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DEVELOPMENT OF SEAMED COMPRESSION SOCKS AND COMPARISON WITH CLASS I SOCKS USING EXISTING MATHEMATICAL MODELS

Engin AKÇAGÜN [*]
Faisal SIDDIQUE [**]
Abdurrahim YILMAZ [*]

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Abstract: Compression therapy is an important method for treating venous diseases such as venous edema and venous hypertension. Regular compression therapy's main objective is to diminish leg swelling by controlling blood flow and avoiding the recurrence of reversible blood flow. Compression socks are often recommended as therapeutic garments. In this study, a seamed compression sock was developed using fabric with an interlock knit structure. Three other sock samples were produced by using circular knitting MERZ CC4 model machine for comparison. The results demonstrate that the developed sock meets all the requirements of compression class I. Statistical analysis reveals that fabric parameters, particularly fabric weight, effectively explain compression pressure intensity according to the values of coefficient of determination, coefficient of correlation (r), and means sum of square errors (MSE). In this work, Laplace's Law and a few preexisting mathematical models were used to calculate the compression pressure of both standard compression socks and socks with seams, with results that were essentially similar. The points of data are tightly clustered around line of regression, showing that there is little variation in the compression pressure for socks with seams.

Keywords: Compression Therapy, Compression Socks, Compression Pressure Prediction Model, Socks

Dikişli Basınç Çorabı Geliştirilmesi ve Mevcut Matematiksel Modelleri Kullanarak Sınıf I Çorapları ile Karşılaştırılması

Öz: Kompresyon tedavisi, venöz ödem ve venöz hipertansiyon gibi venöz hastalıkların tedavisinde önemli bir yöntemdir. Kompresyon terapötik tekniğinin düzenli kullanımının temel amacı, kan akışını nihai olarak düzenleyerek bacak şişmesini azaltmak ve geri dönüşlü kan akışının tekrar oluşmasını önlemektir. Çoğunlukla kompresyon çorapları terapötik giysi olarak tavsiye edilir. Bu çalışmada, interlok örgü yapısındaki kumaş kullanılarak dikişli bir kompresyon çorabı geliştirilmiştir. Üretilen çorabı karşılaştırmak için yuvarlak örgü MERZ CC4 model makinesi kullanılarak üç çorap örneği üretilmiştir. Sonuçlar, geliştirilen çorabın kompresyon sınıfı I'in tüm gereksinimlerini karşıladığını göstermektedir. İstatistiksel analizler, kumaş parametrelerinin, özellikle de kumaş ağırlığının, belirleme katsayısı, korelasyon katsayısı (r) ve hataların karelerinin toplamı (MSE) değerlerine göre sıkıştırma basıncı yoğunluğunu etkili bir şekilde açıkladığını ortaya koymaktadır. Bu araştırmada dikişli kompresyon çoraplarının ve geleneksel kompresyon çoraplarının kompresyon basıncını tahmin etmek için Laplace Yasası ile seçilmiş mevcut matematiksel modeller kullanılmıştır ve benzer sonuçlar sergiledikleri görülmüştür. Veri noktalarının regresyon çizgisi etrafındaki dağılımı çok yakın olduğu görülmüştür. Bu da dikişli çorapların sıkıştırma basıncında daha yüksek bir sapma göstermediğini belirtmektedir.

Anahtar Kelimeler: Kompresyon Tedavisi, Kompresyon Çorabı, Sıkıştırma Basıncı Tahmin Modeli, Çorap

[*] Mimar Sinan Fine Arts University, Vocational School, 34380, İstanbul, Türkiye
[**] Technical University of Liberec, Faculty of Textile Engineering, 461 17, Liberec, Czech Republic
Corresponding Author: Engin AKÇAGÜN (engin.akcagun@msgsu.edu.tr)

1. INTRODUCTION

The incidence of chronic venous insufficiency (CVI) diseases in adults in developed countries is increasing (Sell et al. 2014). Venous insufficiency, venous stasis, venous hypertension, and edema caused by chronic lower extremity in patients result in a variety of discomforts, including pain. Compression therapy can be used to treat or prevent these diseases. This therapy reduces venous hypertension, swelling, pain, and edema, and increases calf muscle pump efficiency. Compression therapy encompasses the utilization of compression socks, bandages, intermittent pneumatic compression devices, and intricate compression systems. Various materials exhibiting distinct levels of elasticity are being employed in conjunction (Berszakiewicz et al. 2020).

1.1. Compression Socks

Compression socks are often used in compression therapy to apply pressure to the lower parts of the leg (Felty and Rooke 2005). In the supine position, ankle intravenous pressure is low, and it rises to 80-100 mmHg when standing (at ankle level). When the venous valves are working properly, this allows the pressure to be reduced. In venous insufficiency, pressure is exerted, and compression socks balance the intravenous pressure (Attaran and Ochoa Chaar 2017). The pressure ought to reach its maximum level at the ankle and progressively diminish towards the calf, as illustrated in Figure 1. Compression of the vessel results in a decrease in its radius, which raises the flow rate. This method increases the velocity and volume of blood flow, facilitating its upward flow towards the heart and relieving many chronic venous diseases (Attaran and Ochoa Chaar 2017; Partsch 2006; Siddique et al. 2020).

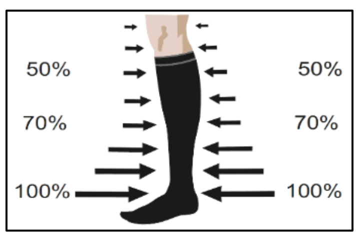


Figure 1:
Graduation of compression pressure

Compression sock production involves a multifaceted process with the goal of creating a highly effective medical compression therapy product. Final product characteristics are heavily influenced by the choice of yarn materials (such as polyamide, polyurethane, cotton, etc.), as well as structural composition and fabrication methods employed. Circular and flat knitting methods enable the manufacturing of both made to order and ready-made compression sock variants possible (Liu et al. 2017).

The process of using circular knitting technology varies from company to company, but it can be summed up as follows: choosing the right main and inlaid yarns, setting up the socks machine knitting program, producing the socks, ensuring compression pressure quality, washing the socks to remove machine oil, ironing the socks, ensuring compression pressure quality, sewing operations, labeling, packaging, and final quality control.

In this method in order to produce a compression socks it is necessary to purchase a very high-cost compression socks knitting machines for every compression sock size. In compression socks market, the size range change from size 1 to size 7 and it is not possible to produce all size from the same machine. Due to this reason, factories must purchase different types of compression socks circular knitting machines. It will conclude high investment cost.

When this process is being evaluated a research question occurs. Is it possible to produce compression socks with different elastic fabrics, materials, design, and methods?

In the literature there are different studies for development of compression socks with different methods and materials. Siddique et al. (2018) developed a V-shaped compression socks by using a conventional sock knitting machine by doing adjustments on a conventional knitting machine. Some other studies used standard compression socks knitting machines. They have changed or used different materials to develop new functional compression socks. In order to increase the comfort features of compression socks, Kırcı et al. (2021) developed them using cotton and bio-designed fibers, and they were then compared to the commonly used nylon compression socks. Oğlakcıoğlu and Marmaralı (2010) developed different socks samples by using Tencel, modal, viscose, cotton fibers and compared their comfort properties with standard nylon products. Liu et al. (2013) developed an elastic compression hosiery by using technical knitting and ergonomic design methodology. They used different yarn and structures to develop a seamless elastic compression hosiery. Duvall et al. (2017) additionally devised three experimental apparatuses targeting orthostatic intolerance, with the primary objective of enhancing venous return through the application of shape memory alloys. Each prototype comprised autonomous thigh and calf segments that could be individually regulated. In a separate study, Pettys-Baker et al. (2018) conceptualized and examined a garment for the calf and thigh regions which is capable of exerting dynamic compression through the utilization of shape memory alloy (SMA) coils as actuators. Kumar et al. (2016) innovatively engineered compression socks by harnessing the potential of shape memory polymers. Their pioneering work resulted in the creation of a sock that enables external manipulation of the pressure level when applied to the leg in a wrapped configuration.

As can be seen from the first part of literature there are many different studies for developing better compression socks with different functions such as comfort etc. The next part of the literature will be about explaining the compression pressure evaluation.

1.2. Evaluating Compression Socks Compression Pressure

Various standards exist for the evaluation of compression socks, including the British Standard BS 6612:1985 (1985), the French standard ASQUAL Certificat Qualite-Produits (1999) and the German standard RAL-GZ 387:2000 (2008). These standards outline the procedures and methods for assessing compression socks. Among these standards, RAL-GZ 387-1 is commonly employed for the evaluation of compression socks. Compression socks are classified based on the level of pressure they exert, with classifications including low (2.4 – 2.8 kPa), moderate (3.1 – 4.3 kPa), high (4.5 – 6.1 kPa), and very high (6.5 kPa and above). The classification and corresponding pressure ranges according to the RAL-GZ 387/1 standard are provided in Table 1 (Liu et al. 2017), (RAL-GZ 387:2000 2008), (Partsch et al. 2006), (Liu et al. 2018).

Table 1. Classification of compression socks according to RAL-GZ 387/1

Compression Class	Compression Intensity	Compression in kPa
I	Low	2.4-2.8
II	Moderate	3.1-4.3
III	High	4.5-6.1
IV	Very High	6.5 and above

The compression pressure evaluation system is crucial for monitoring and assessing the dose of compression pressure to treat chronic venous insufficiency diseases. Four methods can be used to determine the pressure performance: The method most preferred and used in industry is (a) the indirect in vitro method (MST, HATRA etc). The second method is (b) direct in vivo method through various types of pressure sensors (FlexiForce, Kikuhime etc.). The third method (c) is the evidence-based approach to treatment effectiveness. Finally, models which are developed with current theoretical and numerical methods (FMEA etc.) are being used as pressure calculation methods (Liu et al. 2017). This section mainly focuses on comparing existing mathematical models because of their innovation and improvement possibilities.

1.2.1. Mathematical Models for the Prediction of Compression Pressure

Compression pressure can be defined as the application of force to a specific area on the body's surface. Compression socks operate based on the compression of elastic materials. The underlying principles governing the pressure exerted on the surface in compression therapy systems are described by Laplace's law and Pascal's law. Laplace's law is commonly utilized to estimate the skin contact pressure which is generated by compression garments (Gaied et al. 2006). Equation (1) represents Laplace's law, which is frequently employed for predicting the pressure exerted by compression socks (Macintyre et al. 2004).

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

In this equation, P represents the pressure exerted by the compression socks, measured in pascals (Pa), T denotes the tension per unit length expressed in newtons per millimeter (N/mm), and r signifies the radius of the cylinder (mm).

Laplace's law is employed for the calculation of pressure in medical compression socks while in a resting position. This law establishes a connection between pressure, the tension around the circumference, and the leg's radius (Maleki et al. 2011; Stolk et al. 2004). Compression pressure is inversely proportional to the radius of the limb and directly proportional to the tension applied at the skin-garment interface. Consequently, applying the same tension at the ankle will result in a greater pressure compared to the calf, owing to the smaller radius observed at the ankle (Attaran and Ochoa Chaar 2017). Thus, interfacial pressure gradually diminishes as the radius increases from distal to proximal leg which helps decrease intravascular pressure in the legs while ensuring blood flow to the heart (Maleki et al. 2011).

By employing this equation, the pressure exerted by compression socks can be foreseen through the examination of the tensile characteristics of elastic fabrics. In the literature, two approaches have been employed to anticipate compression pressure: finite element analysis and mathematical modeling. Although Laplace's law has been commonly used for compression pressure prediction, there are limited studies that have used modified mathematical models. Recent studies have shown that modified mathematical models have improved prediction of compression pressure. Therefore, this scientific research compares Laplace's law and recently developed mathematical models to compare their accuracy. So, recently developed models are:

(Macintyre et al. 2004) utilized and adapted Laplace's law to estimate the compression pressure and derived an equation in their investigation on the construction and therapeutic applications of compression garments. The formula can be presented as:

$$P = \frac{6.283\ T}{C} \tag{2}$$

In this equation, P represents the pressure exerted by the garment, measured in pascals [Pa], T denotes the tension of the fabric expressed in newtons per millimeter (N/mm), and C signifies the circumference of the cylinder measured in millimeters (mm). Within their study, the researchers utilized Laplace's law to forecast the pressures exerted by compression garments on a cylindrical model with various radii. They observed that certain cases exhibited variations in the predicted compression pressure, for instance, a deviation of 2.1 mmHg was evident in this investigation.

(Leung et al. 2010) proposed a mathematical model based on Laplace's law for predicting compression pressure. Their study focused on knitted fabrics commonly used in compression garments for burn and liposuction surgery. The developed model is represented by the equation:

$$P = \frac{2\ \pi\ E\ A_o\ \varepsilon}{\ell_o (1 + \varepsilon)\ C} \tag{3}$$

In this equation, E denotes the elasticity modulus (N/mm^2), C represents circumference of body (mm), Ao represents the fabric's cross-sectional area (mm^2), and ε signifies fabric strain. The researchers incorporated these factors, including circumference of body, original cross-sectional area, applied strain, and Young's modulus into their prediction model of compression pressure. A 34.6% deviation was observed when comparing the outcomes of their prediction model to the experimental data.

(Siddique et al. 2018) proposed a modified mathematical model based on Laplace's law to predict compression pressure. In their study, they introduced new parameters into the model, such as deformed width, and compared the results with other existing models. The equation for their model is:

$$P_E = \frac{2\ \pi\ E_E\ A_0\ \varepsilon_E\ 1000}{C\ w_f} \tag{4}$$

In this equation, E_E represents the engineering elastic modulus (N/mm^2), w_f denotes the deformed width of the strip (mm), t signifies the thickness (mm), ε_E is the engineering strain, C represents the circumference (mm), and P_E represents the pressure (kPa).

(Dubuis et al. 2012) conducted research to investigate how pressure is transmitted from compression socks to the vessel walls. They aimed to validate and enhance existing treatments involving elastic compression materials. To achieve this, they developed a patient-specific 3D finite element (FE) model of the leg under elastic compression for a group of subjects. The researchers aimed to create a new model for predicting compression pressure. Their proposed model can be described by the equation:

$$P = \frac{\text{stiff}\ \varepsilon}{r} \tag{5}$$

In this model, P represents the compression pressure exerted by the sock. The stiffness (stiff) value of the sock is measured in N/mm, the leg radius is denoted as r (mm), and ε represents the strain experienced by the sock in the horizontal plane. To investigate the transmission of pressure, CT scans of the leg were employed, and in conjunction with socks, CT scans and finite element (FE) models were utilized in their study.

This research has two main objectives. First aim is to develop seamed compression socks by using an elastic knitted fabric materials and compare their compression pressure results with those of Class I compression socks. Second objective is to use the universal Laplace's law and compare the outcomes with the results obtained from recently developed mathematical models (equations 1-5) for predicting the compression pressure of socks. In conclusion, the study aimed to contribute to the body of literature by using the information acquired through this research.

2. MATERIAL AND METHOD

2.1. Materials

In this scientific research work, total four samples were developed and analysed critically. Three pairs of Class I compression socks specimens were developed by using circular knitting MERZ CC4 model machine and denoted as A1, A2 and A3. The fourth sample A4 was developed by using an elastic knitted fabric which is comprised of 60% polyamide and 40% elastane fibers and by seaming this fabric. All production details of samples explained below. Table 2 and Figure 2 represents the yarns and knitting structure detail of all the compression socks samples (A1, A2, A3 and A4). Samples A1, A2 and A3 were comprised of main and inlaid yarn. Sample A1 consists of 50D-40/44F/2 DC (50 denier elastane double-covered with 40 denier polyamides exhibiting 44 filaments) main yarn and 257D-50/44/2 DC (257 denier elastane double-covered with 50 denier polyamides exhibiting 44 filaments) inlay yarn. A1 socks samples exhibit 1×1 laid-in Single jersey as shown in figure 2 (a).

Table 2. Technical specifications of samples yarns

Code	Yarn	Covering Type	Yarn Type	Fiber Type	Linear Density
A1	Main	Double Covered	Core	Elastane	50 denier
			Sheath	PA 6.6	40 denier (44 f) x2
	Inlaid	Double Covered	Core	Elastane	257 denier
			Sheath	PA 6.6	50 denier (44 f) x2
A2	Main	-	Core	PA 6.6	40 denier (13 f) x2 SZ
	Inlaid	Double Covered	Core	Elastane	120 denier
			Sheath	PA 6.6	50 denier (44 f) x2
A3	Main	Double Covered	Core	Elastane	50 denier
			Sheath	PA 6.6	40 denier (44 f) x2
	Inlaid	Double Covered	Core	Elastane	428 denier
			Sheath	PA 6.6	50 denier (44 f) x2
A4	Main	-	Filament	PA 6.6	70 denier
	Elastane	-	Filament	Elastane	105 denier

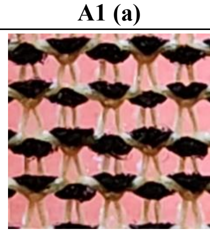
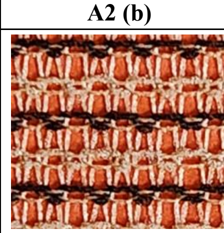
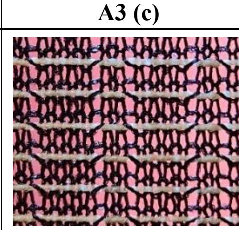
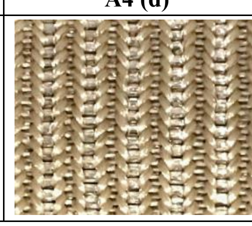
Code	**A1 (a)**	**A2 (b)**	**A3 (c)**	**A4 (d)**
wales **course (inlaid)**				

Figure 2:
Images of the samples

Sample A2 consists of 40/13F/2 SZ (two strands of 40 denier multifilament polyamide yarn twisted) main yarn and 120D-50/44/2 DC (120 denier elastane double-covered with 50 denier polyamides exhibiting 44 filaments) inlay yarn. A2 (Figure 2 (b)) sample structure is for more light compression pressure structure with less yarn linear density. Tuck stitches were used to secure the inlay yarn to the structure. A3 comprised of 50D-40/44F/2 DC (50 denier elastane double-covered with 40 denier polyamides exhibiting 44 filaments) main yarn and 428D-50/44/2 DC (428 denier elastane double-covered with 50 denier polyamides exhibiting 44 filaments) inlay yarn. A3 (Figure 2 (c)) knitting structure was designed by the inlay yarn through tuck and miss stitches. The inlay yarn was used only one time at every two courses and inlay yarn trapped with tuck stitches after miss stitches to the main yarn stitches. A4 - the interlock fabric used to produce A4 socks sample, was made with polyamide yarn, which was used as the main yarn in interlock knitting structure by feeding bare elastane yarn. A4 socks sample fabric has 70 denier Pa 6.6 and 105 denier elastane filament yarn as it can be seen in Table 2.

2.1.1. Development of Seamed Compression Socks

The process for A4 sample preparation was explained below with details and shown in Figure 3.

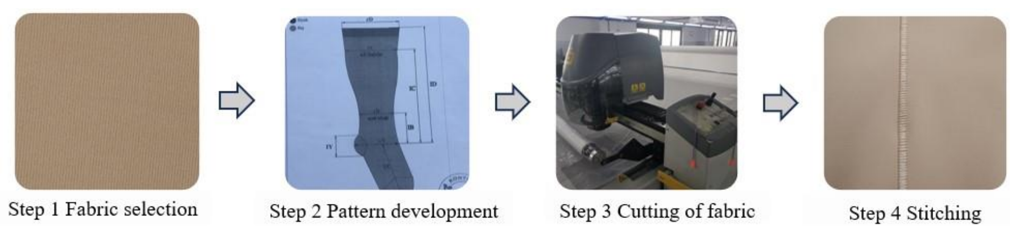


Figure 3:
Development of Class I compression socks by using knitted fabric

Step 1. Fabric Selection: To achieve high pressure, a commercially available interlock structured knitted fabric (circular knitting) was purchased. This fabric was analyzed with more care and accuracy under controlled environmental conditions. All the testing results are shown in Table 2 and Table 5. Due to its compact structure interlock, the mentioned fabric exhibits the highest values of fabric weight per unit area than rest of socks samples A1, A2 and A3. Apart from fabric weight, it was comprised of 40% elastane and 60% polyamide, which are also highest values than rest of three socks samples (Table 5).

Step 2 Pattern Development: Pattern development process is one of the key processes for this research. Gradation in fabric construction is necessary to control blood flow and raise blood from the distal to proximal region of the leg for the intended compression pressure of class I (2.4–2.8 kPa). It was challenging to trim the fabric and impart intensity. Developing the patterns according to a standard sized wooden leg is crucial (as per RAL GZ 387/ 1 size 3 wooden leg). To achieve the desired shape, pressure at ankle and residual pressure percentage (RP %) (pressure gradient), following steps were followed:

1. *The data of the measurements (size):* To create gradual pressure, it is necessary to determine circumference and length measurement values of the leg at the ankle and calf points as it was shown Figure 4. For the development of the A4 sample, standard wooden leg model is used. The circumferences and length values of points B (ankle - minimum girth area), B1 (middle point between B and C), C (calf -maximum girth area) and D (below knee point) for compression socks were measured with a measuring tape as seen Figure 4.

2. *Tensile test of A4 fabric:* The Tensile test results for fabric A4, crucial for the development of compression socks, were conducted in accordance with the BS EN 14704-1 standard test method. The tests were performed at various extensions to achieve the target compression class I range of 2.4 ~ 2.8 kPa. The test samples had dimensions of 150 mm x 60 mm, with a gauge length of 50 mm. The tests were conducted using the Titan Universal Strength Tester by James H. Heal, with a rate of extension set at 500 mm/min. Each sample underwent five tests under standard testing conditions of 20± 2°C and 65% ± 2 humidity.

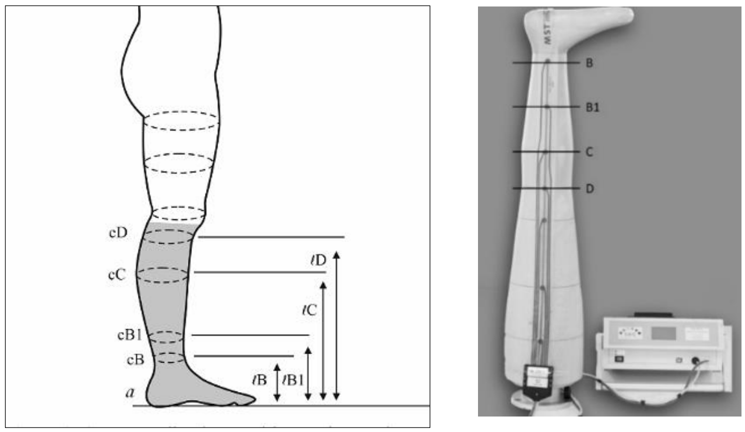


Figure 4:
Measuring points, leg lengths, circumferences, and wooden leg model

3. *Calculation and determining the measurements for pattern:* After tensile test at various extensions on A4 fabric sample to reach compression class I pressure levels (2.4 ~ 2.8 kPa), considering the required pressure values for compression class level 1 (2.4 ~ 2.8 kPa), at different elongation values the compression pressure required at the ankle (B) and calf (C) was calculated using the Laplace's law equation.

$$P = \frac{T}{r} \quad (6)$$

Using this equation, compression pressure values were calculated for each extension, with a particular focus on practical extension values. The ratio of the circumference differences between the socks and legs is known as the practical extension value. This measure quantifies the extent of stretch experienced by the socks when worn on the leg. The compression pressure values associated with the A4 selected fabric are presented in Table 3 below.

Table 3. Compression pressure values of A4 fabric sample under different tensile stress values

Fabric Sample	Force (N)	Extension (%)	Laplace's Pressure (kPa)	Laplace's Pressure (mmHg)
A4	1.5	5.00%	0.71	5.95
A4	3.0	10.00%	1.43	10.70
A4	4.0	15.79%	1.90	14.27
A4	5.8	22.22%	2.76	20.70
A4	6.2	29.41%	2.95	22.12

With this result it has been selected most useful socks measurements for the ankle (B), and calf (C) points of the socks pattern development process to create most suitable compression socks according to the compression pressure requirements (Table 4). According to these measurements A4 socks pattern was developed by using the Gerber CAD program.

Table 4. Width values of the developed socks, A4

Sr. No	Socks circumference	Unit (mm)	Wooden leg width (mm)	Practical extension %
1	Ankle (b)	170 - 187	220	15%~22.72%
2	Calf (c)	330 - 350	370	5.40%-10.81%

Step 3 Cutting of the fabric: The A4 socks were cut using the GERBER cutting machine after the circular knit fabric was spread out on the cutting table and laid out according to the pattern.

Step 4 Sewing the fabric: Finally, the A4 cut fabric pieces were sewn with a special Merrow chain stitch sewing machine. The machine sewed the fabrics with chain stitching to produce the A4 sample. The finished product images can be seen below Figure 5.

Figure 5:
Developed Compression Socks – A4

2.2. Test Methods

All samples have been tested to assess their physical characteristics and technical properties, as outlined in Table 5. These tests were conducted under standard atmospheric conditions, adhering to a relative humidity of 65±5%, a temperature of 20±2°C, and in compliance with the standards CEN 15831:2009 and RAL-GZ 387/1. Courses and wales per centimetres were counted employing a magnifying glass, while stitch density was calculated utilizing the subsequent equation. The outcomes of these measurements (wales per centimetres, courses per centimetres, and stitch density) are presented in Table 5.

Table 5. Technical specifications of samples

Code	Thickness (mm)	Fabric weight (g/m^2)	Course density (per/cm)	Wales density (per/cm)	Stitch density (stitches/cm^2)	Circumference at ankle (cm)	Fiber analysis (%) PA/Elastane	Classification
A1	0.65	338.03	26	21	546	17.6	67/33	CCLI
A2	0.51	139.06	22	25	550	16.0	82.5/17.5	CCLI
A3	0.76	281.7	14	32	448	16.4	61/39	CCLI
A4	0.61	351.2	18	18	324	18.0	60/40	-

$$\text{Stitch density}\left(\frac{\text{stitches}}{\text{cm}^2}\right)=\frac{\text{Wales}}{\text{cm}}\times\frac{\text{Courses}}{\text{cm}} \quad (7)$$

The Mitutoyo digital thickness tester device was employed to measure the thickness of the materials. The test was conducted in accordance with the standard test method ISO 5084:1996. The thickness test results for the samples are provided in Table 5. Additionally, samples measuring 5x5 cm were obtained from each sock sample and weighed using an electronic instrument. The weight was calculated using the formula below, and the results are presented in Table 5.

$$\text{Fabric weight per unit area}\left(\frac{\text{g}}{\text{m}^2}\right)=\frac{\text{Average weight of the fabric (g)}}{\text{Area of fabric(cm}^2)}\ \text{x } 10.000 \quad (8)$$

Fiber analysis of all samples was carried out following the standard procedure specified in AATCC-20A-2013, as presented in Table 5. The analysis results were calculated using the equation mentioned below.

$$\text{Elastane percentage [\%]}=\frac{\text{Weight of elastane threads}}{\text{Total weight of the threads}}\text{x}100 \quad (9)$$

In this research MST Professional II Medical Stocking Tester (Salzmann Ag, St Gallen, Switzerland) device, which is an in vitro method, was used for measurements of experimental pressure as seen in the Figure 6(a) and (b).The test were done under the standard method RAL-GAZ 387/1. Four samples of socks were placed on the MST Professional II Medical Stocking Tester, which was then used to measure the pressure. Five machine tests were conducted in this manner, and the average result is displayed in the outcomes in Figure 8. The compression stocking should provide a continuous pressure reduction from the ankle to the proximal in accordance with the structure of the leg. This factor is called as residual pressure ratio or gradient ratio. It is an important factor at the compression socks design in terms of regulating the flow from ankle to the proximal. This means that the compression pressure in compression socks should be greatest at the ankle and gradually decrease to the proximal (Liu et al. 2013), (RAL-GZ 387:2000 2008), (Partsch et al. 2006), (Wang and Gu 2022).

Residual Pressure Ratio (RP %) from ankle to calf portion is calculated using the formula:

$$\text{Residual Pressure Ratio (RP \%)} = (\text{Pi} \div \text{Pb}) \times 100 \quad (10)$$

P_i = Pressure at i point, (B1-G) P_b = Pressure at B point (ankle)

a. ***b.***

Figure 6:
a. *MST Professional II medical stocking tester* ***b.*** *Test sample*

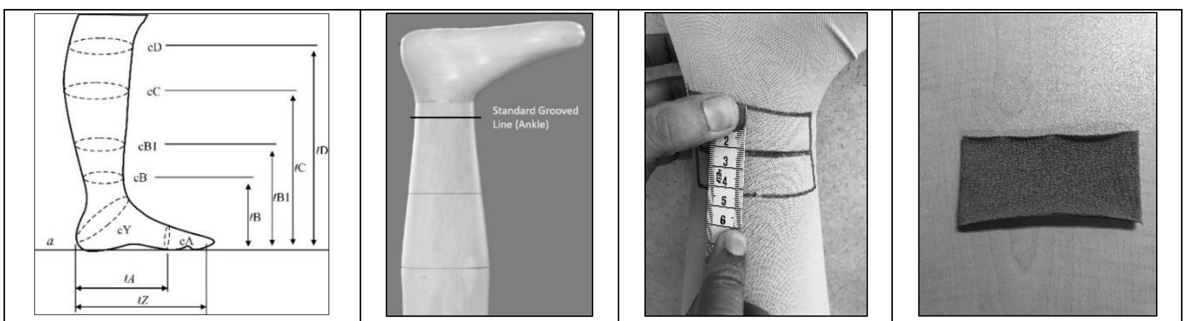
2.3. Tests for Prediction of Compression Pressure by the Mathematical Models

2.3.1. Marking and Cutting Test Strip from Compression Socks for Tensile Testing

The socks samples were initially placed on a wooden leg, which exhibited the specified characteristics illustrated in Figure 7(a), including the ankle circumference (cB) of 220 mm and the ankle position (ℓB) along the leg at a distance of 12 cm from the sole of the foot, as recommended by RAL-GZ 387/1 and CEN 15831. The wooden leg featured a grooved channel-line indicating the points for pressure measurement, as depicted in Figure 7(b). Any wrinkles present on the socks were smoothed out manually. Following this, the socks were removed and allowed to relax. A square measuring 5x5 cm was marked on the socks for conducting physical specification tests and assessing width deformation. Subsequently, the socks were marked, and the pressure was measured before being cut into 60 mm wide strips, as shown in Figure 7(c, d).

2.3.2. Tensile Testing of Compression Socks Strips

During the donning and doffing activities of pressure garments, these garments can be extended up to 100% in the course wise direction. For this reason, the cut-strip test samples extended up to %100 to analyze the actual performance while using (Bera et al. 2015). Tensile tests of the cut strip samples were studied in the course wise direction because the inlaid yarns (double covered elastane yarns) are exerting the pressure in this direction. The test was carried out following the BS EN 14704-1 standard test method. Specimen dimensions was 150 mm x 60mm and gauge length was 50 mm. Test samples were tested on the Titan Universal Strength Tester by James H. Heal at a gauge length of 50 mm and with rate of extension up to 500 mm/min. Five tests per sample were performed under standard testing conditions. With this test method mechanical performance of four socks samples at ankle portion was measured.



(a) *(b)* *(c)* *(d)*

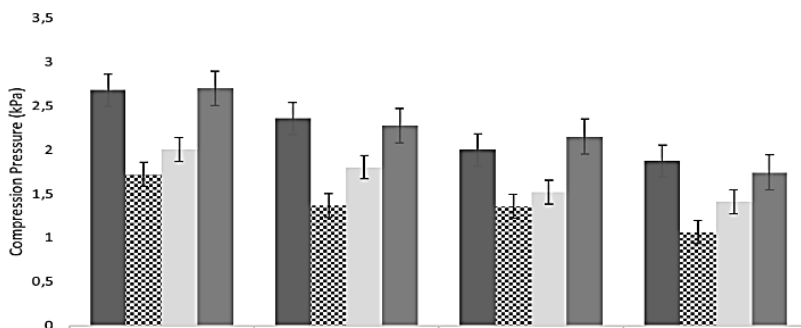
Figure 7:
a. *Standard wooden leg* ***b.*** *standard grooved line* ***c.*** *marking and slicing socks strips.* ***d.*** *socks strips*

3. RESULTS AND DISCUSSION

3.1. Interface Pressure Results of Compression Socks Samples and Statistical Analysis

The experimental compression pressure results and residual percentage (RP %) values were shown in Figure 8. A4 and A1 exhibits the compression pressure values; 2.70 kPa and 2.68 kPa respectively while A3 exhibits 1.95 kPa and A2 exhibits the value of 1.72 kPa which is lowest than rest of all samples. After conducting a comprehensive analysis of the entire set of sample data, encompassing yarn type, weight, and other elements, along with the conclusions presented in Figure

8, it becomes evident that a single fabric parameter having the greatest influence on degree of compression pressure. The fabric parameter, specifically the fabric weight, exerts a substantial influence on compression pressure. Linear regression analysis was employed to examine the statistical impact of the fabric parameter, particularly the influence of fabric weight, on compression pressure. The assessment of its significance in relation to compression pressure was conducted by computing the coefficient of determination values through the utilization of the linear regression analysis tool.



	B	B1	C	D
A1	2,68	2,36	2,00	1,87
RP %	100,00%	87,91%	74,58%	69,86%
A2	1,72	1,37	1,36	1,06
RP %	100,00%	79,40%	78,85%	61,72%
A3	2	1,80	1,52	1,41
RP %	100,00%	90,05%	75,86%	70,25%
A4	2,7	2,27	2,15	1,74
RP %	100,00%	84,20%	79,62%	64,52%

Figure 8:
Experimental Pressure Results and Residual Percentage RP%

Table 6 and Figure 9 depict the fabric weight, showcasing its notable impact on compression pressure as deduced from the measured values of the coefficient of determination (R^2 = 0.8047), correlation coefficient (r = 0.8970), and mean sum of squared errors (MSE = 0.0739) at the ankle portion. Similarly, in Table 6 and Figure 9, the fabric weight highlights a significant effect on compression pressure, with reference to the measured values of the coefficient of determination (R^2 = 0.789), correlation coefficient (r = 0.888), and mean sum of squared errors (MSE = 0.0901) at the calf portion. The Mean Squared Sum of Errors comprises the average sum of squares encompassing both Factors and Errors. The calculation of the Mean Sum of Squared Errors, abbreviated as MSE, entails dividing the Sum of Squares among the groups by the degrees of freedom attributed to the errors. In other words, MSE = SS(Error)/($n-m$).

Table 6. Linear regression analysis of the fabric parameters at ankle and calf portion vs experimental compression pressure

	Regression model	**Coefficient of determination value (R²)**	**Correlation coefficients (r)**	**Squared mean sum of errors (MSE)**
Ankle	Compression pressure = 0.0046 (fabric weight) + 0.974	0.8047	0.8970	0.0739
Calf	Compression pressure = 0.0035 fabric weight + 0.7994	0.789	0.888	0.0901

According to the established guidelines, Class I compression socks should have a pressure gradient (Residual Percentage RP%) that ranges from 70% to 100% at point B and 50% to 80% at point C, in relation to the pressure exerted at the ankle point B (Liu et al. 2013), (Partsch et al. 2006). The residual pressure ratios (%RP) observed in the tested sock samples (A1, A2, and A3), as well as the newly developed A4 sock sample, demonstrated a harmonious and gradual decrease from the distal (ankle) to the proximal regions, thereby aligning with the prescribed gradient variations outlined in the methodology section, as depicted in Figure 8.

3.2. Force Compared to Practical Extension and Experimental Pressure

Figure 10 portrays the relationship between force values of all sock samples at ankle portion measured by different values of practical extension. Practical extension (P_c) is the circumferential difference between leg (L_c) and socks (S_c) which was calculated by using equation 11. The purpose to co-relate the independent variable (extended length/changed length) and dependent variable (force values) was to investigate how much force values varies by changing the length.

$$\text{Practical Extension } (P_c) = L_c - S_c \tag{11}$$

where, Lc is leg circumference, Sc is socks circumference in mm.

Due to varying widths of socks at ankle and calf portion, extended length varies so all the four socks sample exhibit different force values as shown in Table 7 below. These force values were measured by extending them up to the point where practical extension equals to circumference of the wooden leg (220 mm) at ankle point. This cycle was repeated five times. The force values of sample A1, A2, A3 and A4 were 5.6N, 3.5N, 4.2N and 6.2N when extended to 62.5 mm, 68.75 mm, 67.07 mm and 64.71mm respectively as shown in Table 7.

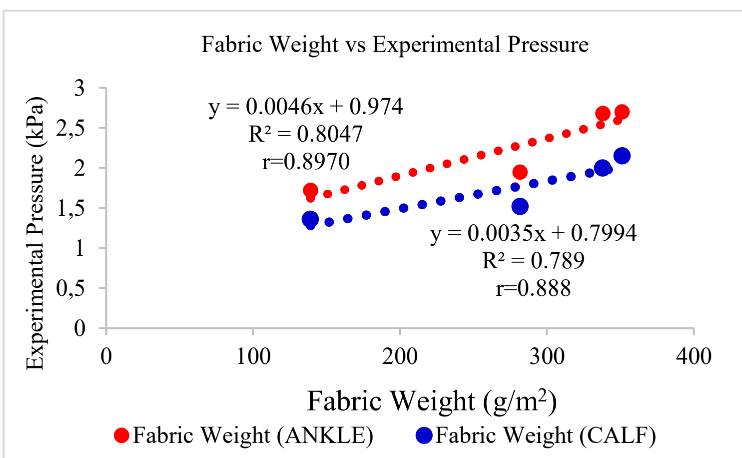


Figure 9:
Fabric weight vs experimental compression pressure

Additionally, Figure 10 demonstrates that Sample A4's curve is steeper than the rest of the socks, demonstrating that its increased stiffness is directly related to the value of the elastic modulus (0.576) shown in Table 8. The highest value of A4 sample is due to its highest fabric weight (g/m^2 = 351.02) as seen in Table 5.

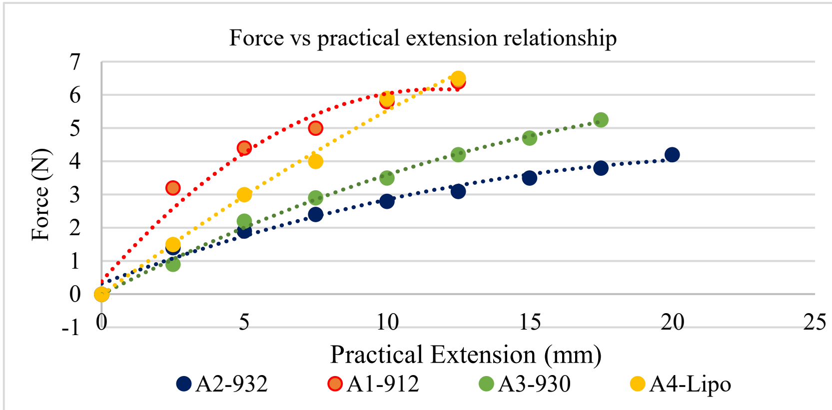


Figure 10:
Force vs Practical Extension Relationship

Table 7. Mechanical properties of compression socks cut strips

Code	Practical force	Extension	Initial width	Thickness	Deformed width	Area	Final length	Socks circumference
Unit	[N]	[mm]	[mm]	[mm]	[mm]	[mm^2]	[mm]	[mm]
	F_L	$\Delta\ell$	w_i	t	w_f	A_o	ℓ	S_c
A1	5.60	12.50	60	0.65	55.7	39	62.5	176
A2	3.50	18.75	60	0.51	56.7	30.6	68.75	160
A3	4.20	17.07	60	0.76	54.8	45.6	67.07	164
A4	6.20	14.71	60	0.61	56.25	36.6	64.71	170

3.3. Statistical Analysis of Force at Practical Extension and Experimental Pressure

The results of the statistical regression analysis, aimed at investigating the correlation between the force at practical extension and the experimental pressure, are illustrated in Figure 11. The coefficient of determination (R^2-value = 0.9545), derived through the least square method, signifies the robustness of the association between the independent and dependent variables. This R^2-value indicates that the force value at practical extension elucidates approximately 95.45% of the variance observed in the experimental pressure results. The figure also shows that sample A4, along with samples A1, A2, and A3, exhibits minimal deviation from the regression line depicted in Figure 11. Furthermore, the regression model incorporates two crucial coefficients: the y-intercept (0.6625) and the slope value (2.4575). These coefficients provide insights into the trajectory of the regression line. The significance of practical extension (mm) can be attributed to Laplace's law ($P = T/r$), where force is directly proportional to compression pressure. X.H. Yan et al. (2019) also emphasized in their study that fabric density and transversal tension performance have a notable impact on static pressure.

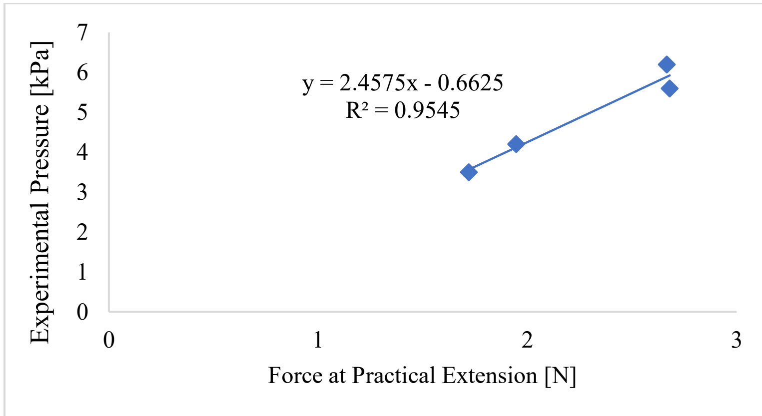


Figure 11:
Force at practical extension compared to experimental pressure

3.4. Comparison of Existing Mathematical Models and Experimental Pressure Results

This section of the results elucidates the mathematical models and their comparison with the original Laplace's Law using the test values obtained from the compression sock samples. Table 8 presents the experimental results alongside the theoretically calculated values, encompassing the measurement of engineering stress (σE), engineering strain (εE), engineering modulus (EE), deformed width (wf), and experimental pressure (Ps) integrated into the existing models.

The theoretical pressure values were subjected to statistical comparison with the experimental pressure results using the linear regression analysis tool, with the coefficient of determination values (R^2-value) serving as the basis for assessment. All existing models utilized in this study are rooted in the fundamental principles of Laplace's law, and they include Basic Laplace's Law, Dubuis's model (equation 5), Leung's model (equation 4), Macintyre's model (equation 2), and Siddique's model (equation 3). In this research, all the existing models were compared with the experimental pressure results to evaluate their accuracy. The calculated pressure values which are obtained using these existing models are presented in Table 8.

Table 8. Comparison of theoretical and experimental pressure values

Code	Engineering stress	Longitudinal (wale wise) engineering strain	Engineering modulus	Experimental pressure	Laplace's law	Siddique model	Leung model	Dubuis model
	σ_E	ε_E	E_E					
	[N/mm²]	No unit	[N/mm²]	[kPa]	[kPa]	[kPa]	[kPa]	[kPa]
A1	0.144	0.250	0.574	2.68	2.66	2.87	2.56	2.66
A2	0.114	0.375	0.305	1.72	1.67	1.76	1.45	1.67
A3	0.092	0.341	0.341	1.95	2.00	2.19	1.79	2.00
A4	0.169	0.294	0.576	2.70	2.95	3.15	2.74	2.95

3.4.1. Basic Laplace's Law Compared to Experimental Pressure

Laplace's Law, the predictor variable, and experimental pressure, the response variable, are shown to be correlated in Figure 12. The linear regression analysis used for the scientific statistical analysis. The R^2 value (coefficient of determination values) was employed as a measurement tool to express the degree of dependence between experimental pressure and the theoretically calculated pressure (Laplace's law). Figure 12 portrays coefficient of determination values between predictor and response variables is (R^2 – value =0.9545). It portrays that experimental pressure result explain the 95.45 % to theoretically measured compression pressure. The slope value used to measure the R^2 value was 0.8164 and the y-intercept value was 0.3599. Figure 12 portrays very strong positive correlation between the two described parameters (r= 0.9769).

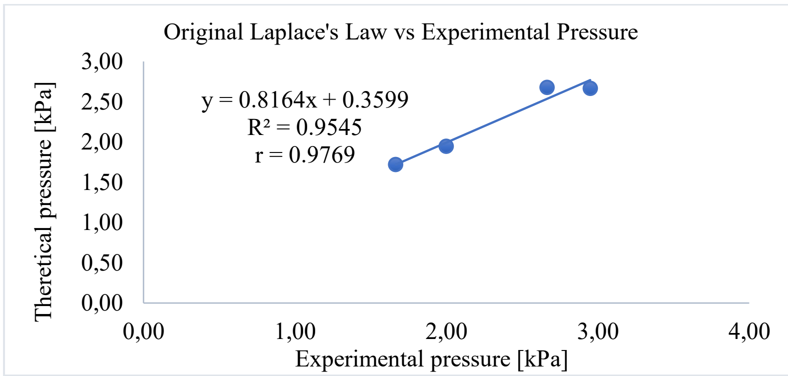


Figure 12:
Comparison of experimental pressure compared to Laplace's Law

3.4.2. Siddique’s Model Compared to Experimental Pressure

Figure 13 represents the strength of the relationship between the experimental pressure as a predictor and Siddique’s model as a response variable. The coefficient of the determination values (R^2-value = 0.9554) shows the strength of the relationship. This value illustrates how the experimental pressure result accounts for 95.54% of the measured compression pressure. The slope value used to measure the R^2 value was 0.7642 and y-intercept value was 0.3492. Figure 13 portrays a very strong positive correlation between the two described parameters (r= 0.9774). Original Laplace’s law and Siddique’s model exhibit minute different values of coefficient of determination values which is due to varying values of the slope and y-intercept.

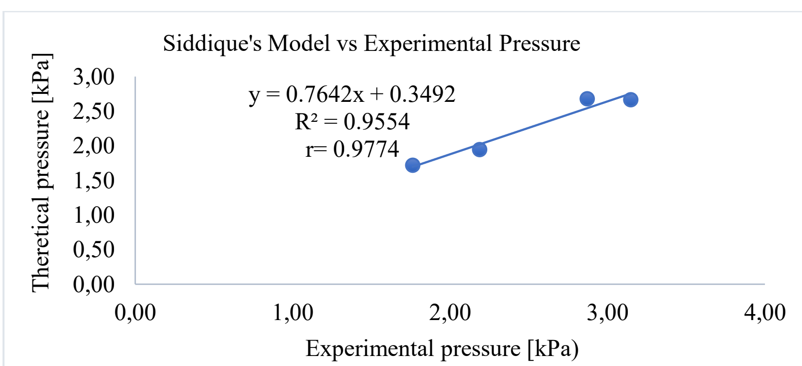


Figure 13:
Comparison of experimental pressure compared to Siddique's model

3.4.3. Leung's Model Compared to Experimental Pressure

In Figure 14, the connection between the experimental pressure and the theoretically measured pressure, utilizing Leung's model as the responsive variable, is graphically presented. The tool used to quantify the strength of dependency between experimental pressure as theoretically measured (Leung's model) was the R^2 value (coefficient of determination values) that is 0.9819. It portrays that experimental pressure result explain the 98.19 % to theoretically measured compression pressure using Leung's model. R^2 was calculated using a slope value of 0.7991 and a y-intercept value of 0.5484. Figure 14 portrays very strong positive correlation between the two described parameters (r= 0.9909).

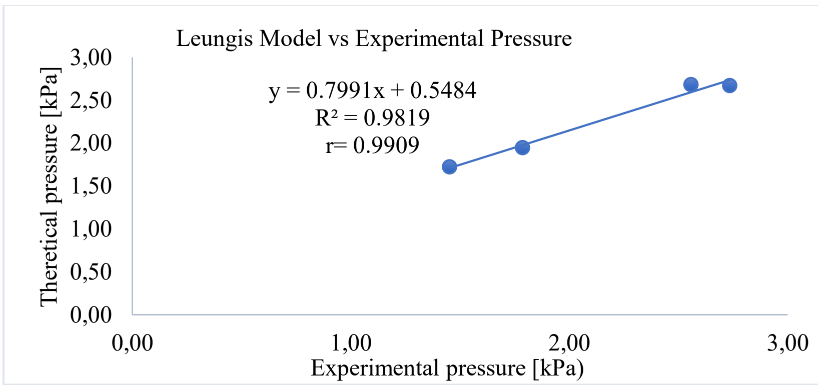


Figure 14:
Comparison of experimental pressure compared to Leung's model

3.4.4. Dubuis's Model Compared to Experimental Pressure

Lastly, experimental pressure and Dubuis's model was also analyzed by measuring the coefficient of determination values. R^2- value = 0.9545 was the measured value for the coefficient of determination. It indicates that the 95.45% correlation between the theoretically calculated compression pressure and the experimental pressure result.

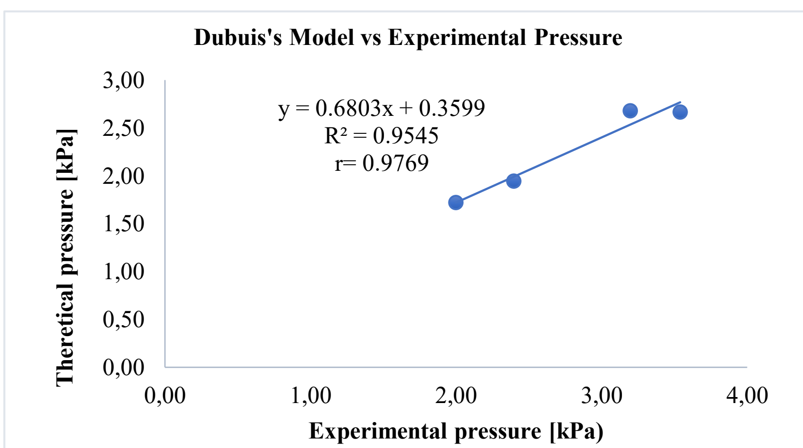


Figure 15:
Comparison of experimental pressure compared to Dubuis's model

Except for the slope and y-intercept values, the R^2-value obtained using Dubuis' model is similar to the original Laplace's law. R^2 was calculated using a slope value of 0.6803 and a y-intercept value of 0.3599. Figure 15 portrays very strong positive correlation between the two described parameters (r= 0.9769).

4. CONCLUSION

This study examined the pressure at the ankle, calf, and residual percentage values between commercially available Class I compression socks and newly developed compression socks.

Summarized results are tabulated below:

- A seamed compression sock was designed that is made of an interlock knitted fabric. The pressure of developed compression socks was compared with the existing compression socks and found that the developed sock samples comply to all the requirements of compression class I (details referenced in RAL- GZ 387/1).
- Compression pressure results of all the sock samples were measured experimentally. While developed socks A4 and A1 has similar experimental pressure results, their pressure values are higher than A2 and A3. Based on the values for the fabric parameter especially the fabric weight well explains the experimental compression pressure values (excellent relationship) based on values for the coefficient of determination (R^2), coefficient of correlation (r), and means sum of square errors (MSE).
- Lastly, all socks' samples compression pressure values calculated by using original Laplace Model and other mathematical models. Experimental and predicted compression pressure results are similar. Also, in this research mathematical pressure estimation methods were compared by using compression socks samples values. It is seen that all selected models were based on Laplace's law, and they were adding some different parameters for better pressure estimation model. As the results show that the models results are close to each other except with some minor differences.

CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

AUTHOR CONTRIBUTION

Engin Akçagün contributed to all stages of the article including determining the concept and design process of the research, research management, data collection and analysis, interpretation of results, preparation of the manuscript, critical analysis of the intellectual content, final approval, and full responsibility. Faisal Siddique contributed to all stages except preparation of the manuscript. Abdurrahim Yılmaz contributed to all stages except data collection.

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