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Influence of manufacturing parameters of knitted compression fabric on interface pressure

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The influence of various parameters, such as knitted structure, elastane percentage, elastane yarn count and stitch length, on the interface pressure generated by compression knitted garment has been studied. An experimental device has been developed to measure interface pressure by using a FlexiForce® sensor. The obtained result shows that the pressure generated by compression garment depends on the considered parameters. It is observed that plain knitted fabric causes high pressures on leg, generating a high value of interface pressure. Moreover, the increase in elastane percentage and elastane yarn count cause an increase in interface pressure. Contrariwise, the increase in stitch length generates a decrease in interface pressure. Mathematical models based on ANOVA analysis are also developed. The validity of these models has been demonstrated using χ^2-test.

Keywords: Elastane percentage, Elastane yarn count, Interface pressure, Knitted fabric, Polyamide 6-6 fibre, Stitch length

1 Introduction

Compression garments are known as a potent medical product designed to treat venous diseases. Many researches proved the importance of wearing compressive clothes to treat the venous insufficiency and lymphatic disorders[1, 2]. The application of an external compression garment has diverse physiological and biochemical effects on venous, arterial and lymphatic systems[3]. Besides their efficiency in the medical sector, compressive clothes also invaded the sports fields[4,5]. This use has been well documented in the literature. This method offers a good improvement in the recovery and the covering of muscles after an intense effort, an increase in blood flow, reduction in fatigue, and a better oxygenation of muscles. A lot of researches have focused on studying the influence of construction parameters on general mechanical properties of knitted fabrics used for garment manufacturing[6, 7], but few studies described the relation between manufacturing parameters and compressive ability of compressive garment. As reported by Estivalet and Brisson[8], the stretch and recovery properties of the knitted fabrics are related to elastane yarn count and the stitch length. They observed that the recovery of the knitted fabric increases according to the increase in elastane percentage and the decrease in stitch length. Cuden *et al.*[9] studied the influence of elastane percentage on knitted fabric mechanical behavior. They reported that the degree of stretch-ability and elasticity depends on the quantity of elastane incorporated in the fabric. In another work[10], the relation between the elastane percentage and the dimensional properties of knitted fabric has been studied. It was concluded that the width of the fabric decreases when tension on lycra yarn during knitting increases[10]. The effect of knitted structure on mechanical properties of fabrics was also studied. Mikucioniene *et al.*[11] reported that the extensibility and strength of knitted fabrics are related to the knitting structure. Knitted fabrics, having in their structure stitches or a mixture of stitches and short floats, are characterized by the maximum elongation and strength in transverse deformation. In case of longitudinal deformation, the maximum elongation and strength are characterized in knitted fabrics which have tucks in their structure. Asif *et al.*[12] studied the effect of three weft knitted structures on several properties, such as dimensional stability, fabric width, pilling resistance and areal density. From their investigation, it was found that with the increase in percentage of tuck loop, the mechanical properties of knitted garment change. According to their studies, elastane percentage, knitted structure, elastane yarn count and stitch length have a noticeable effect on

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general mechanical properties of knitted fabric. Despite the studies on the effect of the cited manufacturing parameters on the mechanical properties of knitted hosiery, there are almost no researches available relating to study of their effect on the interface pressure generated by this garment on human skin.

Until now, the available literature on compressive garments is still insufficient to reflect clearly the complicated relationship between interface pressure and these manufacturing parameters (elastane percentage, knitted structure, elastane yarn count and stitch length). Most studies are often limited to studying the influence of one of these parameters on the compression or on other mechanical properties of the knitted structures [13-16]. The present research is therefore aimed at developing a new experimental device to measure compressive garment pressure and to study the effect of manufacturing parameters on the interface pressure. Also, established a mathematical model which links all these parameters to interface pressure by using experimental design and $\chi 2$-test, was used to test the agreement between predictive and experimental values.

2 Materials and Methods

2.1 Development of Experimental Device

In order to measure the interface pressure applied by a compression garment, an experimental device was developed. The pressure was measured using a force-pressure sensor FlexiForce® A201 (Mescan, France) as presented in Fig. 1. It is a piezoresistive sensor having 14 mm width, 200 mm length and a sensing area of 71.1 mm^2.

The sensor is composed of two layers of film substrate (polyester/polyamide). On each layer, a conductive material (silver) is applied, followed by a layer of pressure-sensitive ink. The electrical resistance of the sensor fluctuates with applied force. The FlexiForce® sensor acts as a force-sensing resistor linked to a developed electrical circuit that converts the resistance of the sensor into a voltage read by a digital multimeter. When the force is unloaded, its resistance becomes very high. When a force is applied to the sensor, the resistance decreases. The sensor's active area is composed of conductive strips connecting them to electronic circuit. The advantage of using this sensor is that it has tolerable drift, repeatability, linearity and hysteres; it is so fine that it does not affect the detected values [17,18]. Most of the force sensors available in the market are not suitable for measuring legging pressure because of their large size and complex equipment involving measurement difficulties. Flexiforce® sensor is considered as the best sensor used for this type of applications which need high sensitivity when compared with piezoelectric, capacitive and hydrostatic sensors [19, 20]. By using weights with different weight levels, external pressures are divided into six levels, viz 0, 5, 10, 20, 30, 40, and 50 g on an area of 71.1 mm^2, which is then transformed into pressure unit mmHg (1 Pa = 133.32 mmHg), as shown below:

$$\text{Load, g (on } 71.7\ \text{mm}^2) = \frac{9.806 \times 10^{-3}}{0.000071}\ \frac{\text{N}}{\text{m}^2}\ (\text{Pa}) = 138.112\ \text{Pa}$$

As a result

$$\text{Load, g (on } 71.7\ \text{mm}^2) = 1.03\ \text{mmHg} \qquad \ldots(1)$$

This external load produces a series of corresponding voltage signals, which are monitored by using a multimeter. When the signals are stable, we record the voltage values to establish the pressure-voltage corresponding relationship. Figure 2 shows the linear relationship between pressure and voltage values of sensors.

Fig. 1 — FlexiForce® Sensor Model A201

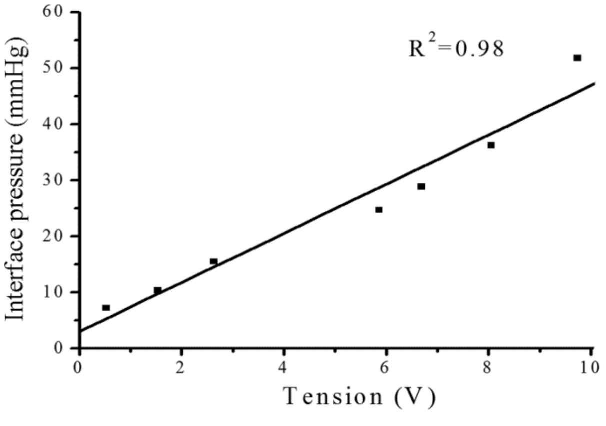

Fig. 2 — Relationship between pressure and voltage values

The regression equation of this curve, as shown below, is used to determine the interface pressure value during the experiment:

$$\text{Interface pressure (mmHg)} = 4.38 \times \text{Tension (V)} + 3.92 \quad \ldots (2)$$

Obviously, it is of great interest to know the *in situ* interface pressure, but the body compressibility is a complex factor that could vary from a person to another, that's why several researchers have prescribed interface pressure measurement on a rigid body[21,22]. In this study, experimental measurements were carried out on a rigid "size S" mannequin leg. The sensor has to be placed first in an adequate position. Then it was fixed to the lower leg of a mannequin made from resin by using an adhesive tape as shown in Fig. 3.

According to the standard (CEN/TC 205 WG2), the most important measurement point is in the ankle region (B level). In fact, pressure classes are classified referring to the pressure measuring at this point[23]. Additionally, the importance of this position on the leg pressure is demonstrated by another research [24]. They proved that passive dorsiflexion of the ankle significantly increases pressure in the others compartments of the leg. Veraart *et al.*[25] have also proved the importance of pressure measurement at the ankle (B level). They demonstrated that the ankle region is the most critical area since it is the predilection region for venous leg ulcers, therefore the interface pressure at this area should be well known in order to prevent or compensate the venous insufficiency. For this reason, we focused our study on pressure generated by samples at B level. After that, the sample is carefully worn on the leg, and covers the active area of the sensor as shown in Fig. 4.

In order to reduce the measurement dispersion, five measurements are realized around this region for each sample. The result was discussed using ANOVA analysis.

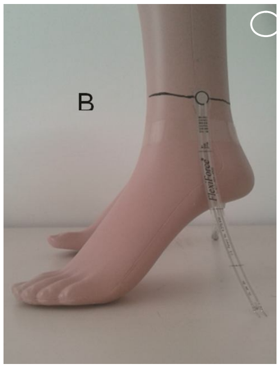

Fig. 3 — FlexiForce® sensor fixed at B level

2.2 Development of Compressive Garments

Sixteen samples of seamless compressive knitted garments with various manufacturing parameters were produced on a "Santoni SM8 TOP2" machine. The gauge of this machine was E28 and diameter was 24 inches. Polyamide 6-6 filament was used as ground yarn in this study because of its moisture resistance, high abrasion resistance, high flexibility and elasticity and low ability to shrinkage. Elastane yarn was knitted simultaneous with the ground yarn according to the plating technique. The polyamide 6-6 yarn count used for the manufacture of the samples was 77 dtex. The used elastane yarn was a monofilament; it is plated at every feeder. The adjustment of elastane percentage in the fabric was obtained through setting elastane delivery system speed. This adjustment was made by setting elastane bobbins driving wheel acting on positive yarn feeder speed. The developed elastic knitted garments have the form of legging. Tow knitted bindings (plain and pique) were studied, as presented in Fig. 5. Size S was chosen for the studied leggings.

2.3 ANOVA Analysis

In order to determine the most important factor influencing interface pressure, a full factorial design was applied using Minitab software. Four factors,

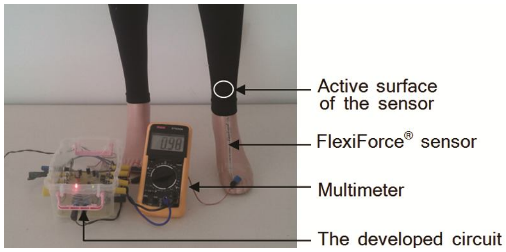

Fig. 4 — Developed pressure measurement device

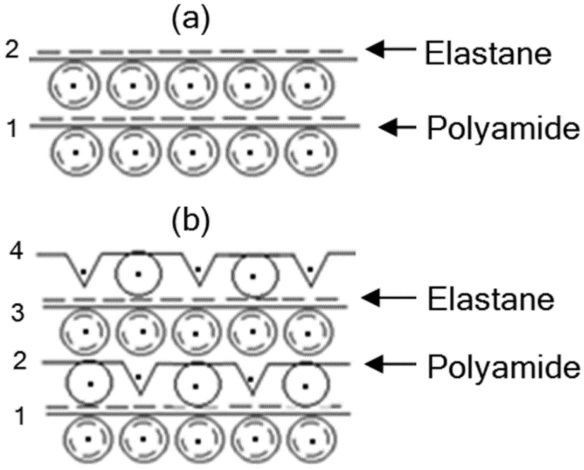

Fig. 5 — (a) Plain and (b) pique knitting structures

such as knitted structure, elastane percentage, elastane yarn count and stitch length, were studied considering two levels for each factor (Table 1).

According to the factorial design, sixteen experiments were established. The characteristics of the tested samples are summarized in Table 2.

The average experimental interface pressure values, as calculated using Eq. (2), are presented in Table 3.

The significance of the studied factors was tested by referring to the statistic Delta (ΔP_B) and p-value. The statistical delta is considered as the difference between the mean values of the levels II and I, irrespective of the fluctuations occurred between these points, as shown below:

$$\Delta P_B = \frac{\sum P_B \text{ in level II}}{\text{No. of experiment in level II}} - \frac{\sum P_B \text{ in level I}}{\text{No. of experiment in level I}} \quad \ldots (3)$$

The validity of the developed models is assured by χ^2-test.

Table 1 — Factors and their levels

Factor	Levels	
	I	II
Knitted structure	Pique	Plain
Elastane percentage, %	8	20
Elastane yarn count, dtex	17	44
Stitch length, mm/needle	2.2	2.8

3 Results and Discussion

3.1 Effect of Factors on Interface Pressure

Table 4 shows that elastane percentage is the dominant factor that influences the interface pressure at B level (P_B), since this factor has the highest delta statistic value (ΔP_B=7.64 mmHg). This is followed by the elastane yarn count with a ΔP_B= 3.84 mmHg, then knitted structure with ΔP_B=2.88 mmHg and finally the stitch length with ΔP_B= 1.45 mmHg.

3.1.1 Effect of Elastane Percentage

There are considerable differences in the compression behavior between knitted compressive garments having different percentage of elastane. Indeed, knitted garment containing the highest elastane percentage generates the greatest interface pressure (ΔP_B=7.64 mmHg). In fact, a high quantity of elastane makes the garment more resistant to deformation and provides more ability to apply pressure. Knitted fabrics containing high elastane percentage have a high tendency to return to their initial dimensional state after wearing and this generates high compression on the body[13]. In their work[13] concluded that with the increase of elastane percentage the garment becomes tighter due to the high degree of recovery.

3.1.2 Effect of Elastane Yarn Count

As shown in Table 4, the interface pressure depends on elastane yarn count. In fact when elastane yarn count is increased from 17 dtex to 44 dtex, the

Table 2 — Characteristics of tested knitted fabric samples

Samples number	Elastane %	Elastane yarn count, dtex	Stitch length mm/needle	Areal density g/m^2	Thickness, mm	Wales/cm	Courses/cm
			Pique fabric				
1	8	17	2.2	199	0.678	41	33
2	20	17	2.2	194	0.644	42	36
3	8	44	2.2	231	0.943	40	34
4	20	44	2.2	229	0.862	42	37
5	8	17	2.8	230	0.821	35	30
6	20	17	2.8	220	0.712	36	32
7	8	44	2.8	236	0.987	35	31
8	20	44	2.8	223	0.823	37	32
			Plain fabric				
9	8	17	2.2	223	0.694	38	28
10	20	17	2.2	220	0.663	40	33
11	8	44	2.2	236	0.942	38	30
12	20	44	2.2	231	0.902	39	35
13	8	17	2.8	235	0.839	33	26
14	20	17	2.8	221	0.722	34	28
15	8	44	2.8	248	1.01	31	30
16	20	44	2.8	246	0.954	37	28

Table 3 — Experimental results of interface pressure

Sample number	P_B, mmHg	SD
1	13.52	0.34
2	15. 37	0.24
3	20.97	0.69
4	24.19	0.36
5	18.76	0.62
6	19.57	0.55
7	20.41	0.59
8	26.89	0.64
9	10.02	0.41
10	12.36	0.53
11	19.21	0.39
12	23.25	0.32
13	16.01	0.30
14	17.67	0.55
15	24.17	0.40
16	25.32	0.56

P_B- Interface pressure at B level and SD- Standard deviation

Table 4 — Effects of factors on interface pressure

Factor	P_B	ΔP_B
Elastane percentage		
Level I	15.41	7.64
level II	23.05	
Elastane yarn count, dtex		
Level I	17.36	3.84
level II	21.1	
Knitted structure		
Level I	17.88	2.88
level II	20.76	
Stitch length, mm/needle		
Level I	19.96	1.45
level II	18.51	

interface pressure increases with ΔP_B= 3.84 mmHg. This is explained by the fact that the increase of elastane yarn count generates a higher inter-stitch force that involves a high pressure. According to this finding, elastane yarn count has a critical role in the construction of the compacting structure of the knitted compression fabric. This observation is in agreement with the finding of Kane *et al*. [14]. They concluded that the compressional resilience increases with increasing elastane yarn count. This is explained by the fact that recovery percentage after compression is increased with yarn thickness.

3.1.3 Effect of Knitted Structure

The type of knitted structure has a significant effect on the interface pressure. As can be seen from Table 4, for the same level of elastane percentage, elastane yarn count and stitch length, plain knitted fabric generates more interface pressure than pique knitted fabric. This is due to the fact that Plain knitted fabric has the most rigid structure than the pique which makes it more tight and compact. The pique bending presents tucks in its structure; this makes it looser than the plain bending which contains only loops. Therefore, pique knitted compression fabric has less compression performance than plain knitted compression fabric. These results concur those reported by Choi and Ashdown [15]. In their investigation they found that knitted fabric which contains tuks or/and miss stitch does not have the same compression behavior as in the case of plain jersey. In fact, pique and cross miss fabrics absorb lower external stress in the course direction when compared to plain fabric.

3.1.4 Effect of Stitch Length

Stitch length has a reverse effect on the interface pressure with lowest value of ΔP_B. When stitch length increases, the interface pressure decreases. This is due to the fact that when the stitch length increases the stitches become larger and more space between them is created. This makes the knitted structure looser and has consequently lower compression. This result demonstrates that the tightness of the fabric is significantly dependent on the variation of stitch length and shows that an increase in stitch length involves a decrease of fabric tightness factor and aptitude to exert pressure on bodies. This finding is in agreement with that reported by Marmarali [16]. In their investigation they concluded that with minimal stitch length, stitch spacing is reduced and this allows knitted garment to be denser, more compact and compressive.

3.2 Pressure Modeling

The goal of this part is developing a mathemtical relationship between interface pressure at B level and the studied factors, refering to AVOVA analysis presented in Table 5.

The basic variables are x_0, x_1, x_2 and x_3. They correspond respectively to knitted structure, elastane percentage, elastane yarn count and stitch length. The interest of this modeling is to predict the interface pressure generated by knitted compression garment before its manufacturing. In this part, mathematical relationships between interface pressure measured at B level (P_B) and studied factors (elastane percentage, elastane yarn count, knitted structure and stitch length) are developed as shown below:

$$P_B = \alpha + \sum_{i=0}^{3} \beta_i x_i \qquad \ldots(4)$$

Since x_0 (knitted structure) is not a numerical factor, tow models are obtained. One model allows to predict interface pressure generated by plain compression garment and the other one is for pique compression garment as given below:

Pique structure:

$$P_{B,Pique}(\text{mmHg}) = 10.82 + 0.64x_1 + 0.14\,x_2 - 2.43\,x_3 \qquad \ldots(5)$$

Plain structure:

$$P_{B,Plain}(\text{mmHg}) = 13.52 + 0.64x_1 + 0.14\,x_2 - 2.43\,x_3 \qquad \ldots(6)$$

The change in studied manufacturing parameters (elastane percentage, stitch length, knitted structure and elastane yarn count) on the compression knitted samples induces a change in interface pressure. It is clearly notable from Table 5 that the different manufacturing parameters significantly affect pressure at B level. In fact their p-values are less than 0.05. According to F-value, we observe that elastane percentage is the factor which has the more influence on the interface pressure followed by elastane yarn count, knitted structure and finally the stitch length. We note that the results of this analysis are in agreement with those presented previously using the statistical delta. However, these influencing factors have not any interaction with each other (p-value > 0.05). This means that the choice of one factor is independent of others.

Table 5 — ANOVA analysis

Source	Degree of freedom	Sum of square	Mean of square	F-value	p-value
Main effect	4	326.95	81.739	52.61	0.000[a]
x_0	1	29.025	29.025	18.68	0.008[a]
x_1	1	233.555	233.555	150.31	0.000[a]
x_2	1	55.876	55.876	35.96	0.002[a]
x_3	1	8.500	8.500	5.47	0.005[a]
2-Way interactions	6	32.352	3.892	2.50	0.166
x_0*x_1	1	4.270	4.270	2.75	0.158
x_0*x_2	1	0.112	0.112	0.07	0.799
x_0*x_3	1	0.630	0.630	0.41	0.552
x_1*x_2	1	8.393	8.393	5.40	0.068
x_1*x_3	1	7.094	7.094	4.57	0.08
x_2*x_3	1	2.853	2.853	1.84	0.233
Residual error	5	7.769	1.554		
Total	15	358.076			

[a] Significant.

3.3 Validity of Models

In order to test developed predictive models, we compared experimental and predicted interface pressure values of new samples having characteristics presented in Table 6. Equations (5) and (6) were tested using χ^2-test, as shown below:

$$\chi^2 = \sum_{i=1}^{n} \frac{(\text{Experimental value} - \text{Predicted value})^2}{\text{Predicted value}} \qquad \ldots(7)$$

where n indicates the number of experiments, in this case n=5 for each model.

In χ^2-test, we have to establish, in the first step, the test hypothesis. In our case, the hypotheses are:

- (H_0)– The experimental values of the interface pressure are near to the predicted value.
- (H_1)– The experimental values of the interface pressure are not near to the predicted value.

Figure 6 shows the relationship between predicted and experimental interface pressure values generated by the two kinds of knitted structure.

Table 6 — Comparison between predicted and experimental values of interface pressure

Experiment number	Elastane %	Elastane yarn count, dtex	Stitch length mm/needle	Experimental pressure mmHg	Standard deviation (SD)	Predicted pressure mmHg
			Plain fabric			
1	6	17	3	11.01	0.13	12.45
2	8	17	2.6	14.52	0.37	15.3
3	10	17	2.4	15.33	0.53	16.47
4	12	44	2.8	19.02	0.86	20.58
5	15	44	2.2	21.76	0.84	23.93
			Pique fabric			
6	8	17	2.8	10.92	0.41	11.51
7	10	17	2.2	13.57	0.53	14.254
8	15	44	3	17.53	0.29	19.29
9	12	17	2.6	19.5	0.58	20.86
10	20	44	2	23.89	0.7	24.92

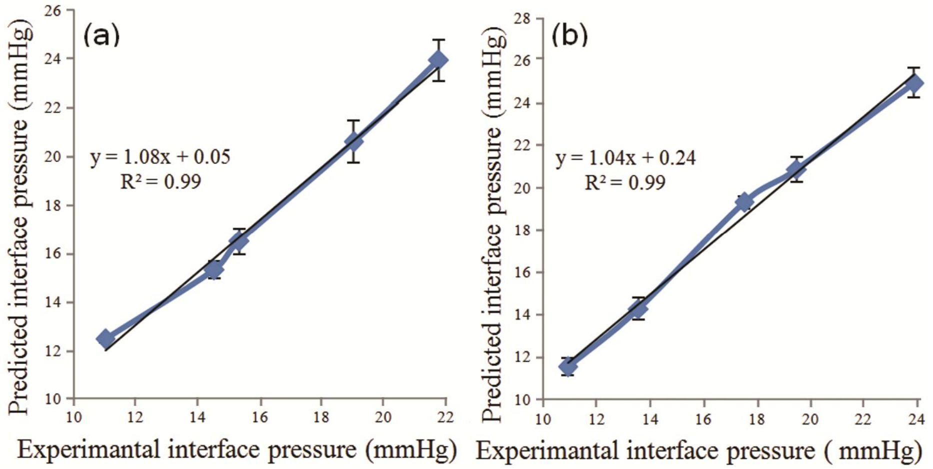

Fig. 6 — Experimental and predicted interface pressure (a) plain structure and (b) pique structure

As shown in Fig. 6, there is a good agreement between experimental and predicted results as R^2 is equal to 0.98 and 0.99.

The second step is the fixation of α-level (significance level). In our study, α-level is defined as 0.05. This means that the correct probability is 95 % when results supporte the hypothesis (H_0).

The third step is the calculation of χ^2 value for each model using Eq. (7).

The fourth step includes comparison between χ^2 value and critical $\chi^2_{0.05}$ as shown below:

- If the calculated χ^2 is inferior to the critical $\chi^2_{0.05}$, we have to accept the hypothesis (H_0) which suggests that the predicted values are near to the experimental ones.
- If the calculated χ^2 is superior to the critical $\chi^2_{0.05}$, we have to refuse the hypothesis (H_0).

Referring to the critical χ^2 value [26] [0.35 Eq (5) and 0.6 Eq (6)], the critical $\chi^2_{0.05} = 9.488$.

It can be seen that for the two models the calculated value of χ^2 is inferior then the critical value. This means that the hypothesis (H_0) is accepted and predicted values of interface pressure obtained by the models are very close to those obtained experimentally. These data is of great interest for compressive garment manufacturers who have to model fabric architecture according to required mechanical pressure on body. In fact, compression of compressive garments is very often criticized by users since they have generally standard characteristics and are not customized to patient's needs. The developed models can be easily used to produce made-to-measure garments and improve reliability of the treatment.

4 Conclusion

The influence of the construction parameters of knitted compression fabric on the interface pressure is studied. It is demonstrated that elastane percentage is the most influential one. The increase in elastane percentage results in an increase in compression of the knitted garment. This result is due to the high elasticity and stretch-ability of this yarn. Moreover, the interface pressure is observed to increase on increasing elastane yarn count since it affects the tightness of the knitted compression garment. Plain knitted structure offers a high compression as compared to the pique structure due to its compact structure. The compression garment depends also on stitch length; the interface pressure is found to be less at high stitch length value. In this study, tow mathematical models are proposed in order to predict the interface pressure in plain and pique fabrics before the garment's manufacturing. The statistical test (χ^2-test) shows that the obtained models are valid and can be successfully used to predict the interface pressure values.

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