation 15), and as a predictors and experimental pressure as (response variable) was analysed using linear regression analysis. Regression analysis of all existing models is discussed below simultaneously.

Hui's model; Figure 16 portrays the relationship between experimental pressure as predictor and Hui's model as a response variable. The strength of the relationship was quantified based on coefficient of determination value (R^2 -value = 0.9319). This value portrays that experimental pressure results explain 93.19% to Hui's model (equation 8). Table 8 depicts that Hui's model (equation 8) exerts lower pressure than experimental pressure but similar values to Laplace's law and modified models; model 1. These results portray that Hui's did not incorporate any new parameter instead of just notational changes defining the Laplace's law and conversion factor that is just for transformation from wooden leg to human leg. Regression model parameters; y-intercept is -0.2296 while slope is 0.9216 shows the line coinciding the point on y-axis and steepness of the regression line.

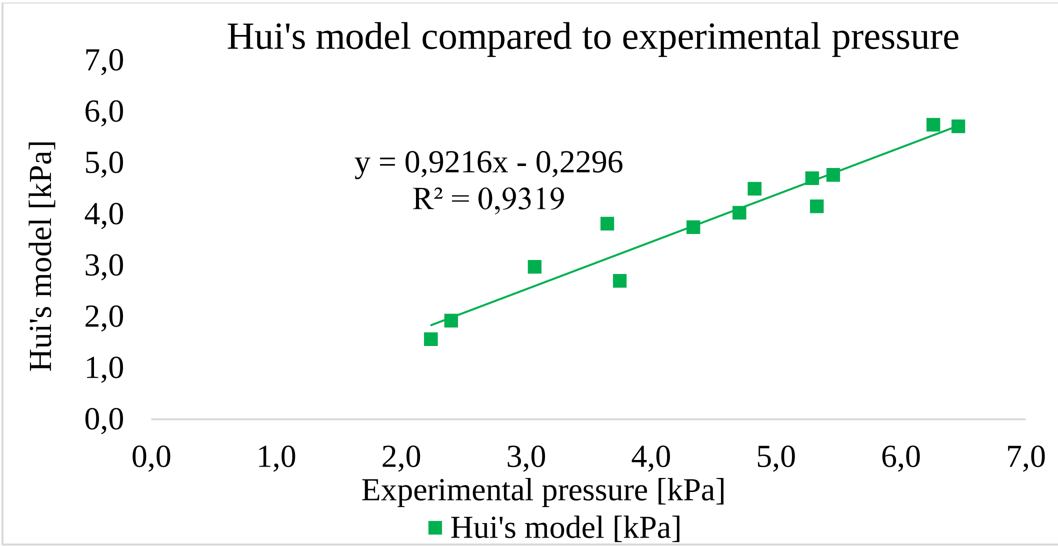


Figure 16. Comparison of experimental pressure compared to Hui's model

Ng's Model (equation 9) was analysed for its efficacy to predict the compression pressure and extent of dependency on experimental pressure results using linear regression analysis (figure 17). Using linear regression analysis, the coefficient of determination value (R^2-value = 0.9318) which means the experimental pressure results explain 93.18% to Ng's model. Table 8 portrays that Ng's model exerts the same pressure like Hui's model and Laplace's law except a very small difference in slope (0.9217) and y-intercept (0.2303) values. The additional parameters introduced by Ng was the reduction ratio (R_e) as a replacement of engineering strain.

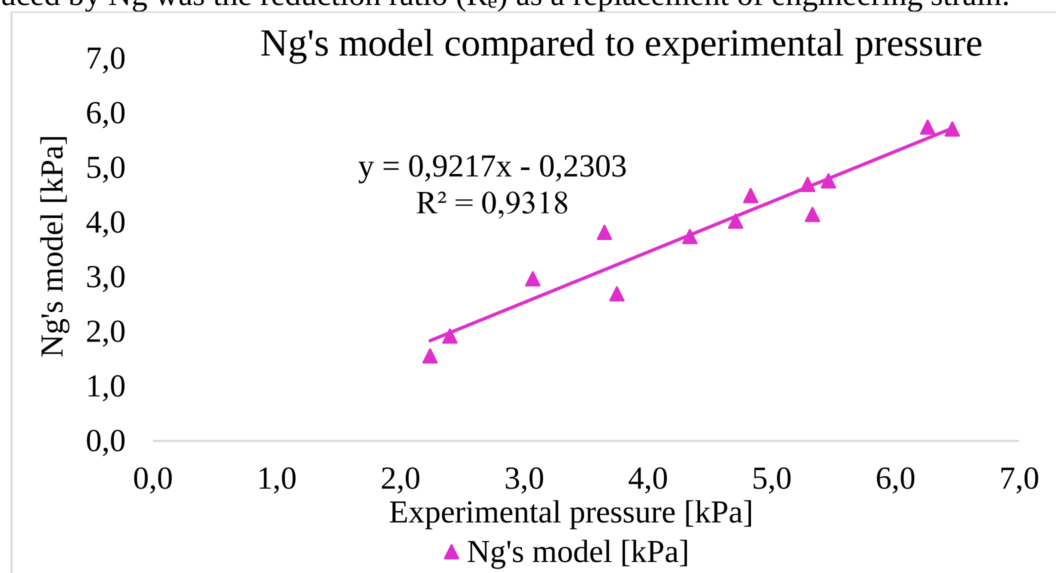


Figure 17. Comparison of experimental pressure compared to Ng's model

Dubuis's model was used for the investigation that how much the experimental results explain the Dubuis model based on the coefficient of determination (R^2-value= 0.9223) This shows that experimental pressure explains 92.23% to Dubuis's model (figure 18). Table 8 portrays that Dubuis's model pressure results are lower than experimental pressure. In his model (equation 11), it was introduced the concept of stiffness (Stiff) and engineering strain (ε) to predict the compression pressure incorporated to Laplace's law claiming the modification of Laplace's law but the extent the results of (R^2-value) was less than Hui's model, Ng's model Laplace's law. The regression model parameters measured using least square method were y-intercept and slope exhibit the values -0.6153 and 1.0239 respectively.

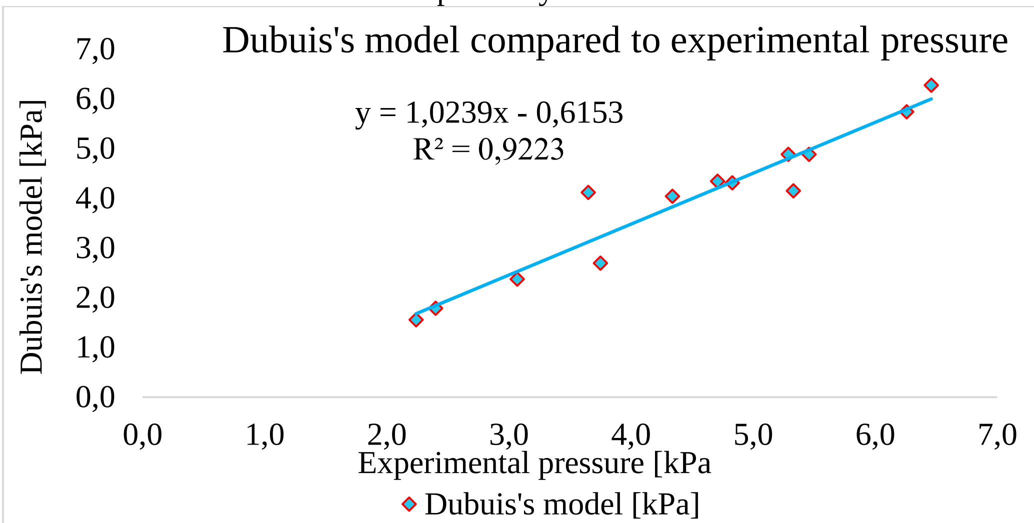


Figure 18. Comparison of experimental pressure compared to Dubuis's model

Leung's Model; Figure 19 shows the statistical relationship between experimental compression pressure results and Leung's model (equation 12). The extent of relationship was quantified by measuring the coefficient of determination value (R^2=0.9187).

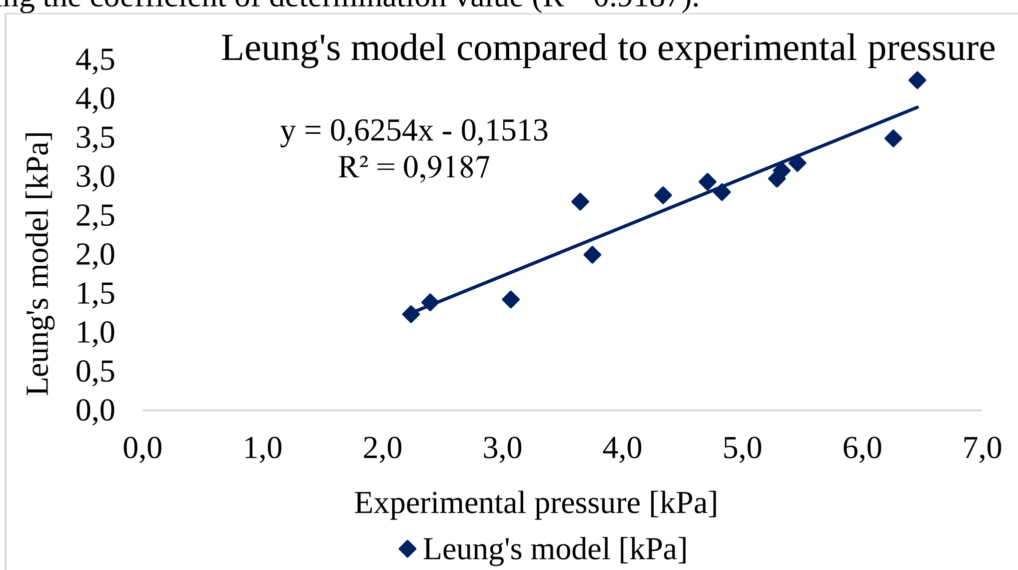


Figure 19. Comparison of experimental pressure compared to Leung's model

This value represents 91.87% significance between experimental pressure and Leung's model. Leung's model (equation 12) defined the tension (T) mentioned in Laplace's law (P=T/r) as $T = F/\ell_o(1 + \varepsilon)$ introduced the parameters additionally to predict the compression pressure. The coefficient of determination values measured using regression model is also lower than newly modified models; model 1 (R^2-value =0.9319) and model 2 (R^2-value =0.9319) as well as existing modes; Huis model (R^2-value =0.9319), Ng's model (R^2-value =0.9318), Dubuis's model (R^2-value =0.9223).

Zhang's Model; Figure 20 represents the strength of the relationship between experimental pressure (predictor) and Zhang's model (response variable).

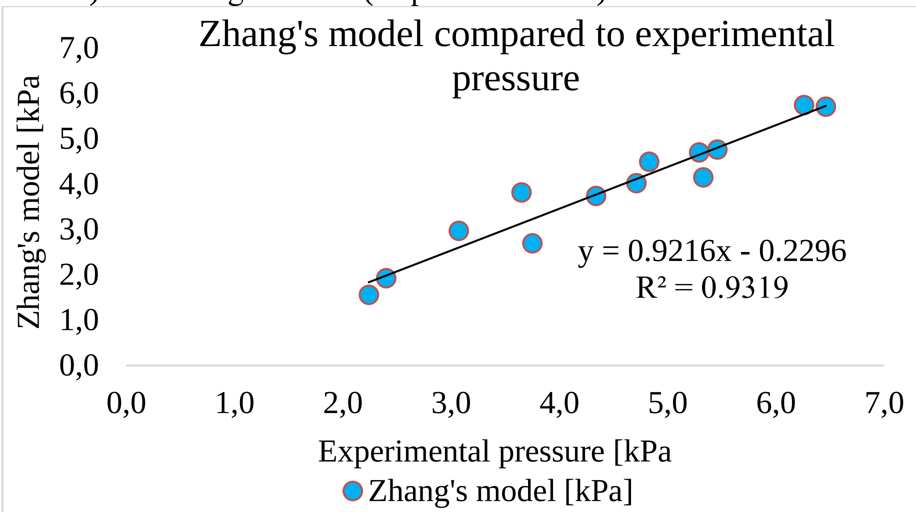


Figure 20. Comparison of experimental pressure compared to Zhang's model

The strength of the relationship was calculated based on coefficient of determination values (R^2 = 0.9319). This value portrays that experimental pressure explains 93.19% to Zhang's model. The regression parameters; y-intercept (-0.2296) and slope (0.9216) of Zhang's model exhibit similar value to Hui's model.

Teyeme's model was compared with experimental pressure based on coefficient of determination values (R^2-value= 0.9319) using linear regression analysis. This shows that experimental pressure explains 93.19% to Teyeme's model results (figure 21).

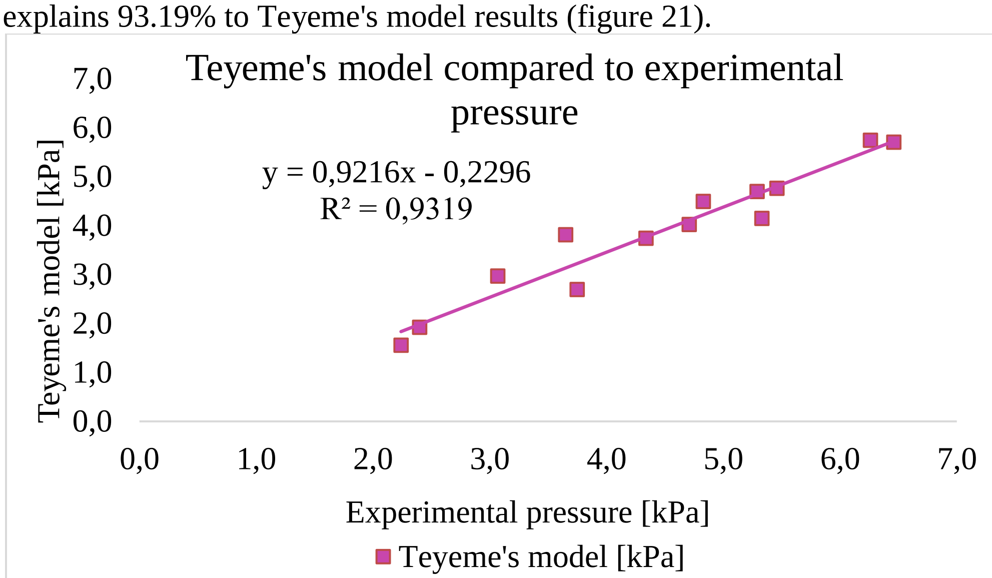


Figure 21. Comparison of experimental pressure compared to Teyeme's model

Table 8 portrays that Teyeme's model results of pressure are lower than experimental pressure but like Laplace's law. In his model (equation 15), he considered that hooks law (F=-kX) is obeyed when socks are circumferentially stretched without considering the axial deformation.

Jariyapunya's model; figure 22 represents the coefficient of determination value (R^2-value= 0.9319), y-intercept (-0.2296), and slope (0.9216) values determined by comparing the experimental pressure with Jariyapunya's model. R^2-value measured using Jariyapunya's model shows the results are similar to Laplace's law, Hui's model, Ng's model, Dubuis's model, Zhang's model, Teyeme's model exhibiting small variation in R^2-value mentioned in figures 16,17,18, 20 and 21 simultaneously.

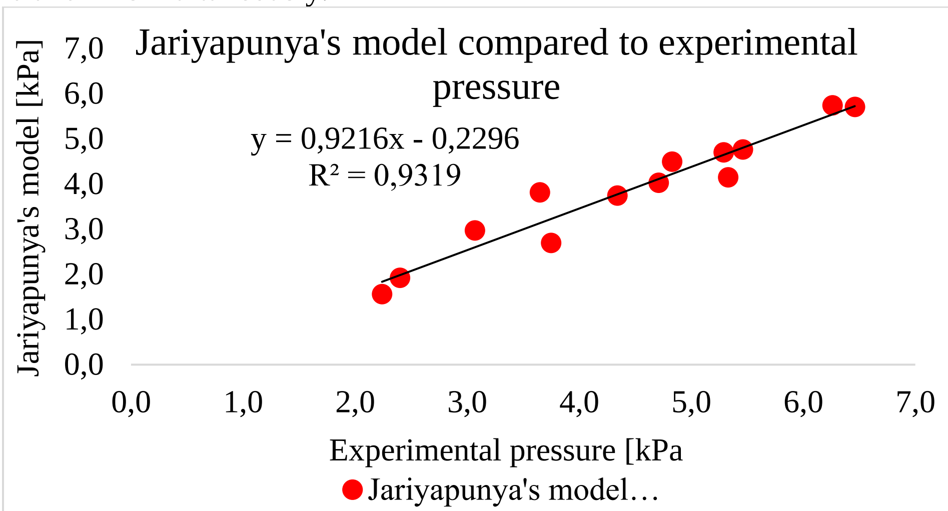


Figure 22. Comparison of experimental pressure compared to Jariyapunya's model

Table 9. Regression analysis summary of experimental pressure results compared to existing models

Experimental pressure compared to existing models	Regression model; Y= bX + a b; slope, a; y-intercept and X; experimental pressure	Coefficient of determination (R^2- value)
Hui's model	y = 0.9216(experimental pressure) - 0.2296	$R^2 = 0.9319$
Ng's model	y = 0.9217(experimental pressure) - 0.2303	$R^2 = 0.9318$
Dubuis's model	y = 1.0239(experimental pressure) - 0.6153	$R^2 = 0.9223$
Leung's model	y = 0.6254(experimental pressure) - 0.1513	$R^2 = 0.9187$
Zhang's model	y = 0.9216(experimental pressure) - 0.2296	$R^2 = 0.9719$
Teyeme's model	y = 0.9216(experimental pressure) - 0.2296	$R^2 = 0.9719$
Jariyapunya' s model	y = 0.9216(experimental pressure) - 0.2296	$R^2 = 0.9319$

6.8. Comparison of developed models and Laplace's law

In this scientific research, modified models; model 1 (T.Y.M) and model 2 (E.Y.M) were compared with the basic Laplace's law statistically to verify their mutual authenticity, significance or compatibility using simple linear regression analysis tool

Figure 23 portrays the relationship between Laplace's law as predictor and developed models; Model 1 (T.Y.M) and Model 2 (E.Y.M) as response variables. The strength of the relationship was measured based on coefficient of the determination value (R^2-value). Coefficient of the determination value between Laplace's law and Model 1 (T.Y.M) was 0.9952 while between Laplace's law and Model 2 (E.Y.M) was equal to 1. These values; R^2= 0.9952 and R^2 =1 shows that Laplace's law explained Model 1 (T.Y.M) to 99.52 % while to Model 2 (E.Y.M) 100%. The results proved that modified models have well approximation to original Laplace's law. The regression models (figure 23) are comprised of two main parameters; y-intercept (a) = 0.0932 (line coincides with y-axis) and the slope, b=1.0842 value (coefficient of predictor) of Model 1 (T.Y.M) and y-intercept (a) = 0.0 (line coincides to origin) and the slope, b=1 value (coefficient of predictor) of Model 2 (E.Y.M). Here the slope represents the steepness of the line.

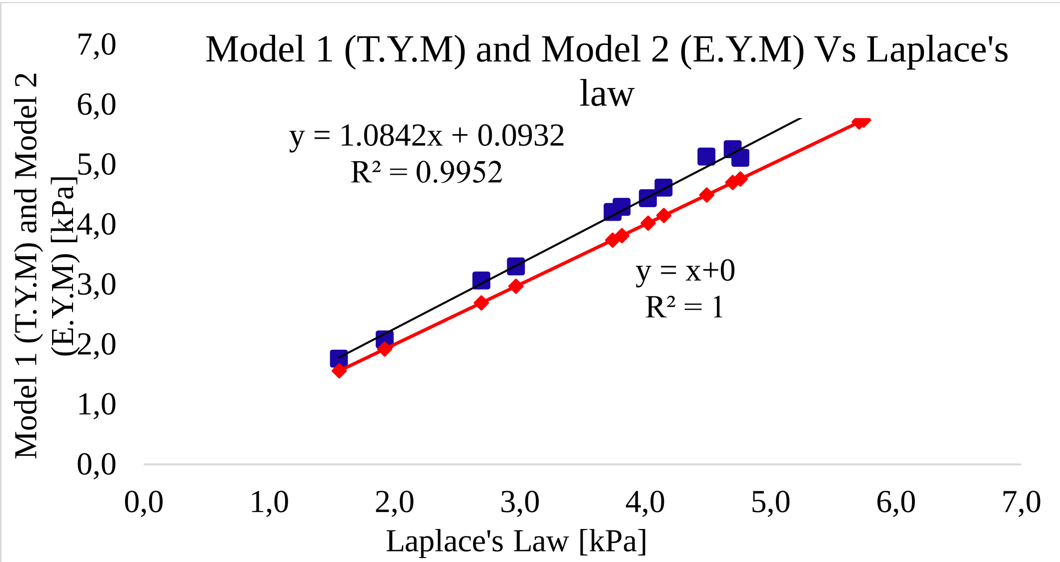


Figure 24. Comparison of developed models and Laplace's law

The summary results of the simple linear regression analysis between Laplace's law and newly developed models are given in table 10.

Table 10. Regression analysis summary between Laplace's law and modified models

Laplace's law compared to Newly developed models	**Regression model; Y= bX + a b; slope, a; y-intercept and X; Laplace's law pressure**	**Coefficient of determination (R^2- value)**
Model 1 (T.Y.M)	y = **1.0842** (Laplace's law pressure) **+ 0.0932**	$R^2 = 0.9952$
Model 2 (E.Y.M)	y = Laplace's law pressure	$R^2 = 1$

7. Conclusions

In this scientific research work, it was concluded that;

Tensile properties of compression socks are of great importance to describe the engineering of compression socks. Many of these directly relate to present the intensity of exertion of compression pressure especially Hysteresis, loading energy, unloading energy, and tensile linearity.

Force at practical extension (F_L) values context to the circumferential difference between the socks and leg at the ankle portion have a strong relationship with the values of the experimental pressure (Ps). Tensile indices especially; hysteresis (H), loading energy (LE), unloading energy (UE), tensile linearity combined with the force at practical extension (F_L) portrayed a significant relationship to experimental pressure.

Two new mathematical models were developed by introducing the missing parameters ever introduced or incorporated for the prediction of compression pressure. These introduced parameters are true stress/true strain and true modulus along with the deformed width of ankle cut-strips considering the modelization technique.

Both of newly developed were statistically compared with the experimental pressure and existing models.

Developed models; model 1 (T.Y.M) and model 2 (E.Y.M) along with Laplace's law were compared with experimental pressure (Ps). Model 1 (T.Y.M) exhibits a slight less strength when compared to Laplace's law. While the model 2 (E.Y.M) exhibits the similar strength of the relationship with Laplace's law when was compared with experimental pressure.

Existing models were also compared to experimental pressure and found that Hui's model, Ng's model, Jariyapunya's model, Laplace's law, and Model 2 (E.Y.M) portrays the similar extent of the relationship exhibiting the different regression parameters (y-intercept and slope) values. From the existing models; Dubuis's model portrays the strength higher than model 1 (T.Y.M) and slightly lower than model 2 (E.Y.M). While Leung's model exhibits the strength lower than both modified models. Statistical analysis between existing models and developed models also portrays that Zhang's model and Teyeme's models exhibit the higher strength of the relationship than both modified models.

Developed models were also statistically compared with the Laplace's law to quantify their mutual strength of significant.

The strength of the relationship between modified models and basic Laplace's law was also quantified based on the coefficient of the determination values (R^2-value). Both of modified models; model 1 (T.Y.M) and model 2 (E.Y.M) have well explained the Laplace's law model exhibiting the highest value of the coefficient of the determination values; R^2-value =0.9952 and R^2-value =1 respectively. Conclusively, developed models predicts almost the same pressure results as Laplace's works.

8. Future work

In the future work tensile indices values (hysteresis, loading energy, unloading energy and tensile linearity) can be incorporated to predictor mathematical models based on the theory of Laplace's law.

As a future work, the cylindrical coordinate system should be used to develop mathematical models for the prediction of compression pressure.

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9. References

[1] SCHUREN, Jan. and Kay. MOHR. Pascal's law and the dynamics of compression therapy: a study on healthy volunteers. *International Angiology* [online]. 2010, 29(5), 431–435 [accessed 2022-04-26]. ISSN 1827-1839.
Available at: https://pubmed.ncbi.nlm.nih.gov/20924347/

[2] DAI, X.Q., Yi LI, Rong LIU and Yi Lin KWOK. Biomechanical engineering of compression stockings. In: *Biomechanical Engineering of Textiles and Clothing*. B.m.: Elsevier Inc, 2006, s. 332–346. ISBN 978-1-84569-148-6.

[3] MACINTYRE, Lisa, Margot BAIRD and Phil WEEDALL. The study of pressure delivery for hypertrophic scar treatment. *International Journal of Clothing Science and Technology*

[online]. 2004, 16(1/2), 173–183 [accessed 2022-03-29]. ISSN 0955-6222. Available at: doi:10.1108/09556220410520450

[4] NAVE, Carl Rod. *Wall Tension* [online]. 1998 [accessed 2021-05-15]. Available at: http://hyperphysics.phy-astr.gsu.edu/hbase/ptens.html.

[5] HOPKINS, Alison and Fran WORBOYS. Understanding compression therapy to achieve tolerance. *Wounds UK* [online]. 2005, 1(3), 26–34. ISSN 1746-6814. Available at: https://www.wounds-uk.com/journals/issue/4/articledetails/understandingcompression-therapy-to-achieve-tolerance-1

[6] LIU, Rong, Terence T.H. LAO and Xin WANG. Impact of weft laid-in structural knitting design on fabric tension behavior and interfacial pressure performance of circular knits. *Journal of Engineered Fibers and Fabrics* [online]. 2013, 8(4), 96–107 [accessed 2020-05-15]. ISSN 1558-9250. Available at: doi:10.1177/155892501300800404

[7] RAL DEUTSCHES INSTITUT FUR GUTESICHERUNG UND KENNZEICHNUNG E.V. *Medical compression hosiery—Quality assurance RAL-GZ 387/1*. B.m.: RAL Deutsches Institut fur Gutesicherung und Kennzeichnung e.V. 2008.

[8] SAU-FUN, Ng, Hui CHI-LEUNG. Model to Predict Interfacial Pressures in Multilayer Elastic Fabric Tubes. *Textile Research Journal* [online]. 2001, 71(8), 683–687 [accessed 2022-08-18]. ISSN 1746-7748. Available at: doi:10.1177/004051750107100806

[9] HALFAOUI, Rachid. and Bachir. CHEMANI. New approach to predict pressure produced by elastic textile in the therepeutic treatment of venous leg. *Journal of Fundamental and Applied Sciences* [online]. 2016, 8(2), 297–312 [accessed 2020-01-27]. ISSN 1112-9867. Available at: doi:10.4314/jfas.v8i2.9

[10] NG, Sau-Fun. and Chi-Leung HUI. Pressure model of elastic fabric for producing pressure garments. *Textile Research Journal* [online]. 2001, 71(3), 275–279 [accessed 2021-05-03]. ISSN 1746-7748. Available at: doi:10.1177/004051750107100314

[11] MAKLEWSKA, Elżbieta, Andrzej NAWROCKI, Jolanta LEDWOŃ and Krzysztof KOWALSKI. Modelling and designing of knitted products used in compressive therapy. *Fibres and Textiles in Eastern Europe* [online]. 2006, 14(5 (59)), 111–113. ISSN 2300-7354. Available at: http://www.fibtex.lodz.pl/article1128.html

[12] DUBUIS, Laura, Pierre-yves ROHAN, Stéphane AVRIL, Pierre BADEL and Johan DEBAYLE. Patient-specific FE model of the leg under elastic compression. In: *10th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering*. 2012, s. 1–7.

[13] LEUNG, W. Y., D. W. YUEN, Sun Pui NG and S. Q. SHI. Pressure prediction model for compression garment design. *Journal of Burn Care & Research* [online]. 2010, 31(5), 716–727 [accessed 2021-11-29]. ISSN 1559-047X. Available at: doi:10.1097/BCR. 0b0 1 3e318-1eebea0

[14] JARIYAPUNYA, Nareerut and Blažena MUSILOVÁ. Predictive modelling of compression garments for elastic fabric and the effects of pressure sensor thickness. *The Journal of The Textile Institute* [online]. 2019, 110(8), 1132–1140 [accessed 2022-07-15]. ISSN 0040-5000. Available at: doi:10.1080/00405000.2018.1540285

[15] ZHANG, Luolan, Guangwu SUN, Jiecong LI, Yu CHEN, Xiaona CHEN, Weihong GAO and Wenfeng HU. The structure and pressure characteristics of graduated compression stockings: experimental and numerical study. *Textile Research Journal* [online]. 2019,

89(23–24), 5218–5225 [accessed 2021-11-21]. ISSN 1746-7748. Available at:doi:10.117-7/0040517519855319

[16] TEYEME, Yetanawork, Benny MALENGIER, Tamrat TESFAYE, Simona VASILE, Wolelaw ENDALEW and Lieva VAN LANGENHOVE. Predicting compression pressure of knitted fabric using a modified laplace's law. *Materials* [online]. 2021, 14(16), 4461 [accessed 2022-03-25]. ISSN 1996-1944. Available at: doi:10.3390/ma14164461

[17] LIU, Rong., Yi-Lin. KWOK, Yi LI, Terence-T.H. LAO and Xin ZHANG. Quantitative Assessment of Relationship between Pressure Performances and Material Mechanical Properties of Medical Graduated Compression Stockings. *Journal of Applied Polymer Science* [online]. 2007, 104(1), 601–610 [accessed 2020-07-07]. ISSN 1097-4628. Available at: doi:10.1002/app.25617

[18] LIU, Rong. *Comfort and mechanical function of compression stockings*. B.m., 2006. PhD Thesis. Hong Kong Polytechnic University.

[19] LIU, Rong, Yi-Lin KWOK, Yi LI, Terence-T.H. LAO, Xin ZHANG and Xiao Qun DAI. Objective evaluation of skin pressure distribution of graduated elastic compression stockings. *Dermatologic Surgery* [online]. 2005, 31(6), 615–624. ISSN 1076-0512. Available at: doi:10.1097/00042728-200506000-00001

[20] LIU, Rong, Yi-Lin KWOK, Yi LI and Terence T.H LAO. Fabric mechanical-surface properties of compression hosiery and their effects on skin pressure magnitudes when worn. *Fibres and Textiles in Eastern Europe*. 2010, 79(2), 91–97. ISSN 1230-3666.

[21] LIU, Rong, Yi-Lin KWOK, Yi LI, Terence-T.H. LAO, Xin ZHANG and Xiao Qun DAI. A three-dimensional biomechanical model for numerical simulation of dynamic pressure functional performances of graduated compression stocking (GCS). *Fibers and Polymers* [online]. 2006, 7(4), 389–397 [accessed 2021-02-20]. ISSN 1875-0052. Available at: doi:10.1007/BF02875771

[22] ZHANG, Mei, Henan DONG, Xuerong FAN and Rui DAN. Finite element simulation on clothing pressure and body deformation of the top part of men's socks using curve fitting equations. *International Journal of Clothing Science and Technology* [online]. 2015, 27(2), 207–220 [accessed 2021-04-04]. ISSN 0955-6222. Available at: doi:10.1108/ IJCS T-12-2013-0139

[23] KERMAVNAR, Tjaša, Valerie POWER, Adam DE EYTO and Leonard W. O'SULLIVAN. Computerized cuff pressure algometry as guidance for circumferential tissue compression for wearable soft robotic applications: A systematic review. *Soft Robotics* [online]. 2018, 5(1), 1–16 [accessed 2022-01-28]. ISSN 2169-5172. Available at: doi:10.1089/soro.2017.0046

[24] BRUNIAUX, Pascal, David CREPIN and Bertrand LUN. Modeling the mechanics of a medical compression stocking through its components behavior: Part 1 – modeling at the yarn scale. *Textile Research Journal* [online]. 2012, 82(18), 1833–1845 [accessed 2020-06-27]. ISSN 1746-7748. Available at: doi:10.1177/0040517512441992

[25] ZHANG, Xinyue, K.W. YEUNG and Yi LI. Numerical simulation of 3d dynamic garment pressure. *Textile Research Journal* [online]. 2002, 72(3), 245–252 [accessed 2020-10-03]. ISSN 1746-7748. Available at: doi:10.1177/004051750207200311

[26] YANMEI, Li, Zhang WEIWEI, Ju FAN and Han QINGYUN. Study on clothing pressure distribution of calf based on finite element method. *The Journal of The Textile Institute* [online]. 2014, 105(9), 955–961 [accessed 2021-10-30]. ISSN 0040-5000. Available at: doi:10.1080/00405000.2013.865883

[27] SOLTANZADEH, Zeynab, Saeed SHAIKHZADEH NAJAR, Mohammad HAGHPANAHI and Mohammd Reza MOHAJERI-TEHRANI. Prediction of compression properties of single jersey weft-knitted fabric by finite element analysis based on the hyperfoam material model. *Fibres and Textiles in Eastern Europe* [online]. nedatováno, 24(2 (116)), 82–88 [accessed 2021-03-29]. ISSN 1230-3666. Available at: doi: 10.5604/12-303666.1191431

[28] FRAUZIOLS, Fanny, Jérôme MOLIMARD, Laurent NAVARRO, Pierre BADEL, Magalie VIALLON, Rodolphe TESTA and Stéphane AVRIL. Prediction of the biomechanical effects of compression therapy by finite element modeling and ultrasound elastography. *IEEE Transactions on Biomedical Engineering* [online]. 2015, 62(4), 1011–1019 [accessed 2022-06-20]. ISSN 1558-2531. Available at: doi:10.1109 / T B M E . 2 0 14.2378553

[29] YU, Annie, Kit Lun YICK, Sun Pui NG, Joanne YIP and Ying Fan CHAN. Numerical simulation of pressure therapy glove by using Finite Element Method. *Burns : journal of the International Society for Burn Injuries* [online]. 2016, 42(1), 141–151 [accessed 2021-09-19]. ISSN 0305-4179. Available at: doi:10.1016/j.burns.2015.09.013

[30] DAN, Rui, Xue-rong FAN, Zhen SHI and Mei ZHANG. Finite element simulation of pressure, displacement, and area shrinkage mass of lower leg with time for the top part of men's socks. *The Journal of The Textile Institute* [online]. 2015, 107(1), 72–80 [accessed 2022-05-22]. ISSN 0040-5000.Available at: doi:10.1080/00405000.2015.10076-21

[31] CHASSAGNE, Fanette, Jerome MOLIMARD, Reynald CONVERT, Pascal GIRAUX and Pierre BADEL. Numerical model reduction for the prediction of interface pressure applied by compression bandages on the lower leg. *IEEE transactions on bio-medical engineering* [online]. 2018, 65(2), 449–457 [accessed 2019-05-09]. ISSN 1558-2531. Available at: doi: 10.1109/TBME.2017.2774598

[32] European committee for standardization (CEN) non-active medical devices. *ENV 12718:2001 - Medical compression hosiery*. B.m.: Brussels, CEN/TC205. srpen 2001.

[33] LIU, Rong, Terence T.H. LAO, Trevor J LITTLE, Xinbo WU and Xiao KE. Can heterogeneous compression textile design reshape skin pressures? A fundamental study. *Textile Research Journal* [online]. 2018, 88(17), 1915–1930 [accessed 2020-11-22]. ISSN 1746-7748. Available at: doi:10.1177/0040517518779254

[34] SARI, Burak and Nida OĞLAKCIOĞLU. Analysis of the parameters affecting pressure characteristics of medical stockings. *Journal of Industrial Textiles* [online]. 2018, 47(6), 1083–16 [accessed 2020-06-09]. ISSN 1528-0837. Available at: doi:10.1177/15280837-16662587

[35] CHOI, Ka-Fai, Ameersing LUXIMON. Contact pressure of tubular fabrics for compression sportswear. In: *Proceedings of Textile Bioengineering and Informatics Symposium Vol.1-3*. 2010, s. 1425–1429.

[36] COSTANZO, Francesco and James G. BRASSEUR. The invalidity of the Laplace law for biological vessels and of estimating elastic modulus from total stress vs. strain: a new practical method. *Mathematical Medicine and Biology: A Journal of the IMA* [online]. 2015, 32(1), 1–37 [accessed 2021-11-22]. ISSN 1477-8599.Available at: doi: 10. 1093 / i m ammb/-/dqt020

[37] LIU, Rong, Yi-Lin KWOK, Yi LI, Terence T. LAO and Xin ZHANG. Skin pressure profiles and variations with body postural changes beneath medical elastic compression

stockings. *International Journal of Dermatology* [online]. 2007, 46(5), 514–523 [accessed 2020-02-19]. ISSN 1365-4632. Available at: doi:10.1111/j.1365-4632.2007 . 0 3175.x

[38] CIEŚLAK, Małgorzata, Agnieszka KARASZEWSKA, Ewa GROMADZIŃSKA, Izabela JASIŃSKA and Irena KAMIŃSKA. Comparison of methods for measurement of the pressure exerted by knitted fabrics. *Textile Research Journal* [online]. 2017, 87(17), 2117–2126 [accessed 2021-07-29]. ISSN 1746-7748.Available at: doi:10.1177/0040517516665-255

[39] BERA, Mukesh Kumar, Rabisankar CHATTOPADHAY and Deepti GUPTA. The effect of fibre blend on comfort characteristics of elastic knitted fabrics used for pressure garments. *Journal of The Institution of Engineers (India): Series E* [online]. 2014, 95(1), 41–47 [accessed 2020-06-29]. ISSN 2250-2491. Available at: doi:10.1007/s40034-014-0029-x

[40] CHEN, Dongsheng, Hong, LIU, Qiaoling ZHANG and Hongge WANG. Effects of mechanical properties of fabrics on clothing pressure. *Przegląd Elektrotechniczny*. 2013, 89(01b/2013), 232–235. ISSN 0033-2097.

[41] CHATTOPADHYAY, Rabisankar, Deepti GUPTA and Mukesh Kumar. BERA. Effect of input tension of inlay yarn on the characteristics of knitted circular stretch fabrics and pressure generation. *The Journal of The Textile Institute* [online]. 2012, 103(6), 636–642 [accessed 2021-11-12]. ISSN 0040-5000. Available at: doi:10.1080/00405000.2012.665-23

[42] WANG, Lijing, Martin FELDER and Jackie Y. CAI. Study of properties of medical compression fabrics. *Journal of Fiber Bioengineering and Informatics* [online]. 2011, 4(1), 15–22 [accessed 2021-03-19]. ISSN 1940-8676. Available at: doi:10.3993/jfbi04201102

[43] TAMOUE, Ferdinand and Andrea EHRMANN. First principle study: parametric investigation of the mechanics of elastic and inelastic textile materials for the determination of compression therapy efficacy. *Textile Research Journal* [online]. 2018, 88(21), 2506-2515 [accessed 2019-05-10]. ISSN 1746-7748. Available at: doi:10.1177/-004051717725123

[44] HEGARTY, Meghan Sarah. *Technology for Continuously Monitoring the Effectiveness of Compression Therapy for Improving Patient Outcome*. B.m., 2013. PhD Thesis. North Carolina State University.

[45] HEGARTY-CRAVER, Meghan, Cassandra KWON, William OXENHAM, Edward GRANT and Lawrence REID. Towards characterizing the pressure profiles of medical compression hosiery: an investigation of current measurement devices and techniques. *The Journal of The Textile Institute* [online]. 2015, 106(7), 757–767 [accessed 2020-08-21]. ISSN 0040-5000. Available at: doi:10.1080/00405000.2014.941535

[46] ROYLANCE, Daaccessed *Stress-Strain Curves* [online]. B.m.: Massachusetts Institute of Technology. srpen 2001 [accessed 2019-09-22]. Available at: https://resources.saylor.org /wwwresources/archived/site/wp-content/uploads/2012/09/ME1022.2.4.pdf.

[47] KWON, Cassandra Hyun. *Characterizing the Relationship of Tensile Properties and Pressure Profiles of Compression Bandages and Fabrics*. B.m., 2014. PhD Thesis. North Carolina State University.

[48] LAKES, R. S. and A. WINEMAN. On poisson's ratio in linearly viscoelastic solids. *Journal of Elasticity* [online]. 2006, 85(1), 45–63 [accessed 2019-11-30]. ISSN 1573-2681. Available at: doi:10.1007/s10659-006-9070-4

[49] LIN, Yinglei, Kai-Fi CHOI, Ameersing LUXIMON, Lei YAO, JY HU and Y. LI. Finite element modeling of male leg and sportswear: contact pressure and clothing deformation. *Textile Research Journal* [online]. 2011, 81(14), 1470–1476 [accessed 2019-08-12]. ISSN 1746-7748. Available at: doi:10.1177/0040517510395997

[50] HIGUCHI, Kenji and Hideo TAKAI. Stress-strain diagram, young's modulus and poisson's ratio of textile fibers. *Journal of the Textile Machinery Society of Japan* [online]. 1961, 7(1), 4–12 [accessed 2022-12-01]. ISSN 0040-5043. Available at: doi:10.4188/jte-1955.7.4

[51] MILITKÝ, Jiří, Mohanapriya VENKATARAMAN and Rajesh MISHRA. The chemistry, manufacture, and tensile behavior of polyamide fibers. In: Anthony R. BUNSELL, ed. *Handbook of Properties of Textile and Technical Fibres* [online]. B.m.: Woodhead Publishing, 2018, The Textile Institute Book Series, s. 367–419. [accessed 2020-07-13] ISBN 978-0-08-101272-7. Available at: doi:10.1016/B978-0-08-101272-7.00012-2

10. List of papers published by the author

10.1. Publications in journals (Main author)

[1] **SIDDIQUE, Hafiz Faisal**, Zdeněk KŮS, Jiří MILITKÝ, Antonin HAVELKA, Adnan Ahmad MAZARI and Lubos HES. Development of new mathematical models and their comparison with existing models for the prediction of compression pressure using the cut-strip method. *Textile Research Journal* [online]. 2022, 00405175221088747. Available at: doi:10.1177/00405175221088747. **(Impact factor =2.455)**

[2] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonín HAVELKA, Zdeněk KŮS a Engin AKCAGUN. Washing characterization of compression socks. *AUTEX Research Journal* [online]. 2022. ISSN 2300-0929. Available at: doi:10.2478/aut-2022-0009. **(Impact factor =1.944)**

[3] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonin HAVELKA, Zdeněk KŮS, David CIRKL and Lubos HES. New approach for the prediction of compression pressure using the cut strip method. *Textile Research Journal* [online]. 2020, 90(15–16), 1689–1703. Available at: doi:10.1177/0040517519896757. **(Impact factor =2.455)**

[4] **SIDDIQUE, Hafiz Faisal,** Adnan Ahmed MAZARI, Antonin HAVELKA and Zdeněk KŮS. Performance characterization of compression socks at ankle portion under multiple mechanical impacts. *Fibers and Polymers* [online]. 2019, 20(5), 1092–1107. Available at: doi:10.1007/s12221-019-8965-1. **(Impact factor =2.153)**

[5] **SIDDIQUE, Hafiz Faisal**, Adnan MAZARI and Muhammad TANVEER. Sweat-management properties of semi bleached-socks using different main yarn and plating yarn combinations. *Fibres and Textiles* [Online]. 2019, **27**(1), 69–75. ISSN 1335-0617. **(Cite score =0.80)**

[6] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonin HAVELKA and Zdeněk KŮS. Performance characterization and pressure prediction of compression socks. *Fibers and Polymers* [online]. 2020, 21(3), 657–670. Available at: doi:10.1007/s12221-020-9420-z. **(Impact factor =2.153)**

[7] SIDDIQUE, Hafiz Faisal, Adnan Ahmed MAZARI, Antonín HAVELKA and Radka LAURINOVÁ. Analysis of thermal properties affected by different extension levels of compression socks. *Fibres and Textiles* [Online]. 2019, 64–69. ISSN 1335-0617. **(Cite score =0.80)**

[8] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonin HAVELKA, Tariq MANSOOR, Azam ALI and Musaddaq AZEEM. Development of V-shaped compression

socks on conventional socks knitting machine. *Autex Research Journal*. [online]. 2018, 18, 377–384. Available at: doi:10.1515/aut-2018-0014. **(Impact factor =1.944)**

[9] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonin HAVELKA, Sajid HUSSAIN and Tariq MANSOOR. Effect of elastic elongation on compression pressure and air-permeation of compression socks. *Fibres and Textiles* [Onlinee]. 2018, 1, 35–43. ISSN 1335-0617. **(Cite score =0.80)**

[10] **SIDDIQUE, Hafiz Faisal**. Assessment of mechanical properties of compression socks using cut-strip method. *Journal of Textile Engineering & Fashion Technology* [online]. 2019, 5(5). ISSN 2574-8114. Available at: doi:10.15406/jteft. 2019.05.00206.

[10] **SIDDIQUE, Hafiz Faisal**, Musaddaq AZEEM, Tanveer HUSSAIN, Azam ALI, Tariq MANSOOR and Amal BOUGHATTAS. Effect of elastane linear density on compression pressure of V-shaped compression socks. *Industria textila* [online]. 2018, 69(2), 118–127. Available at: doi:10.35530/IT.069.02.1433. **(Impact factor =0.823)**

10.2. Publications in journals (Co-author)

[1] AZEEM, Musaddaq, Amal BOUGHATTAS, **Hafiz Faisal SIDDIQUE**, Antonin HAVELKA, and Sajid HUSSAIN. Comfort properties of nano-filament polyester fabrics: Sensory evaluation. *Industria Textila* [online]. 2018, 69(1),3-10. Available at: doi: 10.35530 /it.069.01. 1440. **(Impact factor =0.823)**

[2] AZEEM, Musaddaq, Zuhaib. AHMAD, Jakub WIENER, Ahmad. FRAZ, **Hafiz Faisal SIDDIQUE** and Antonin HAVALKA. Influence of weave design and yarn types on mechanical and surface properties of woven fabric. *Fibres and Textiles in Eastern Europe* [online]. 2018, **26**(1). ISSN 12303666. Available at: doi:10.5604/01.3001.0010.7795. **(Impact factor = 1.045)**

[3] KHAN, Muhammad Zaman, Sajid HUSSAIN, **Hafiz Faisal SIDDIQUE**, Vijay BAHETI, Jiri MILITKY, Musaddaq AZEEM, and Azam ALI. Improvement of liquid moisture management in plaited knitted fabrics. *Tekstil ve Konfeksiyon* [online]. 2018, 28(3), 182-188. **(Impact factor = 0.692)**

[4] MANSOOR, Tariq, Lubos HES, Zenun SKENDERI, **Hafiz Faisal SIDDIQUE**, Sajid HUSSAIN, and Asif JAVED. Effect of preheat setting process on heat, mass and air transfer in plain socks. *The Journal of the Textile Institute* [online]. 2019, 110(2), 159-170. Available at: doi: 10.1080/00405000.2018.1523990. **(Impact factor = 2.17)**

[5] MANSOOR, Tariq, **Hafiz Faisal SIDDIQUE**, Azam ALI, Petra KOMARKOVA, Antonin HAVELKA, and Zahid HUSSAIN. Wrinkle free plaited knitted fabrics without pre-heat setting. *Journal of the Textile Institute* [online]. 2018, 109(3), 307-311. Available at: doi: 10.1080/00405000.2017.1342585. **(Impact factor = 2.17)**

10.3. Contribution in the conference proceeding

[1] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonín HAVELKA and Zdenek KŮS. Mathematical model for the prediction of compression pressure. 2019.

[2] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonin HAVELKA and Zdeněk KŮS. Incorporation of some new parameters and modification of Laplace's law for prediction of compression pressure. In: . B.m.: PhD Day at Technical University of Liberec, 2019.

[3] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonin HAVELKA and Zdeněk KŮS. New approach for the prediction of compression pressure using cut-strip method. In: Conference Fiber Society (proceeding), The University of Austin in Texas. 2019.

[4] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI, Antonín HAVELKA and Zdeněk

KŮS. Study of Performance Measurement of Compression Socks. In: Nanofibers, applications and related technologies–NART. 2019.

[5] **SIDDIQUE, Hafiz Faisal**, Adnan Ahmed MAZARI and Antonín HAVELKA. Thermal properties of compression socks at various extension levels. In: 18th AUTEX world textile conference. 2018.

[6] **SIDDIQUE, Hafiz Faisal,** Zdeněk KŮS and Adnan Ahmed MAZARI. Effect of Extensibility on Compression Pressure and Air-Permeation in Compression Socks. In: . Technical University of Liberec: Technical University of Liberec, 2017.

[7] NAEEM, Jawad, Adnan Ahmed MAZARI, Michal KREJCIK and **Hafiz Faisal SIDDIQUE**. Impact of metallic coating on thermal protective behavior of multilayer protective clothing. In: Nanofibers, applications and related technologies–NART. 2019.

[8] ALI, Azam, Vijaykumar BAHETI, Abdul JABBAR, Jiri MILITKY, Sundaramoorthy PALANISAMY, **Hafiz Faisal SIDDIQUE** and Daniel KARTHIK. Effect of jute fibre treatment on moisture regain and mechanical performance of composite materials. In: IOP Conference Series: Materials Science and Engineering [online]. B.m.: IOP Publishing, 2017, s. 042001. Available at: doi:10.1088/1757-899X/254/4/042001

10.4. Research projects

1. Project leader SGS-19 (21309), Functional characterization of textile garments to improve their overall performance characteristics, Faculty of Textile Engineering, Technical University of Liberec, Czech Republic.
2. Member of SGS-18 (21246), Comfort and durability of compression socks, way of involvement, Faculty of Textile Engineering, Technical University of Liberec, Czech Republic

10.5. Citations

SIDDIQUE, Hafiz Faisal, Adnan Ahmed MAZARI, Antonin HAVELKA, Tariq MANSOOR, Azam ALI and Musaddaq AZEEM. Development of V-shaped compression socks on conventional socks knitting machine. *Autex Research Journal*. [online]. 2018, 18, 377–384. Available at: doi:10.1515/aut-2018-0014. **(Impact factor =1.944)**

Cited in 8 articles

SIDDIQUE, Hafiz Faisal, Adnan Ahmed MAZARI, Antonin HAVELKA, Zdeněk KŮS, David CIRKL and Lubos HES. New approach for the prediction of compression pressure using the cut strip method. *Textile Research Journal* [online]. 2020, 90(15–16), 1689–1703. Available at: doi:10.1177/0040517519896757. **(Impact factor =2.455)**

Cited in 5 articles

SIDDIQUE, Hafiz Faisal, Adnan Ahmed MAZARI, Antonin HAVELKA and Zdeněk KŮS. Performance characterization and pressure prediction of compression socks. *Fibers and Polymers* [online]. 2020, 21(3), 657–670. Available at: doi:10.1007/s12221-020-9420-z. **(Impact factor =2.153)**

Cited in 3 articles

SIDDIQUE, Hafiz Faisal, Adnan Ahmed MAZARI, Antonin HAVELKA, Sajid HUSSAIN and Tariq MANSOOR. Effect of elastic elongation on compression pressure and air-permeation of compression socks. *Fibres and Textiles* [Onlinee]. 2018, 1, 35–43. ISSN 1335-0617. **(Cite score =0.80)**

Cited in 4 articles

SIDDIQUE, Hafiz Faisal, Adnan Ahmed MAZARI, Antonin HAVELKA and Zdeněk KŮS. Performance characterization of compression socks at ankle portion under multiple mechanical impacts. *Fibers and Polymers* [online]. 2019, 20(5), 1092–1107. Available at: doi:10.1007/s12221-019-8965-1. **(Impact factor =2.153)**

Cited in 2 articles

SIDDIQUE, Hafiz Faisal, Adnan Ahmed MAZARI, Antonín HAVELKA and Radka LAURINOVÁ. Analysis of thermal properties affected by different extension levels of compression socks. *Fibres and Textiles* [Online]. 2019, 64–69. ISSN 1335-0617. **(Cite score =0.80)**

Cited in 1 article

Curriculum Vitae

Hafiz Faisal Siddique

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Email:faisalsiddique3648@gmail.com , **Phone:** +905526806025,

CAREER GOAL:

To attain professional excellence in dynamic and challenging organization by actively exercising my unique skills and abilities and bringing to bear my integrity.

PROFESSIONAL EXPERIENCE

Organization 1: Masood Spinning Mills [1.5 years]

Designation: Assistant Spinning Manager

Organization 2: Interloop Ltd. [5 Years]

Designation: Assistant manager sourcing and development

Organization 3: Technical University of Liberec, Czech Republic [4 Years]

Designation: PhD Research Scholar

Proficiencies:

- Research activities on development of compression socks and analysis of yarns used for production
- Tensile testing of knitting circular compression stockings
- Modification of Pressure prediction model for the prediction of compression pressure
- Expertise the use of MST MKIV Salzmann and MST professional pressure measuring devices
- I have published about 15 research articles including international conferences

Organization 4: Variteks Orthopedic Textile Company (Istanbul, Turkey)

Designation: Manager Production and Planning

Proficiencies

- Compression socks production/development/quality control as per RAL-GZ-387/1&2
- Development of face shield and face mask to avoid COVID-19 pandemics
- Corsets and liposuction garments quality control
- FDA registration of all products required to export to USA
- Know-how and registration according to Medical Device Directives
- Registration for ISO 13485 Medical devices -- Quality management systems
- Production and quality control of compression stockings
- Knitting faults control and their remedial measures

- Basic knowledge of MERZ machine fixation of measurements
- Compression socks stretch and compression pressure measurements using KIKUHIME pressure measuring device/SALZMANN MST MKIV/ SALZMANN Professional 2 /DINEMA stretch measuring device
- Washing/stitching/ pressing expertise of compression stockings

QUALIFICATION

Institution: National Textile University, Faisal Abad, Pakistan
Year : 2012~15
Degree: M.Sc. Textile Engineering
Project Title: Improving the comfort and performance properties of Compression Socks
Institution: Bahauddin Zakariya University, Multan, Pakistan
Year: September 2007 – July 2011
Degree: B.Sc Textile Engineering (Yarn Manufacturing Specialization)
Institution: Faran Model College Jhang
Year: 2004~2006
Intermediate: Foundation of science
Main Subjects: Physics, Chemistry, Math
Standard Grades: English, History, Islamic Studies

REFERENCES

Will be furnished on demand

Brief description of the current expertise, research, and scientific activities

Doctoral studies

Studies	Textile Engineering Textile Technics and Materials Engineering full time
Exams	Mathematical statistics and data analysis, 09.02.2016 Structure and properties of textile fibers ,17.05.2016 Heat transfer in porous structures, 23.01.2017 Clothing Comfort, 27.02.2017 Experimental technique of the field,30.01.2019
SDE	State Doctoral Exam completed on 29.11.2019
Research projects	1) Project participant SGS-17 (21200) by Technical University of Liberec, Czech Republic 2) Project participant of SGS-18 (21246), Comfort and durability of compression socks, way of involvement, Faculty of Textile Engineering, Technical University of Liberec, Czech Republic 3) Project leader of SGS-19 (21309), Functional characterization of textile garments to improve their overall performance characteristics. Faculty of Textile Engineering, Technical University of Liberec, Czech Republic
Other projects	1) 4 months internship at Niederrhein University of Applied Sciences, GERMANY 2) 2 months internship at RMIT University (Royal Melbourne İnstitute of Technology, AUSTRALIA)

11. Recommendation of Supervisor

FACULTY OF TEXTILE ENGINEERING TUL

Recommendation of Supervisor

Supervisor's opinion on Ph.D. thesis of Mr. Hafiz Faisal Siddique, M.Sc.

His Ph.D. thesis is entitled " Tensile Characterization of Compression Sock's Ankle Cut-Strips and Development of Models to Approximate Laplace's Law ".

This dissertation is focused to analyze the engineering of commercially available compression socks and their therapeutic interaction to wooden leg. Therapeutic interaction was subscribed by analyzing the mechanism of exertion of interface pressure on the face of the leg. To analyze the mechanism of working, ankle cut strips were detached from the ankle position and tested for the tensile characterization. Tensile characteristic especially hysteresis, loading energy, unloading, tensile linearity and force at practical extension were compared to experimental pressure to estimate their level of significance. This research highlighted the appropriate missing parameters that can be incorporated in mathematical models for precise estimation of compression pressure. Latterly, using modelization technique, two developed models based on theory of true Young's modulus and engineering Young's modulus compared to Laplace's law, existing developed mathematical models and experimentally measured pressure results. Developed models can be used to estimate the interface pressure for any part of static object using elastic compression garments.

He used 13 socks samples of different brands belonging to three different compression class levels (compression class I, II and III). All socks sample were precisely analyzed for their physical, structural and tensile characteristics under controlled environmental conditions. Detachment of circular cut trips at ankle part was done by wearing on standard wooden leg and marked according to engrave grooved line. The experimental part of this dissertation is unique as very few studies exist in which the tensile characteristics are ever evaluated using uniaxial tensile teste instead of Kawabata evaluation system.

During his Ph.D., he validated his skill to execute high-quality research, with motivation and hard work. Naturally, he needed guidance, but once the goal was set, he performed very well

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to reach goal. It is very pleasant for me to see him working on a high level of research that is valuable for venous ulcer patient's and compression garments manufacturers. During his research work period, he has been very punctual, discipline and followed the given instructions. He participated in all events (Ph.D. student days, conferences and SGS programs) organized by the department and FT, TUL.

He has published **17 articles** in highly impact factor journal, of which he is the first author in 12 articles. All published articles reflect the orientation related to his Ph.D. work. He completed part of his experimental work at Variteks Orthopedics and RMIT, Australia, where his co-supervisors were Okan Öztürkatalay (CEO of Variteks orthopedics) and Prof. Dr. Lijing Wang. With 4 years of industrial experience at the medical compression socks company, he utilized his skills perfectly for his research work at university.

Consequently, I strongly recommend Mr. hafiz Faisal Siddique's thesis to be accepted for defense.

14.3.2023

Ing. Adnan Ahmed Mazari, PhD.
Supervisor

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12. Reviews of the Opponents

TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Maschinenwesen Institut für Textilmaschinen und Textile Hochleistungswerkstofftechnik

Institutsdirektor: Univ.-Prof. Dr.-Ing. habil. Dipl.-Wirt. Ing. Chokri Cherif

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Dresden, 13.09.2023

Review to the thesis of ***Hafiz Faisal Siddique, M.Sc., entitled "Tensile Characterization of Compression Sock's Ankle Cut-strips and Development of Models to Approximate the Laplace's Law"***

Dear Ladies and Gentlemen,

The dissertation of Mr. Hafiz Faisal Siddique is dedicated to creation and improvement of model for computations of medical compression socks.

It is written on 55 pages of text, distributed in 8 chapters. The literature research covers 90 sources of international journals.

The dissertation is mainly devoted to the two different and unique areas of medical class I compression garments (according to MDR), especially to varicose compression stockings useful for the mitigation of venous ulcer and to regulate or streamline the blood flow from lower extremity to upper extremities.

The literature shows that only a few studies exists in which the tensile properties using uniaxial tensile testers is used for the measurement of the tensile indices values of the compression socks rather than biaxial tensile testers. In this dissertation, the tensile properties, especially loading energy, unloading energy, hysteresis, tensile linearity are compared, to force at practical extension and compression pressure statistically using linear regression analysis which is not done before.

The applicant demonstrate understanding of the basic scientific laws of physics and was able to reproduce the derivation of the Laplace's Law based on analysis of the forces and geometry. The elasticity behaviour of the fabrics is introduced in the Laplace law. The main contribution are the large set of experiments and the finally performed correlation analysis, which allows the introduction of a correction coefficient 1.08 into the Laplace's law. It remains unclear if the 8% correction are based on the deviation of the material parameters, of the friction or it indeed considers some additional nonlinearities in the contact between the material and body, which are not considered in the idealized Laplace Law.

The material and methodological part is well explained and the author remained concise and briefly described the sock's physical and fabricated specifications. I must add the missing of the functionality of sock's knitting machine? and their specifications including models; diameters and related data. The results and discussion part is also written in a good way and all statistical tools are applied and explained scientifically used to explain the significance between dependent and independent parameters. Both parts of this dissertation are very interesting and helpful for the commercial use.
The publication record of the applicant is as well very goo, he is first and corresponding author of 11 journal papers in internationally recognized peer review journals like Textile Research Journal, Autex Research Journal, Fibers and Polymers, Fibers and Textiles, which confirms the value of his research.

I have few minor remarks and suggestions required to be answered by the candidate:

Why the strips only selected at ankle?

Why these are only hand washed?

What kind of pressure devices exists and why you have chosen this? The working principle of this device should be explained?

Will be a difference in the results if you use cylindrical coordinate system for the prediction of the compression? This is usual for such kind of geometry. And principally the derivative of the Laplace Law is provided in several books, it is great, that you have succeed to document it, but I can not consider it as contribution and you should provide citation.

Which therapeutic tool is more useful and helpful; bandage or varicose socks? and why?

What is the working life of compression socks? Can some of your investigated parameters be used for its prediction?

Did you considered the hysteresis in the results?

Are the values of the pressure time dependent? From which parameters of the material can be obtained the time dependence and how you can investigate this?

I recommend the dissertation submitted by Hafiz Faisal Siddique M.Sc for the dissertation defense and at the same time recommend to award him the PhD degree if he succeed to answer my questions for satisfaction of the committee.

Best regards

Prof. Dr.-Ing. habil. Yordan Kyosev

Hafiz Faisal Siddique dissertation review

The present topic presents a complex analysis of the deformation of compression socks for optimal radial pressure development. In the first part, the author conducted an experimental study to measure the mechanical properties of selected commercial socks and in the second part, he empirically modeled the compression pressure using Laplace's relation.

In the first part, the author reviewed the application of Laplace's law in biomedicine and further introduced the basic mechanical aspects of compression socks and presented the necessary mathematical relationships between the mechanical quantities. Here, the opponent pauses on the connection of 'tensile linearity' as a quantity that is comfort dependent. The relationship to linearity of what and the range of units is not clear. Such a delicate unit should be better explained and substantiated. For example, similar to the description of 'hysteresis', which in contrast is quite clear and clearly deserved a coarser description.

In the experimental section, the author carried out a number of experiments to analyse the textile properties of the socks and then delved into tensile tests. The author considered a number of load/unload cycles, but it is not clear how he chose them and why, for example, he took data from the 5th cycle. It is also not clear what the diagram in Figure 10 is ultimately for. Was this data used in the next part of the paper?

It is not clear how the author intends to use regression modeling as a tool to analyze the statistical properties of the data he obtained from the experiments. From this perspective, the statistical analysis is very grossly underestimated.

What is the point of relating hysteresis and radial pressure and force? The experimental section does not define the strategy and significance of each experiment relative to the previous sections of the paper. Figure 17 rather suggests that the relationship between pressure and tensile linearity is non-linear. Why was a linear curve used as an approximation? It is surprising that the determination ability of the newly developed TYM model is worse than that of the original model. Why is this so? The referee appreciates that the author compared other models from the literature.

The results show that the accuracies of the proposed models are at a similar level to Laplace's model and other models in the literature. In the discussion of the thesis, the author does not mention the reasons why his models are at the same level as the others. For example, the author does not qualitatively discuss the proposed models that he composed by comparing the forces calculated from the radial progression with the forces from Hooke's definition. Although this is formally permissible, the opponent is not clear about the validity of such an approach. The conclusion of the paper also lacks a deeper comparison with other models. For example, why were the other variables not automatically considered already in the proposed models?

Overall, the thesis appears coherent. In particular, the review part of the thesis is well outlined and the author has thus prepared a very good springboard for his own scientific work. However, from the opponent's point of view, the author's own scientific approach is disjointed. In particular, because the mathematical models are set up vaguely without deeper justification. In the experimental part, many results are combined with regression analysis but without direct connection to the analytical models. From a scientific point of view, the work looks inconsistent with insufficient description. The statistical treatment and conclusion of the thesis are inadequately addressed. Despite the obvious shortcomings, the referee still believes that the author should be awarded the academic degree of Ph.D.

Petr Henyš

14. 11 2023