Investigating the Accuracy of Prediction Pressure by Laplace Law in Pressure-Garment Applications

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ABSTRACT: To suitably treat and cure special skin damage, the exertion of pressure on the injured limb is advised by therapists. This type of therapy is called *pressure therapy.* Currently, pressure therapy is performed with pressure garments on the tissue. In all pressure-garment applications, the amount of exerted pressure on the limb is very essential, and the success of treatment is extremely dependent on this pressure. Accordingly, the accurate prediction of exerted pressure is very important. Until now, in most related articles and researches, Laplace law has been used as the pressure predictor equation. In this study, the accuracy of Laplace law for two types of structures, elastic fabric and rubber, were investigated. The obtained results indicate that the measured pressure in all specimens was considerably more than that predicted by Laplace law. Therefore, the accuracy of Laplace law was proven to be inefficient for the prediction of pressure, and as such, more investigation is recommended. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 121: 2699–2704, 2011

Key words: mechanical properties; sensors; strain; tension; theory

INTRODUCTION

In many kinds of industrial applications, such as pressurized fabric tubes, pressure-stabilized beams (known as *air beams*), air inflated structures, balloons,[1] medical applications, and clothing, there are thin cylindrical or spherical shells with an internal pressure. As a result of this pressure, the mentioned shells are exposed to uniaxial (wall tension) and biaxial deformation in their cylindrical and spherical shells, respectively. Other materials that exhibit similar properties include physiological applications (heart and blood vessels).[2] In clothing applications, bagging deformation is a good example of these shells.[3]

In medical applications, these shells are usually named *pressure garments* and are widely used around the world. For some issues (e.g., varicose veins, hypertrophic scars), exerting pressure on the limb is an efficient method of treatment; this is known as *pressure therapy.* Pressure garments are mainly made of elastic fabrics and are constructed in a tubular form in a size smaller than the limb, and as such, the expanded shape of the elastic fabric exerts pressure on the inner layer when the fabric is worn. In all applications, the amount of the pressure is very important because the level of treatment is strongly dependent on this quantity.[4] Therefore, the major focus of research on pressure garments is on the pressure itself. The governing equation that is used in most research is Laplace law. This equation can explain the relation between the pressure (p) and the tension on a curved surface and is expressed by the following equation:

$$p = \frac{T}{R} \tag{1}$$

where T is the tension of the shell (N/m), R is the radius of curvature (m), and P is the pressure (Pa). This equation is derived from the theory of membrane equilibrium.[5] The origin of the use of Laplace law to estimate interfacial pressures in pressure garments is not clear.[6] In the meantime, the oldest available report that used the Laplace law to explain the relationship between the exerted pressure by pressure garments and the radius of cylindrical shape is attributed to Cheng et al.[7] Although the accuracy of Laplace law has been doubted by many researchers, thus far, no alternative equation has ever been suggested or offered.

Liu et al.[8] examined multiple fabric mechanical behaviors of graduated compression stockings with different pressure levels and medical functions with the Kawabata standard evaluation system. They reported the specific quantitative relationship between the pressure levels and the multiple mechanical behaviors of the graduated compression

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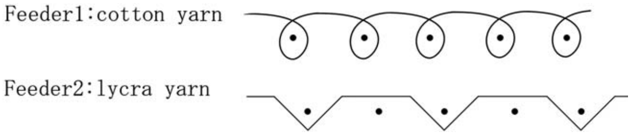

Figure 1 Yarn path notation of the elastic weft plain fabric.

stocking fabrics. However, they did not discuss the theoretical pressure prediction by Laplace law and its accuracy. Yildiz[9] studied the accuracy of Laplace law on trilaminated composite fabrics. She measured the exerted pressure on five different sized mannequin legs with a special prototype pressure-testing device. She claimed that there was no significant difference between the theoretical and experimental values. In another research, the accuracy of Laplace law was evaluated by Gaied et al.[10] They measured the pressure of two types of stockings on a rigid mannequin leg with a SIGaT device, which was based on a pneumatic sensor. The results show that Laplace law underestimated the experimental values by 20–30%. Furthermore, they observed that the stiffer fabric possessed the minimum diversion from Laplace law.

Macintyre et al.[6] evaluated the effects of cylinder circumference variations, fabric structures, and the reduction factor on the pressures exerted by pressure garments. They used I-scan pressure sensors for the pressure measurements. The fabrics used in the experiment were commonly used in pressure-garment construction in hospitals in the United Kingdom. The tension of these fabrics ranged from 27 to 177 N/m at 25% extension. The authors indicated that Laplace law predicted accurate pressure for most of the fabrics, except for a fabric structure called *powernet.* To remedy this situation, they reduced the power of the radius of curvature from 1 (in Laplace law) to -0.835 to obtain a better prediction than that given by Laplace law. Conclusions cited in the article by Macintyre et al.[6] and work done by Macintyre alone[11] indicated that in some cases, Laplace law significantly overestimates the exerted pressure on small-circumference cylinders. Ng and Hui[12–14] investigated several subjects related to pressure garments and presented a few theoretical models based on Laplace law. They used elastic fabrics, which are common for making pressure garments in Hong Kong hospitals. Fabric tubes were sewn according to the desired size of each cylindrical model to exert a particular pressure. The pressures of the fabric tubes on the surface of the cylindrical model were measured by an Oxford MKII pressure monitor. In the first stage,[12] they developed an objective method for drafting pressure garments used on injured limbs. They claimed that there was no significant difference between their theoretical and measured values. Subsequently, they derived a theoretical model to predict the interfacial pressure of multilayer elastic fabrics. The model was found to be valid for low-thickness fabric layers with similar fabric tensile behaviors.[13] Furthermore, they theoretically analyzed the tension and pressure decay for a single-layer tubular elastic fabric. An exponential decay model was assumed for the fabric tube on pressure, which was consistent with the experimental data.[14]

The main parts of thin sheet materials, for example, textiles and polymer films, during processing and usage, are loaded by perpendicular force on their surfaces. Shells are exposed to biaxial deformation under the influence of this force. The well-known and widely used method for the investigation of textiles and polymer materials is called *punch deformation.*[3] In the punch deformation method, the sheet is loaded by a rigid spherical punch; therefore, an internal tensile stress is induced in the sheet, and also, interfacial pressure is created between the punch and the sheet. Amirbayat[15] studied punch deformation using Laplace law. He explained the punch deformation by two parameters of Laplace law very well.

According to Kawabata et al.,[5] many authors have used Laplace law to estimate the interfacial pressure on human limbs exerted by pressure garments. However, a fabric differs from a film in structure, so it is not apparent whether Laplace law can be used in this field. Kawabata et al.[5] cited Hasegawa's work as a reason for claiming that at larger strains, a discrepancy exists between the measured pressure and the theoretical estimation for a sample girdle in wear. This might be attributed to the complexity of knitted fabrics, which indicates that there still exist some problems in the application of Laplace law. However, Kawabata et al.,[5] to simplify the described problem, investigated the accuracy of Laplace law on a plain-woven fabric made of slender rubber tapes. On the basis of their results, one might conclude that Laplace law is applicable for calculating the approximate pressure.

Most of the reports published in the literature have mainly focused on Laplace law. In these studies, the accuracy of Laplace law has been

TABLE I
Particulars of the Tested Fabric

Property	Units
Loop length	3.9 mm
Course per length (cpc)	15 cm^{-1}
Wale per length (wpc)	15 cm^{-1}
Cotton yarn count	30/2 NeC
Lycra yarn count	61 Tex
Fabric weight	470 g/m^2
Composition	72% cotton, 28% Lycra

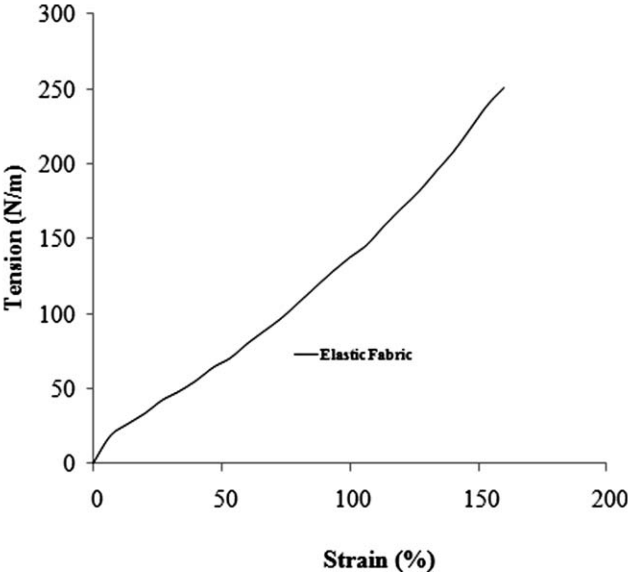

Figure 2 Tensile behavior of the elastic weft plain fabric.

investigated with several types of fabrics. For some kinds of fabrics, Laplace law prediction has been good, and for others, it has not been so good. In the meantime, the relationship between the structure of the fabric and Laplace prediction accuracy has not yet been discussed. In the first attempt in this research, the accuracy of Laplace law on the plain fabric structure was investigated. The results show a discrepancy in Laplace prediction on the elastic fabric structure. To obtain the relation between the discrepancy and the complicated structure of the fabric, we decided to develop a study on an isotropic continuous material (i.e., rubber). To achieve a wide range of Laplace law coverage, different tubes were stretched on different cylinder sizes with various reduction factors.

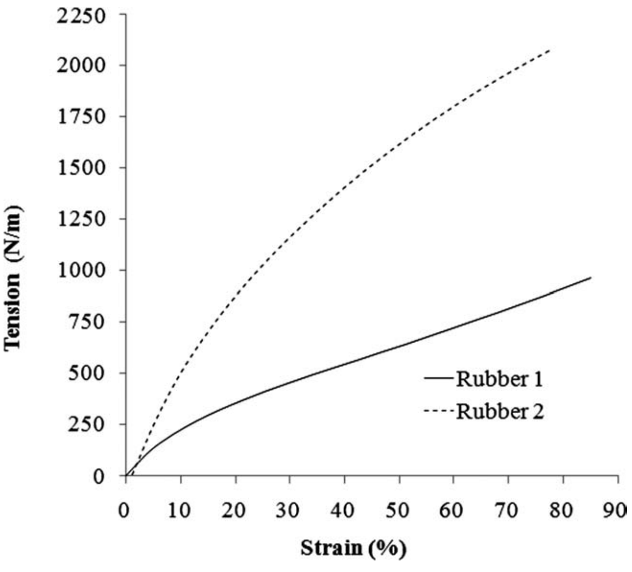

Figure 3 Tensile behavior of the two tested rubbers.

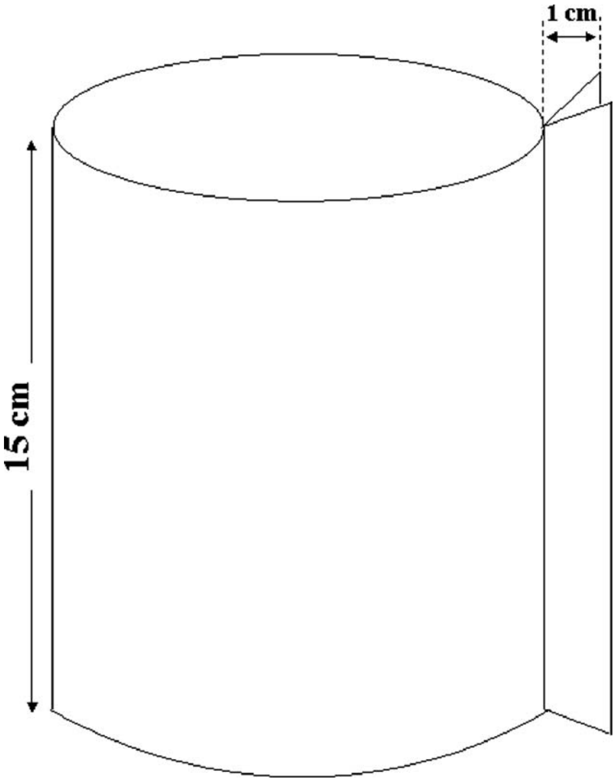

Figure 4 Schematic of a tube sample.

EXPERIMENTAL

To investigate the accuracy of Laplace law, two kinds of materials, anisotropic discontinuous and isotropic continuous materials, were selected. The investigation was broken down into the following stages:

1. Evaluation of Laplace law for predicting the pressures exerted by pressure garment sleeves on cylinder models.
2. Evaluation of Laplace law for predicting the pressures exerted by rubber sleeves on cylinder models.

TABLE II
Dimensions of the Tubular Fabric and Rubber Samples

Material	Strain (%)	Diameter of the cylinder model (cm)	Dimensions of the rectangular sample (cm^2)
Fabric	20	11	28.8 × 15
	40	11	24.7 × 15
	80	11	19.2 × 15
	31	16	38.4 × 15
	54	16	32.6 × 15
	72	16	29.2 × 15
Rubber 1	10	11	31.4 × 15
	10	16	45.7 × 15
	20	16	41.9 × 15
Rubber 2	4	11	33.2 × 15
	5	16	47.8 × 15

TABLE III
Measured and Theoretical Pressures

	Induced tension (N/m)	Calculated pressure (kPa)	Mean measured pressure (kPa)	$(p_{\text{measured}} - p_{\text{calculated}})/p_{\text{measured}}$ (%)
Strain = 20%, D = 11 cm, fabric	33.1	0.6	1.7	64.7
Strain = 40%, D = 11 cm, fabric	55.0	1.0	2.4	58.3
Strain = 80%, D = 11 cm, fabric	107.3	2.0	3.0	33.3
Strain = 31%, D = 16 cm, fabric	44.6	0.6	1.1	45.5
Strain = 54%, D = 16 cm, fabric	77.7	1.0	1.8	44.4
Strain = 72%, D = 16 cm, fabric	103.6	1.3	2.1	38.1
Strain = 10%, D = 11 cm, rubber 1	223.0	4.1	6.7	39.5
Strain = 10%, D = 16 cm, rubber 1	223.0	2.8	6.2	55.0
Strain = 20%, D = 16 cm, rubber 1	352.8	4.4	7.1	37.9
Strain = 4%, D = 11 cm, rubber 2	185.6	3.4	8.1	58.8
Strain = 5%, D = 16 cm, rubber 2	247.1	3.1	7.2	57.1

Materials

A sample of elastic weft plain fabric was used as anisotropic discontinuous material. The selected structure of the fabric is commonly used in compression stockings. This fabric was knitted on a Matec sock-knitting machine, (Brescia, Italy). The fabric was made from cotton and Lycra. The cotton yarn and Lycra yarn were used in the first and second feeders of the Matec sock-knitting machine, respectively. The fabric structure is shown in Figure 1, and its specifications are tabulated in Table I. The tensile properties of the fabric were measured, and the results are shown in Figure 2. The specimens were extended at a constant rate of 200 mm/min with a gauge length of 5 cm (because of the diameter of the sock-knitting machine) and a width of 5 cm.

Two different rubbers (rubbers 1 and 2) were prepared as isotropic continuous materials. The tensile behavior of these elastic materials was measured based according to ASTM D412, as demonstrated in Figure 3. The tensile behavior of the rubbers in three directions (x, y, and 45°) was measured, and we was observed that rubbers had the same tensile behavior in the three directions. Thus, we concluded that the rubbers behaved as isotropic materials. The tensile behavior test was done with an Instron 5566 tensile strength device, (Buckinghamshire, England). To measure the rubber thickness, a Shirley thickness tester was used, (Stockport, England). The thicknesses of rubbers 1 and 2 were 0.78 and 1.13 mm, respectively. Five samples of each rubber and the fabric specimen were measured by the tensile strength test.

Preparation of the specimens for cylindrical tubes

To represent the sizes of the lower and upper legs, two rigid polyethylene cylindrical tubes with diameters of 11 and 16 cm were selected. Tubular samples of the fabric and each identified rubber were sewn according to the Ng and Hui[12] method (Figure 4) for stretching on each of the cylinder tubes at preselected strains, as shown in Table II. Fresh rubber was used for each preselected strain. The specimen was made in the form of a tube by seaming at the two vertical edges. The length of each specimen was 15 cm with a 1 cm seam allowance from the cut edge added.

Measuring interfacial pressure

In this study, a Kikuhime pressure sensor HPM-KH-01, (Sorø, Denmark) was used to measure the

TABLE IV
Details of the Measured Data by the Instron Device for the Fabric and Two Rubbers

	Strain (%)	Tension (N/m)		Strain (%)	Tension (N/m)		Strain (%)	Tension (N/m)
Rubber 1	4.2	117.9	Rubber 2	1.1	7.5	Fabric	6.7	18.3
	8.5	199.9		5.3	268.5		13.3	26.2
	12.7	264.7		9.6	485.0		20.0	33.1
	17	319.4		13.8	659.8		26.7	41.9
	21.2	367.2		18.1	812.5		33.3	47.8
	25.5	411.7		22.3	947.4		40.0	55.0
	29.7	452.1		26.6	107.2		46.7	63.9
	34	491.2		30.8	1183.0		53.3	70.2
	38.3	528.4		35.1	1288.6		60.0	79.9
	42.5	564.8		39.3	1388.0		66.7	88.4
	46.7	602.5		43.6	1481.9		73.3	97.0
	51	639.3		47.8	1570.0		80.0	107.3

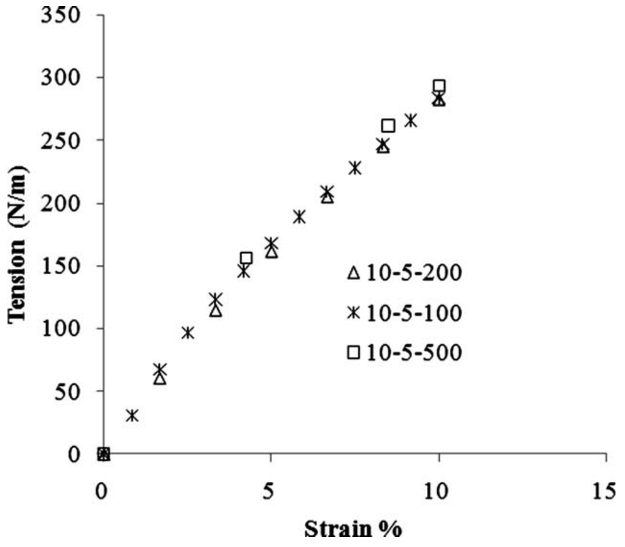

Figure 5 Tensile behavior of rubber samples with different constant rates of the upper jaw of the Instron device.

interfacial pressure. The pressure range of this device was 0–16kPa (0–120 mmHg), and the sensing part was composed of an air pack (diameter = 2 cm) made of a very soft material linked to a digital pressure meter. The interfacial pressure was measured two times at five marked locations on the mentioned circumferential line at a position 7.5 cm from the raw edge. The averages of all of the measured pressures are listed for each physical situation as well as the details. The details of the experimental results are presented in Table III. The coefficients of variation of the measured pressures were 7.6, 5, and 6% for rubber 1, rubber 2, and the fabric, respectively.

Pressure calculation

The interfacial pressures between the tubular samples and rigid cylinders were calculated with eq. (1). As shown in eq. (1), the value of the induced tension in the fabric and rubber was required for pressure calculation. The induced tension for a particular strain was obtained on the basis of the measured data of the Instron device and application of the interpolation method. The interpolated values of induced tension are listed in Table III for the rubbers and fabric, whereas the measured values obtained from the Instron device are reported in Table IV.

Rubber tensile measurements

The tensile tests were performed according to ASTM D 412, in which the extension was required to be at a constant rate of 510 mm/min and the size of specimen was 5 × 15 cm^2, with a gauge length of 10 cm. To investigate the effects of the variation of these standard values on the tensile results, a parametric study was performed on the gauge lengths, widths, and constant rates of jaw. Consequently, the tensile strength was measured for the rubber.

To accomplish this, three different values of each of these three parameters were chosen, and the experiments were repeated five times with new rubber. Accordingly, 15 measured values were registered for each of the parameters, so a total of 45 measurements were involved in the parametric study. The results are shown in Figures 5–7. The legends on the right of each figure show the gauge length, width, and constant rate from left to right, respectively. As demonstrated in Figures 5–7, the tensile behavior of the tested rubber was not

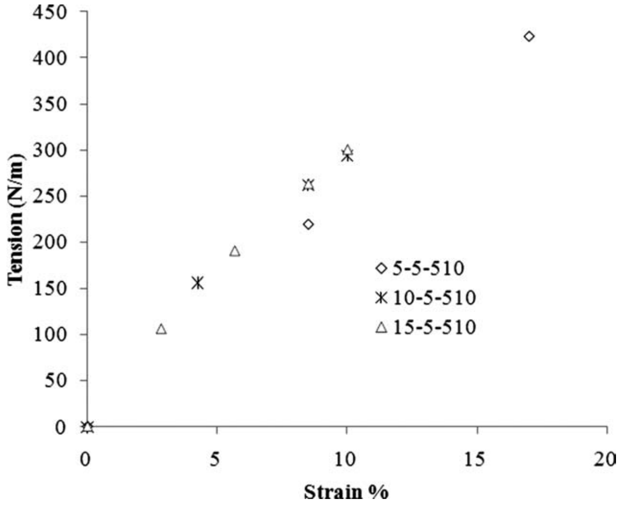

Figure 6 Tensile behavior of rubber samples with different gauge lengths.

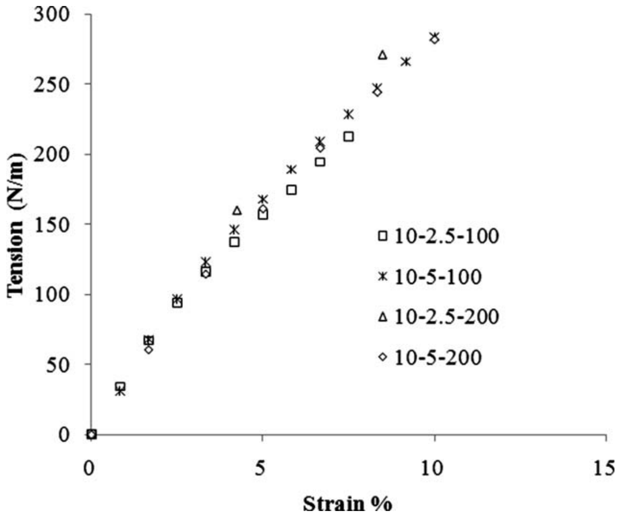

Figure 7 Tensile behavior of rubber samples with different sample widths.

dependent on the dimensions of the sample and the constant rate. Therefore, we concluded that the amount of tension, which is substituted in Laplace law, was not related to the tensile test parameters.

DISCUSSION

In this investigation, the accuracy of Laplace law was investigated for the elastic plain fabric structure. Column 5 of Table III shows the error percentage of Laplace law for the fabric samples. At the first glance, this discrepancy may have been due to the complexity of the fabric structure. For this reason, to eliminate the complexity of the structure of the fabric, an isotropic continuous material was chosen to investigate the accuracy of Laplace law. As shown in column 5 of Table III, Laplace law predicted the pressure for rubber samples with approximately49% deviation. It turned out that, surprisingly, the discrepancy was not related to the structural characteristics of the samples.

Also, we proved that the discrepancy was not caused by the tensile strength testing conditions, such as different gauge lengths, widths, and constant rates of jaw, as explained in the section on rubber tensile measurements. Consequently, it is imperative that more investigations be performed to determine the sources of the discordance.

As mentioned in introduction, Kawabata et al.[5] and Gaied et al.[10] claimed that this difference was caused by the large strain in fabrics, but our study furthermore indicated that there still existed a significant discrepancy between the experimental values and Laplace law predictions, even for small strains (Table III). On the other hand, Gaied et al.[10] explained that the deviations were related to the curvature change on the rigid model leg, but in this study, a deviation was observed even with rigid cylindrical models with a constant curvature. This observation was, by a different means, corroborated by Macintyre and coworkers[10,11] who reported that Laplace law overestimated the pressure on small-circumference cylinders.

It seems there are other important factors that influence the accuracy of Laplace law prediction. Needless to say, the tension that produced the pressure was measured with the Instron device in a flat manner, whereas the actual tension was induced from the rubber extending on the curved surface. Hence, it seemed that the curvature factor may have had some weight in this analysis. Thus, an investigation of the induced tension on curved surfaces would be informative for detecting the sources of the discordance of Laplace law with the experimental results.

CONCLUSIONS

In many industrial and medical applications, the need to predict the pressure induced by the tension of an extended shell on a curved surface is essential. Although it has been common to predict the pressure with Laplace Law, some research[5,10] has indicated that there can be considerable discrepancy between Laplace law prediction and experimental results. On the basis of this observation, Laplace law is not applicable for predicting accurate pressures for all situations and for every type of fabric structure. This research also focused on the evaluation of the accuracy of Laplace law for fabric structure. The results of this study demonstrate that Laplace law was not able to predict the measured pressure values in the fabric. As a result, we chose an isotropic continuous material (i.e., rubber) to investigate the deviation of Laplace law. We observed another deviation in the isotropic continuous material. Hence, for any material, Laplace law cannot predict the pressure. In addition, the results show that the discrepancy of the Laplace prediction did not originate from the structure of the material (isotropic continuous or anisotropic discontinuous). The outcome of this research did not offer any source for this discordance; however, the measurement of the tension on a curved surface and its comparison with the tension on a flat geometry will be explored in a future study.

References

1. Cavallaro, V.; Johnson, M. E.; Sadegh, A. M. Compos Struct 2003, 61, 375.
2. Basford, R. Arc Phys Med Rehabil 2002, 83, 1165.
3. Strazdiene, E.; Gutaukas, M. Text Res J 2003, 73, 530.
4. Macintyre, L.; Baird, M. Burns 2006, 32, 10.
5. Kawabata, H.; Tanaka, Y.; Sakai, T.; Ishikawa, K. Sen-I Gakkaishi 1987, 44, 142.
6. Macintyre, L.; Baird, M.; Weedall, P. Int J Clothing Sci Technol 2004, 16, 173.
7. Cheng, J. C. Y.; Evans, J. H.; Leung, K. S.; Clark, J. A.; Choy, T. T. C.; Leung, P. C. Burns 1984, 10, 154.
8. Liu, R.; Kwok, Y. L.; Li, Y.; Lao, T. T.; Zhang, X. J Appl Polym Sci 2007, 104, 601.
9. Yildiz, N. Burns 2007, 33, 59.
10. Gaied, I.; Drapier, S.; Lun, B. J Biomech 2006, 39, 3017.
11. Macintyre, L. Burns 2007, 33, 579.
12. Ng, S. F.; Hui, C. L. Text Res J 2001, 71, 275.
13. Hui, C. L.; Ng, S. F. Text Res J 2001, 71, 683.
14. Hui, C. L.; Ng, S. F. Text Res J 2003, 73, 268.
15. Amirbayat, J. Int J Clothing Sci 2006, 18, 303.