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Determination of the Pressure of Knitted Abdominal Bandage of Women Legging Pants Using Laplace Laws

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Abstract

Compression garments are used for medical therapies and sports products such as bandages, socks, workout clothes and so on, with different degrees of compression. The pressure exerted on the body by compression products must be measured and calculated during the design. This paper investigated a method to determine the required pressure in the design of legging pants with a given abdominal pressure by using knitted CVC fabric (60% Cotton and 40% Polyester) with all stitches plated with 100% Spandex yarn. The pressure was calculated based on Laplace laws and was checked by using the designed FSR402 force sensor. Eight volunteers have participated in the trial. Calculating the volunteer's abdominal pressure in wearing legging pants using Laplace's formula was resulted in a range of 5.0 mmHg to 5.7 mmHg when the fabric extension was 20% and between 7.1 mmHg and 8.0 mmHg with a fabric extension of 35%. In that case, the actual pressure measured by the force sensor FSR402 was from 24.3 mmHg to 27.6 mmHg at 20% fabric extension and from 34 mmHg to 39 mmHg at 35% extension. Research shows that using the Laplace equation requires correction to fit a particular design with different circumferences.

Keywords: Knitted fabric, knitted bandage, compression garment, Laplace laws, legging pants.

1. Introduction

Compression garments were often used for medical treatment such as keloid scars, burns, varicose veins. Compression clothing could enhance performance and promote recovery in athletes, whereas in the garment design, for some kind of garment, the coverage and the tightness, may affect the functions of the garment. The tightness of the compression garment has been hypothesized to change the interfacial pressure to the body. However, there is a lack of studies exploring the influence of body coverage with different compression garments [1]. Compression garments were special clothing containing elastomeric fibers and yarns to apply substantial mechanical pressure on the surface of needed body zones for stabilizing, compressing, and supporting underlying tissues. The given efficacy of compression garments as a treatment in the medical field pushes the use of compression garments in the athletic industry which has became increasingly popular over the past decade. Several commercial companies reported that the associated medical benefits can be applied to enhance recovery in an exercise setting [2]. However, there was still much controversy among studies about the ergogenic effects in the utilization of compression garment in the aerobic performance and in the neuromuscular responses. It appears that the compression garment can be more effective in the recovery of the muscular damage after the exercise. The removal of blood lactate also appears to be favoured by some kind of the compression clothing [3].

With the loop construction the knitted fabrics have good elasticity and they were widely used for the sportwear, textile medical field such as compression garment. Knitted fabric has great advantages in sportwear and functional textile especially in the medical field and compression garment because of their loose structure, high flexibility, porosity and flexible. Moreover, the different structures of knitted fabric which can be varied to meet different requirements in the medical field. So knitted fabrics were considered very suitable for medical textiles. To obtain the better compressive properties of knitted fabrics, Lycra yarns were used with cotton, wool, polyester and other yarns. Such blends give the appropriate elastic properties in the knitted fabrics. They also bring a comfort feeling due to easy movement of the body in the clothes. As a result, they provide more convenience for consumers. Pressure applied by the fabric on the body depends on three factors, namely the shape of the body that was supposed to be covered by fabric, the fiber type and the fabric structure. To achieve the desired compression of garment, predicting and calculating the pressure was necessary [4].

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The pressure exerted by the compression garment should not be too small or too large. If too small, it will not have curative effect, while if too large, it may occur some pathological response such as blood circulation obstacle, accelerated breathing, indigestion and internal organs deformation includes the gastrostomies. Therefore, for the application of compression garments, the key factor is how to design the compression garment's sizes to achieve the required pressure exerted on the body part. So, the only key factor affects the garment pressure was the accuracy of the sizes of compression garment. At present, the main methods for designing the compression garments include the reduction factor method, using the Laplace law and the numerical simulation methods. The reduction factor method refers to select a standard reduction factor (generally 10%, 15% or 20%) firstly, and then calculate the sizes of compression garment based on the sizes of human body. The design method for compression garment based on Laplace law considers the fabric properties as well as the body sizes, easy to implement, having low cost and high popularization value [5]. There were two kinds of stretch fabric in use, namely, comfort stretch (25 - 30%) and power stretch (30 - 50%). Stretch fabrics find particular applications in the design of active sport clothing such as swimsuits and athletic clothing. As the human skin can be extensible from 20 to 200% due to physical movement, the compression materials can be developed that can exert the exact required pressure on the body utilizing the elasticity of knitted fabric properties as material, clothing design and the influence of clothing pressure on the body [6].

Compression bandages designs were usually utilized with high stretch or low stretch as well as single layer or multilayer. The compression pressure of less than 20 mmHg has been categorized as mild, from 20 mmHg to 40 mmHg as medium, the compression pressure from 40 mmHg - 60 mmHg as strong, and greater than 60 mmHg as very strong. The pressure exerted by girdles is a significant parameter since it is closely concerned with body shaping effects and wearing comfort. Manufacturers can refer to the optimum clothing pressure distribution to develop and design girdles to satisfy the needs of most people [7]. Using the Laplace laws was one of the useful methods to design the compression garment with the required pressure.

The Laplace laws was originally developed by Thomas Young and Pierre Simon de Laplace in 1806 to explain the surface tension phenomenon in liquids. However, while Laplace's original formula provided a mechanistic view of the pressures exerted on curved surfaces, it did not take into account the adaptations that can occur in living body which was neither solid nor has a constant curved structure. Thomas modified Laplace's law to include the importance of bandage width and the number of layers applied so that it can be used in clinical practice, The modified equation below, often referred to as Laplace's law, is frequently used to calculate the sub-bandage pressures of compression systems [8]:

$$P = \frac{\boldsymbol{T} \times \boldsymbol{n} \times 4620}{CW} \tag{1}$$

where, *P* was the bandage pressure (mmHg), *T* was the tension of bandage (Kgf), *n* was the layer of bandage, *C* was the circumference of the limb (cm), *W* was the width of bandage (cm)

In order to determine the required pressure that meet the application of the garment with pressure on the outer fabric surface using Laplace laws formula, several studies had designed measuring devices to place under the garment. The device was a ready-made, easy-to-measure system for reference when calculating pressure for compressed garments [9, 10].

In this article, the research of the compression forces of double-layer bandages were carried out. The aim was to evaluate the compressive forces provided by the bandage with different waist sizes and to compare the calculated results with these ones of device. Pressure gauge with force sensors was used to verify accuracy, reliability of the Laplace laws that was the useful tool in predicting and calculating compressive band pressure. Moreover, the legging pants were designed to keep the unchanged pressure at the abdomen area. The application was oriented to aromatherapy and the required pressure had to suitable to release the essential oil from the microcapsules coated on the knitted fabric surface [11]

2. Methods and Materials

2.1. Materials

In this study, the material chosen was a CVC (composed of 60% Cotton and 40% PE) single jersey knitted fabric. The spandex yarn (40D) was platted on all loops of the fabric to improve the elasticity of the designed legging pants. The CVC ground yarn count was Ne 30/1. The fabric was prepared on a Runshan (Taiwan) single bed knitting machine. The investigated knitted fabric properties were presented in the Table 1.

2.2. Participants

This study was performed on eight women aged 35 - 46 years (40.5 ± 5.5 years) whose height and weight were 154 ± 6 cm and 58.9 ± 3.4 kg.

Eight pairs of legging pants were designed according to the body measurements of the eight participants.

Table 1. The properties of the investigated fabrics

Material	Knitted fabric	Composition (%)	Thickness (mm)	Weight (g/m^2)	Loop length for 100 stitches (cm)	Horizontal stretching force at 200% (Kgf)
CVC	Single jersey	Cotton 60 Polyester 40	0.52	195.6	3.2	41.357

Table 2. The body measurements of the subjects

	Participants								**The average measurements**	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Mean**	**Standard Deviation**
Waist girth (cm)	76	76	72	75	70	77	74	79	74.9	2.9
Waist width (cm)	31	33	32	32	33	33	33	35	32.8	1.2
Belly girth (cm)	86	88	79	81	80	89	83	90	84.5	4.3
hip girth(cm)	92	92	92	92	92	89	92	97	92.2	2.2
Thigh girth(cm)	51	53	52	60	56	55	53	57	54.6	3.0
Knee girth(cm)	37	38	39	38	36	38	34	38	37.3	1.6
crotch depth (cm)	25	24	24	25	24	23	25	26	24.5	0.92
Height (cm)	154	148	155	151	152	150	155	160	153.1	3.7
Weight (cm)	56.3	54.5	51.3	54.9	51.0	56.1	52.5	65.0	55.2	4.5

2.3. Methods

2.3.1. Design of the legging pants

The legging pants were designed at 20% and 35% fabric extension at the abdomen area. The referencing pressure investigated on compression garments, the pressure for pants and the compression bandages showed the values was calculated based on the formula of Laplace laws [6, 7]. The pressure requirement was 21 mmHg to 27 mmHg for compression legging pants and 34 mmHg to 39 mmHg for compression bandages [6-8]. These values were considered to be the best pressures for compression legging pants designs that still ensure comfort for the wearer, respectively, with an elongation of 20% to 35%.

The fabric tensile was measured by TENSILON Instrument (Japan). The experiment parameters were Per-tension was 0.1 N, tensile rate was 100 mm/min and gauge length were 100 mm. Specimen size (widthways direction) was 200 mm × 50 mm (length x width). Each fabric was tested at a continuous elongation to 200 %, and their tensile forces at every elongation was recorded in the excel table. The test was taken 5 samples for every kind of investigated fabric and the mean value was calculated. Tensile force for elongation bandage of 20% to 35% was taken from the excel table of CVC fabric tensile results. The values were calculated as 0.84 Kgf and 1.18 Kgf for the bandage width of 14 cm at tensile force for 20% to 35%., respectively.

C. D. Huong had reported that the fabric extension could influence on the liberation of the active agent from the core microcapsules coated on the knitted fabric [11]. So, the design of the legging pants with suitable pressure may control the release of the essential oil, the active agent packaged on the microcapsules if they were coated on the compressive bandages.

In preparation for the design of compression pants, the reduction was calculated directly on the body measurements table with the fabric extension of 20% and 35% (Table 3).

The legging pants were designed with compression bandage in front of the abdomen. The bandage had a width of 14 cm, sews on 2 layers and had an adjustable bar in the middle of the abdomen. The legging pants with rips at the front belly of 15 cm of the back. Then, each paper pattern was completed using the calculated dimensions (Table 3). An over lock machine and the sewing machine were used to sew the body and hem of the legging pants, respectively.

Table 3. The body measurements in reduction with 20% and 35% fabric extension

Participant	At 20% fabric extension					At 35% fabric extension	
	Waist girth (cm)	abdomen girth (cm)	Hip girth (cm)	Thigh girth (cm)	Knee girth (cm)	Waist girth (cm)	abdomen girth (cm)
1	60.8	68.8	73.6	40.8	29.6	49.4	55.9
2	60.8	70.4	73.6	42.4	30.4	49.4	57.2
3	57.6	63.2	73.6	41.6	31.2	46.8	51.6
4	60.0	64.8	73.6	48.0	30.4	48.8	52.7
5	56.0	64.0	73.6	44.8	28.8	45.5	52.0
6	61.6	71.2	71.2	44.0	30.4	50.1	57.9
7	59.2	66.4	73.6	42.4	27.2	48.1	54.0
8	63.2	72.0	77.6	45.6	30.4	51.4	58.5

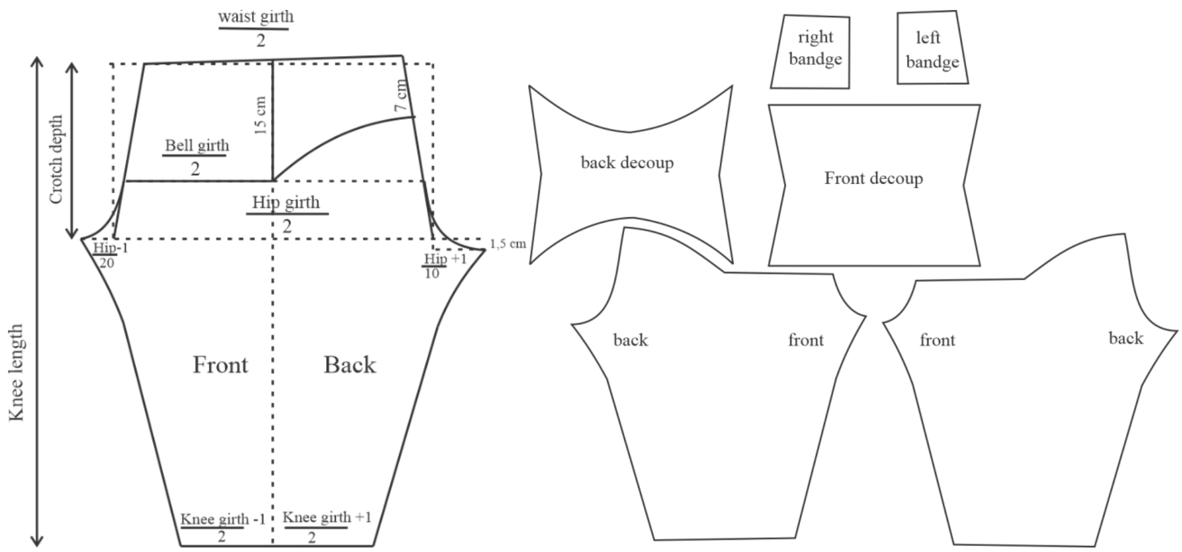

Fig. 2. Pattern of legging pants with 20% fabric extension

2.3.2. *Pressure measurement*

In this study, pressure sensor FSR402 was used for pressure test of compression bandage. This was a resistive inductive force sensor. The sensor could change its impedance depending on the pressure applied to the sensor. The sensor converts the pressure applied to the area of the FSR sensor membrane to change the resistance value and to obtain pressure information: the higher the pressure, the lower the resistance. It allowed to use the pressure from 0 gf to 10 kgf.

Before measuring the pressure, the device has been checked for accuracy of the sensor. The calibration process was as follows: Put a continuous load with a known weight (10 g, 20 g, 30 g, 50 g and 70 g) on the sensor; each load was hold for 1 minute; record the output voltage value during loading; check the results and convert units from gf to Newton and from Newton to mmHg for the best value between input force value and output voltage.

The eight participants wore legging pants with their legs straight, arms hanging down along the body in a natural position, and then tested the pressure exerted by the pants and compression bandages on different points of the abdomen near the navel. Two points (left and right) were measured at regular intervals at the abdominal circumference and three values were recorded at each point.

3. Results and Discussion

During designing, we have selected a reduction factor of 20% and 35% for the compression bandage on the anterior abdomen. The elongation was calculated right from the measurement data table before being included in the design formula. Corresponding to the reduction factor of 20% and 35%, the tension of the bandage fabric was 0.84 Kgf and 1.18 Kgf respectively, for the width of 14 cm with 2 layers of the designed bandage (See the section 2.3.1). The pressure results were calculated theoretically by Laplace's formula (1) and were presented in the Table 4. The pressure results were then measured by pressure sensor FSR402 and showed in the Table 5 and Table 6.

The eight participants were the middle-aged women and rather over-weight. So, we considered their abdomen as the haft of the circle with diameters as waist width [12]. So, the *C* value (waist circumference) of the eight participants was determined according to the waist width value (Table 2). Their abdomen circumferences and the pressure calculated by the Laplace's law were presented in the Table 4.

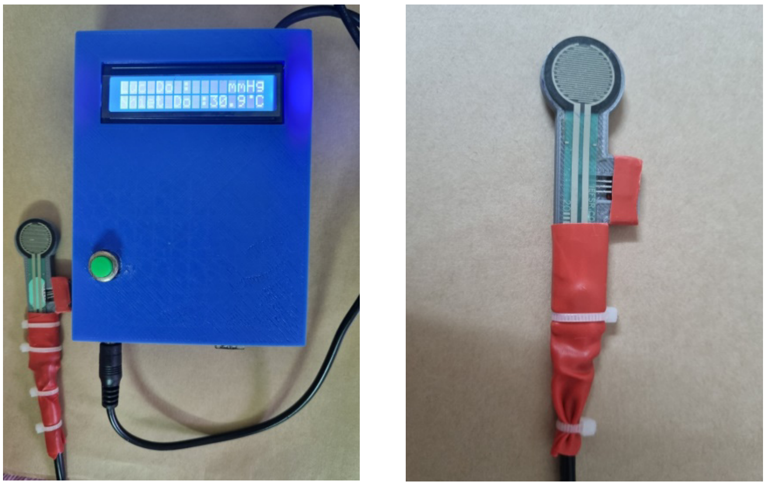

Fig. 3. Force Sensing Resistor (Length 6cm, Overall width 1.9cm, sensor area diameter 1.27cm)

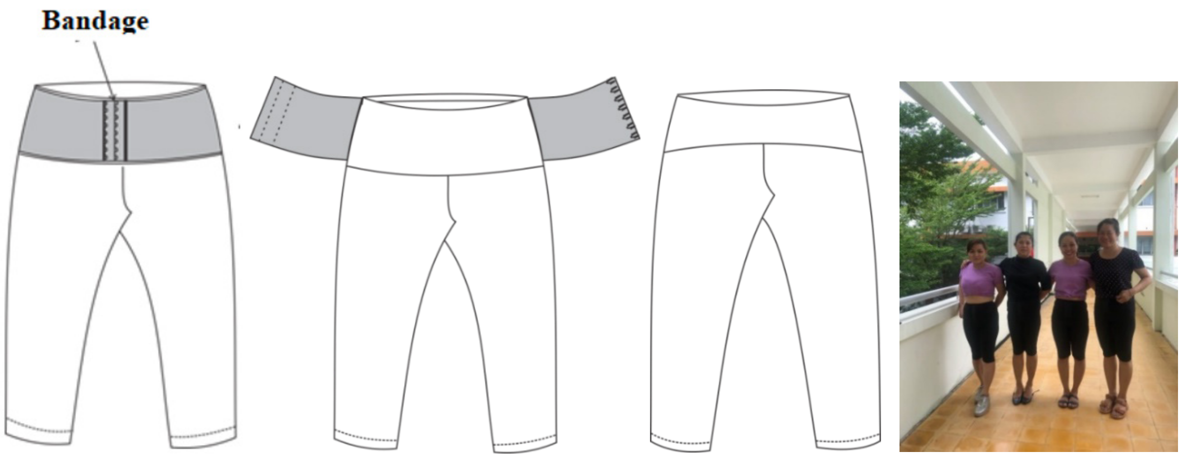

Fig. 4. Legging pants designed according to body measurements

Table 4. Theoretical pressure of compression bandage at 20% and 35% fabric extension using Laplace's law for 8 abdomen circumferences

Extension of fabric (%)	Tension force of bandage (KgF)	The calculated abdomen circumferences of 8 wearers (mm)							
		97	103	100	100	104	104	104	110
		Pressure calculated according to Laplace equation corresponding to the waist circumference of the wearer (mmHg)							
20	0.84	5.7	5.4	5.5	5.5	5.3	5.3	5.3	5.0
35	1.18	8.0	7.6	7.8	7.8	7.5	7.5	7.5	7.1

Table 5. Pressure is provided by compression bandages with 8 different abdominal circumferences with the fabric extension of 20%

Abdomen circumference (cm)	**Compression bandage pressure value measured by sensor device on 8 subjects at abdomen circumference with 20% of the fabric extension**						
	1	**2**	**3**	**4**	**5**	**mean**	**SD**
79	27	37	19	23	27	26.6	6.69
80	28	20	25	28	14	23.0	6.00
81	22	25	26	29	27	25.8	2.59
83	16	37	24	26	23	25.2	7.60
86	37	10	19	22	21	21.8	9.73
88	21	24	29	22	27	24.6	3.36
89	14	16	20	37	24	22.2	9.12
90	27	18	37	22	28	26.4	7.16

Table 6. Pressure is provided by compression bandages with 8 different abdominal circumferences and a fabric stretch of 35%.

Abdomen circumference (cm)	**Compression bandage pressure value measured by sensor device on 8 subjects at abdomen circumference with 35% of the fabric extension**						
	1	**2**	**3**	**4**	**5**	**mean**	**SD**
79	37	37	21	37	37	33.8	7.16
80	37	20	37	28	37	31.0	7.66
81	37	21	37	48	37	36.0	9.64
83	37	49	55	44	37	44.4	7.80
86	37	37	37	37	37	37.0	0.00
88	18	37	37	49	37	35.6	11.13
89	43	47	37	29	44	43.6	7.14
90	27	45	37	37	48	38.8	8.20

The pressure of leggings and compression bandages on the abdominal was calculated by Laplace laws with circumferences of eight participants. For a bandage width of 14 cm, the calculated pressure was low, ranging from 5.0 mmHg to 5.7 mmHg when the extension was 20% and from 7.1 mmHg to 8.0 mmHg when the fabric extension was 35%. These values did not match the pressure ratings referenced in previous studies. The Table 4 and Fig. 4 showed that the calculated pressure was inversely proportional to the circumference of the bandage, that was, the larger the circumference, the smaller the pressure. Therefore, when applying Laplace formula to calculate pressure for large objects, it was not always suitable [6-8].

The knitted fabric bandage pressure was then measured by pressure sensor FSR402 and results were showed in the Table 5 and Table 6.

Table 5 and Table 6 showed the compression bandage pressure measured by the pressure sensor. The values were 21.8 mmHg to 26.6 mmHg when the bandage designed with the fabric extension of 20% and they were from 31 mmHg to 44.4 mmHg when the bandage designed with the fabric extension of 35%. The results did not show the inverse relationship tendency between pressure and waist circumference as shown in the theoretical pressure calculation by Laplace formula in Tables 4 and Fig. 4. The small difference between the waist circumferences could be the reason of these results. The accuracy in measurement by pressure sensor may be influenced also on the results.

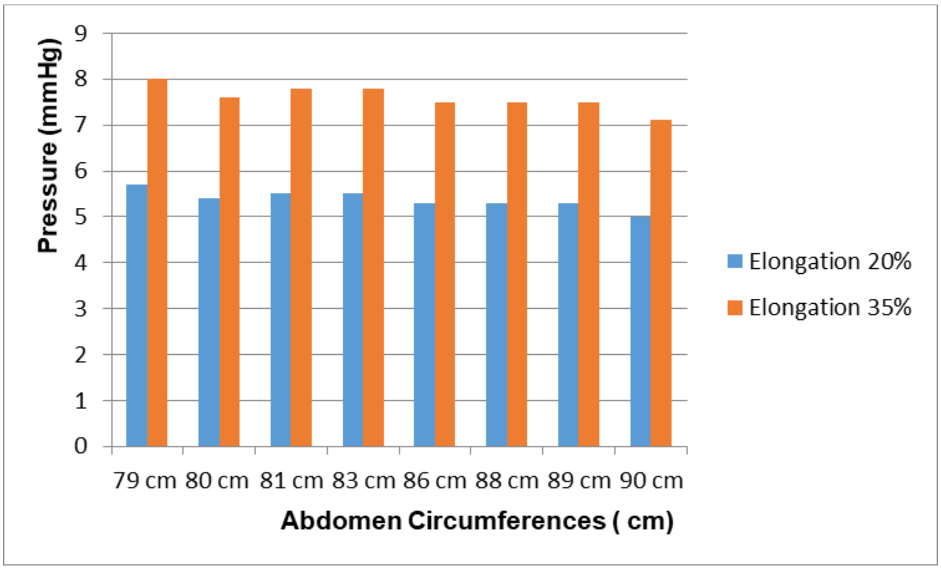

Fig. 4. Pressure calculated by Laplace's law formula at 8 waist circumferences.

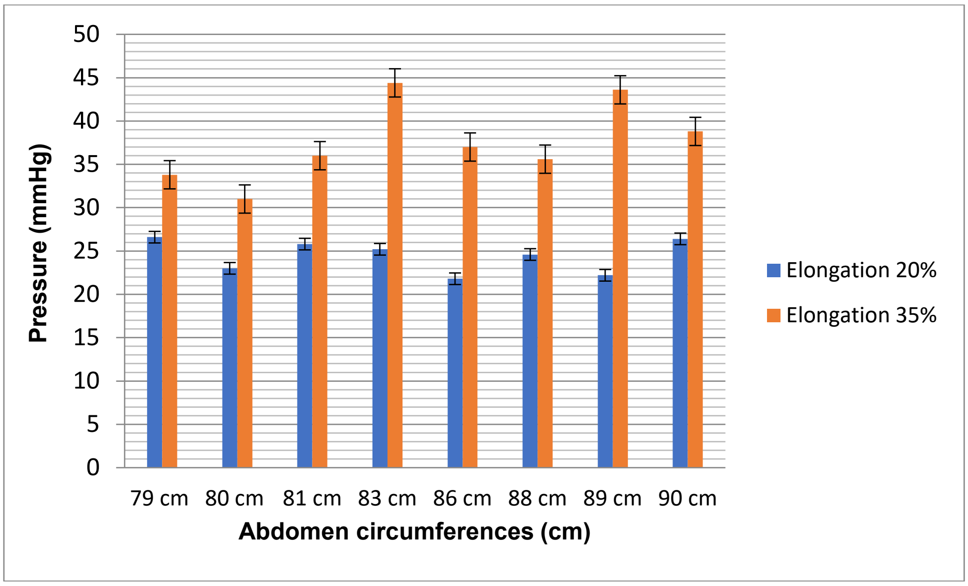

Fig. 5. The graph of mean pressures of the 8 abdomen circumferences measured by the sensor with elongation of 20% and 35%.

Table 7. The mean pressures of the 8 waist circumferences measured by the sensor with elongation of 20% and 35%.

Elongation (%)	**Average pressure measured by pressure sensor FSR402 at 8 different abdomen circumferences (mmHg)**							
	79 cm	**80 cm**	**81 cm**	**83 cm**	**86 cm**	**88 cm**	**89 cm**	**90 cm**
20	26.6	23.0	25.8	25.2	21.8	24.6	22.2	26.4
35	33.8	31.0	36.0	44.4	37.0	35.6	43.6	38.8

Table 7 and Fig. 5 were the mean values pressure of 5 measurements of 8 waist circumferences obtained by the force sensor. The average value of pressure measured by the sensor was much higher than the theoretical pressure calculated according to Laplace's law formula. The results have met these ones from other research [6-8] which determined that the Laplace laws gave the pressures that were not always exact in comparison to the practical values. The pressure calculated by Laplace Laws tended to bigger with the small circumferences and they became smaller with the large circumferences compared to the real values pressures [6-8]. The difference may come from the friction force between the fabric and the human body, The bandage width and the circumference abdomen are bigger, the friction force is more important. A coefficient could be added into the Laplace equations to adjust the values. In this research the real pressure were about 4 - 5 times greater than that one calculated (see table 6 and table 7). However, the measured pressure was still within a suitable level and could be used to designed the legging pants with the demanded pressures. The investigated measured pressures ranged from 31 mmHg to 44.4 mmHg. As the abdominal circumference of the subjects was not circular, the body surface was not flat and there was tissue in the abdomen, so the results of the measurements may vary while the sensor was placed to measure the pressure. The survey of 8 volunteers wearing legging pants with bandages was assessed as comfortable feeling. The pressure of the pants and bandages did not cause a contraction in the abdomen and lower body.

The pressure of leggings with compression bandage was trend to distribute more important at the abdomen than at the waist or hips, and the front and back of the pants are sewn with two layers of fabric. Pressure at the hips and waist was less than pressure at other locations on the abdomen. It is possible that these were sunken so the pressure sensor may not make good contact with the compression garment. Therefore, it is necessary to place an additional support of a pressure pad on the surface of the sensor to increase the contact, so that it can reach the real pressure value.

4. Conclusion

The legging pants with compression bandage for 8 different waist circumferences were designed. The extension of 35% and 20% for bandage were taken as the suitable design pressure range for this kind of clothing. The CVC fabric with 60% of cotton, 40% polyester and the spandex yarn plated on the al stitches. There were the differences between the sensor measurement results obtained and the calculated pressure value using Laplace formula. The results have met these ones reported by some studies that have used the equation to calculate pressure for garments such as compression socks, compression bandages and so on [6-8]. With small circumference the calculated pressure can be suitable. In this study, the measuring position was the waist circumference that was quite large, so there was too much difference between theoretical calculation and direct measurement by sensor. The coefficient was recommended to add into the Laplace equation to meet the measured values. So, in using Laplace's law formula, it is necessary to consider the width and circumference of the bandage, which were two factors that greatly affect the pressure. So, the measurement of the friction force between the fabric and the body and the fabric could be carried out for the further research to calculate the coefficient for the specific case. Thus, when determining the pressure for the design of compression legging pants, the measurement by force sensor could be used to get more feasible values and to adjust the Laplace equations.

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