Rong Liu [a,b],
Yi-Lin Kwok [b],
Yi Li [b],
Terence-T Lao [c]

Fabric Mechanical-Surface Properties of Compression Hosiery and their Effects on Skin Pressure Magnitudes when Worn

[a] **College of Textiles, North Carolina State University,**
Raleigh, USA;
E-mail: lively_liurong@yahoo.com

[b] **Institute of Textiles and Clothing, The Hong Kong Polytechnic University,**
Hong Kong, China;

[c] **Department of Obstetrics & Gynaecology, The Chinese University of Hong Kong, Prince of Wales Hospital,**
Shatin, Hong Kong, China

Abstract
Compression hosiery (CH) is one kind of mechanical therapeutic approach for the prophylaxis and treatment of venous disorders in the lower limbs. Their compression functional performance and comfort sensations are largely related to their material properties. The objective of this study was to comprehensively investigate the mechanical and surface properties of CH fabrics and their effects on corresponding skin pressure magnitudes in practical application. The mechanical testing of the material and skin pressure objective measurements applied to different kinds of CHs with four pressure levels were carried out using the Kawabata Standard Evaluation System and Multichannel skin pressure measuring system. This study shows that significant differences in material properties existed in CH fabrics with different pressure levels. Tensile energy (WT), tensile strain (EM), shearing stiffness (G) and bending rigidity (B) are key mechanical material indices, significantly correlative to skin pressure magnitudes; CHs fabrics with higher levels of pressure were rougher, stiffer and had less extensibility, but they had better dimensional stability. Significant differences in tensile, compression and surface properties existed between CHs fabrics in series A and those in B. The hosieries in series A produced more linear correlations between the key material indices and skin pressure magnitudes, which can be attributed to their fabrics having a smoother surface, greater elasticity, resilience and better dimensional stability. Moreover, proper surface properties of the material and hose design may enhance the pressure functional performance of compression hosiery products.

Key words: *mechanical property, surface property, skin pressure, compression hosiery, magnitudes.*

Introduction

Compression hosieries (CHs) are one type of medical textile products widely used in compression therapy, which has been demonstrated to be an effective non-operative option to relieve symptoms associated with venous disorders in lower human limbs, such as leg discomfort, heaviness, varicose veins, venous thrombosis, etc.[1 - 3]. By providing a controlled pressure gradient and support to the skin and underlying tissue from the ankle to the thigh (i.e. higher in the ankle then in the thigh), compression hosiery can help to reverse increased venous hypertension and augment calf muscle pump, thus improving the circulation and venous return in lower limbs [4, 5]. Panty-hose as well as knee-high and thigh-high stockings are three major forms. For the aforementioned medical functions, "pressure magnitude" and "gradient distribution" are two critical parameters for the pressure profiles of CHs, which largely depend upon the fabric's physical properties and structural design of hosiery. However, it should be noted that compression hosieries are normally designed to be smaller than the actual size of the wearer's leg; thus, they have to be stretched before application on the leg using high elastic fabric which would produce almost no space in the contact interface between the hosiery and skin. Material-related discomfort would induce or increase the patient's noncompliance with the treatment. Therefore, fundamental researches on the physical properties of various hosiery fabrics are necessary to improve the therapeutic benefits and wearing comfort sensation of medical compression hosiery products.

Textile research has shown that the mechanical behaviour, surface and dimensional properties of fabrics are the most important characteristics which ultimately determine their performance during tailoring as well as the quality of the final garment [6]. Under conditions of wear, the pressure functional performance of CHs are an integrated effect resulting from the multidimensional deformations of hosiery knitted fabrics, which are closely related to their multi-mechanical behaviour, such as stretching, shearing, bending, and compression. Characteristics of the fabric surface and knitted structures directly influence comfort perception when the fabric and skin are in contact.

In early related research, Johnson *et al* indicated that the tensile modulus of stocking fabric influenced the uniform distribution of pressure over the leg circumference [7]. By using girdle fabric, Ito *et al* found that the change in clothing pressure largely depends on the biaxial extension and stress relaxation properties [8]. However, most of the work was focused on clothing for daily-use. Little attention has been devoted to the study of medical textile products, such as compression stockings. Furthermore, there have been few comprehensive investigations into the material properties of various compression hosieries and their effects on the compression functional performance during wear.

Therefore, the objective of the present study was to systematically investigate and compare the material mechanical properties and surface characteristics of CH fabrics with different levels of pressure, and to quantitatively examine and evaluate the effects of the material properties of CH fabrics on corresponding skin pressure magnitudes in practical wear by combining a series of physical testing and pressure objective measurements of the materials. This study allowed us to explore the mechanisms of the action of compression hosieries and to provide a useful reference for designing and developing more efficient CHs as well as other medical textile products for compression therapy.

Experimental

Physical testing of the materials

"Pressure level" is recognised as a significant index in assessing pressure magnitudes, which mainly depends on the severity of the venous disease. and is categorised according to the pressure exerted on the ankle region of a human leg. In this study, two series (A & B) comprising eight kinds of pantyhose-like elastic compression hosieries were tested at diverse pressure levels (light, mild, moderate and strong). Basic descriptions are shown in ***Table 1***.

Table 1. *Basic characteristics and medical functions of the CH samples tested.*

Pressure level	Sample Code	Specified ankle pressure, mm Hg	Fiber content	Thickness mean ± s.d, mm	Weight mean ± s.d, g/m²	Medical functions
Light	A1	10-14	Polyamide 80% Elastomeric yarn 20%	0.41 ± 0.01	106.7 ± 21	for preventing
	B1	12-16	Polyamide 83% Elastomeric yarn 17%	0.28 ± 0.01	63.3 ± 15	
Mild	A2	18.4-21.2	Polyamide 64% Elastomeric yarn 36%	0.74 ± 0.02	246.7 ± 21	for curing
	B2	18-25	Polyamide 75% Elastomeric yarn 25%	0.36 ± 0.01	89.0 ± 18	
Moderate	A3	25.1-32.1	Polyamide 73% Elastomeric yarn 27%	0.75 ± 0.03	250.16 ± 15	
	B3	20-30	Polyamide 74% Elastomeric yarn 18% Gomma 8%	0.97 ± 0.04	251.3 ± 23	
Strong	A4	36.4-46.5	Polyamide 73% Elastomeric yarn 27%	1.18 ± 0.02	376.3 ± 16	
	B4	30-40	Polyamide 50% Elastomeric yarn 15% Gomma 35%	1.45 ± 0.04	435.7 ± 39	

The material properties to be tested were divided into three groups: mechanical properties, surface characteristics and basic structural features. The tensile, bending, shearing and compression properties of the stocking fabrics together with the surface roughness and friction were investigated using the Kawabata KES-FB standard evaluation system (Kato-Tec Co., LTD, Japan) under standard testing conditions - temperature: 21 ± 1 °C and relatively humidity: 65 ± 2% (according to Standard ASTM D1776-04). The physical properties involved in the KES test and their corresponding instrument settings, as well as the measure mechanisms of the main mechanical properties are shown in ***Table 2***.

To objectively analyse the material properties of CH fabrics and their effects on real skin pressure magnitudes, three swatches of a standard size of 20 cm × 20 cm were directly obtained from three different segments of each pantyhose, which were named 'ankle', 'knee', and 'thigh', respectively. Due to differences in hose length between the two series, the division of the three segments was different. From ***Figure 1.a***, it can be seen that the average lengths of series A hoses were around 40 cm, therefore the three segmental swatches were obtained from the right and left hoses of the same pair of hosiery. The hose lengths of series B were about 60 cm, which were directly separated into three parts (as ***Figure 1.b***). These differences in hosiery shape, to some extent, reflect one of the structural traits in the current design of compression hosiery products.

In order to minimise the shape instability of knitted fabric, all the test swatches were placed on a flat surface in a controlled environment for 24 hours to reach equilibrium prior to the formal measurements. For biaxial deformations or bidirectional tests, such as the tension, bending, shearing and surface, each sample was measured three times in each direction (i.e. wale and course), while for the compression property, each fabric sample was tested in five different positions. In this study, mean values of the test swatches in the wale and course directions were used to evaluate and compare the material properties and characteristics of different compression hosiery fabrics and their effects on skin pressure magnitudes.

Objective measurement of skin pressure

To analyse the impacts of material properties on their corresponding pressure

Table 2. *Outline of physical indices involved in the testing of material properties.*

Properties	Test Nature	Indices	Symbol	Unit	Instrument settings
Mechanical	Tensile	Tensile energy	WT	mN·cm/cm^2	KES-FB1 Velocity: 0.2 mm/s Elongation: 50 mm/10v Processing rate: 2.5 s, 0.5 s (only for GCS_A4 & B4) Maximum load: 490 mN/cm
		Linearity	LT	--	
		Tensile resilience	RT	%	
		Tensile strain	EM	%	
	Bending	Bending rigidity	B	mN·cm^2/cm	KES-FB2 Rate of bending: 2.5/cm K= 0.5 to 1.5 cm^{-1} K=1.0 cm^{-1}
		Hysteresis of bending moment	2HB	mN·cm/cm	
	Shearing	Shear stiffness	G	mN/cm·degree	KES-FB1 Shear tension: 98 mN/cm Maximum shear angle: + 8.0 to -8.0 2HG = 0.5, 2HG5 = 5.0, G = 0.5 to 2.5
		Hysteresis at φ= 0.5°	2HG	mN/cm	
		Hysteresis at 0 = 5.0°	2HG5	mN/cm	
	Compression	Linearity	LC	--	KES-FB3 Velocity: 50 s/mm Compression area: 2 cm^2 Processing rate: 0.1 s Maximum load: 50 g/m^2
		Compressional energy	WC	mN·cm/cm^2	
		Resilience	RC	%	
Surface	Surface	Coefficient of friction	MIU	--	KES-FB4 Velocity: 1.0 mm/s Roughness contactor comp: 98 mN
		Mean deviation of MIU	MMD	--	
		Geometrical roughness	SMD	μm	
Construction	Weight	Weight	W	mg/cm^2	Weight per unit area
	Thickness	Thickness	T	mm	Thickness at 4.9 mN/cm^2

magnitudes, objective measurements of skin pressure were conducted in vivo within a climate chamber (temperature: 23 ± 0.5 ºC; relative humidity: 65 ± 3%). Six healthy females of 25 - 39 yrs were recruited for testing. ***Table 3*** shows anthropometric parameters of the subjects studied.

Each of them was instructed to wear all the hosiery samples of suitable size in a standing posture.

Since there was no machine available that would be able to measure pressure over the entire surface of the leg [9], skin pressures at sixteen typical locations distributed over four height levels (ankle, calf, knee, and thigh) and in four directions (anterior, posterior, medial, and lateral) were examined using FlexiForce ™ interface pressure sensors (Tekscan, Inc., U.S.A) and a multichannel pressure measuring system. To achieve accurate and reliable pressure measurement, all pressure sensors used in the objective testing were strictly calibrated prior to the test. The pressure sensor has a circular probe of 9.525 mm diameter and 0.127 mm thickness. The pressure signals produced by compression stockings were recorded at a sampling frequency of 10 Hz. During calibration, by using weights of different levels of weight, external pressures were divided into seven levels: 0, 5, 15, 25, 35, 45, and 55 g over an area of 71.1 mm^2 (i.e. circular probe of the sensor), which is then transformed into the pressure unit Pa (= 1 N/m^2). The external load produced a series of corresponding voltage signals, which were monitored and recorded automatically using a computer. The calibration results show that linear relationships exist between the pressures and voltages. Their correlation coefficients were all greater than 0.98, signifying that all the pressure sensors used are reliable and accurate in pressure measurement. More detailed information about this pressure testing can be found in our correlative report [10,11]. The experimental procedures have been approved by the Human Ethics Committee of the University.

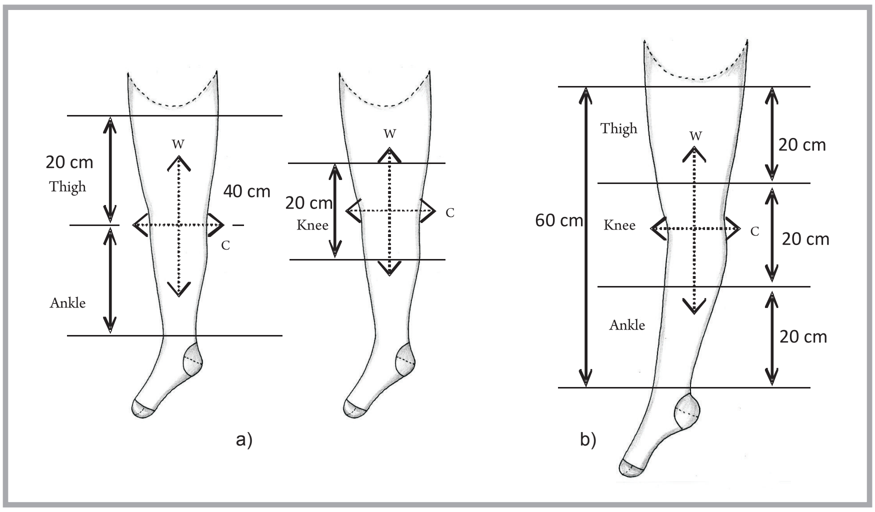


Figure 1. *Schematic diagram of test fabric samples taken from the hosieries; W - wale direction, C - course direction, a) series A hosiery samples, b) series A hosiery samples.*

Table 3. *Basic anthropometric characteristics of subjects; * Body Mass Index.*

Items	Height, cm	Weight, kg	BMI*, kg/m²	Minimum ankle girth, cm	Maximum calf girth, cm	Knee girth, cm	Mid-thigh girt, cm	Groin high, cm
Mean	159.67	52.58	20.48	26.08	32.12	39.05	52.75	70.3
S.D	4.70	5.04	1.90	2.67	2.29	3.37	5.30	4.3

Results and discussion

General analysis of the material properties of CH(s) at different pressure levels

Comparisons of the fabric mechanical and surface properties of eight kinds of CHs with four different pressure levels are displayed in the form of a chart in ***Figure 2***. In order to plot all the test indices on the same scale for comparison, the results measured have been normalised using the relationship $x = (X - \overline{X})/\sigma$, in which x = normalised value, X = measured value of a typical index, $\overline{X}$ = mean value of all test CH fabrics for one typical index, σ = standard deviation of all test CH fabrics for one typical index. The "zero" axes indicate the mean values of all the CH fabrics for corresponding physical properties of the materials tested.

From ***Figure 2*** it can be seen that some inerratic changing tendencies in the material properties occurred among the CHs at different specified pressure levels. For tensile properties, the CH fabrics with higher pressure levels had higher values of LT, and lower values of WT, EM and RT, meaning that at higher pressure levels, CHs have less extensibility but better behaviour with respect to tension linearity. As for bending, shearing and surface properties, higher values of bending rigidity (B) and shear stiffness (G) occurred in the CH fabrics with higher pressure levels, meaning that these fabrics possess a higher resistance to shearing and bending deformation than those with lower ones. Moreover, their fabric surfaces were more accidented and rougher (i.e. higher values for MIU, MMD and SMD). Meanwhile, during the elevation of pressure levels, the CH fabrics became thicker and heavier. The values of compressional energy (WC) and resilience (RC) were also greatly increased. These testing results implied that CH fabrics with lower pressure levels would have a softer handle and are easier to compress, while those with higher pressure levels would have a better compressional recovery and dimensional stability.

Using one way-ANOVA analysis, differences in the mean values of each index of the material properties among CHs with four pressure levels were quantified and summarised in ***Table 4*** (see page 95). It can be seen that, except for the surface properties, significant differences ($P < 0.05$) occurred in the structure characteristics (e.g. value of thickness $P = 0.022$, value of weight $P = 0.026$) and most of the indices of mechanical properties (***Table 4***). For instance, significant differences dominate in the bending and shearing properties ($P < 0.01$) (e.g. value of bending rigidity $P = 0.006$, value of shear stiffness $P = 0.009$). Significant differences in the tensile properties also existed among CH fabrics with different pressure levels, especially for the tensile linearity (LT) ($P = 0.001$), whereas for compression properties, significant differences ap-

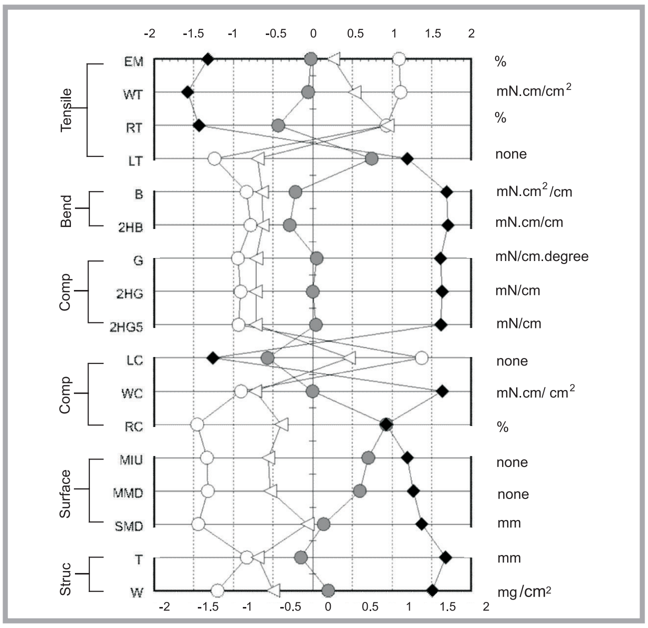


Figure 2. Material properties of CH fabrics with different pressure levels; a - the corresponding practical unit, ○ - light pressure (A1 & B1), Δ - mild pressure (A2 & B2), ● - moderate pressure (A3 & B3), ♦ - strong pressure (A4 & B4).

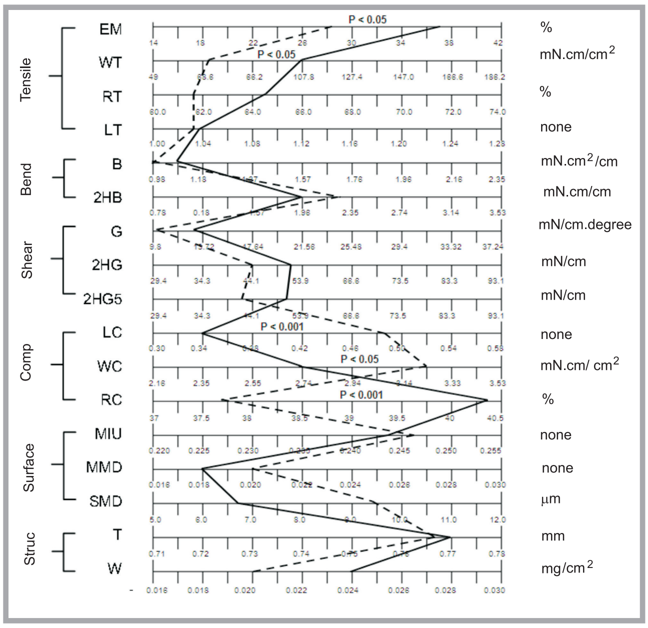
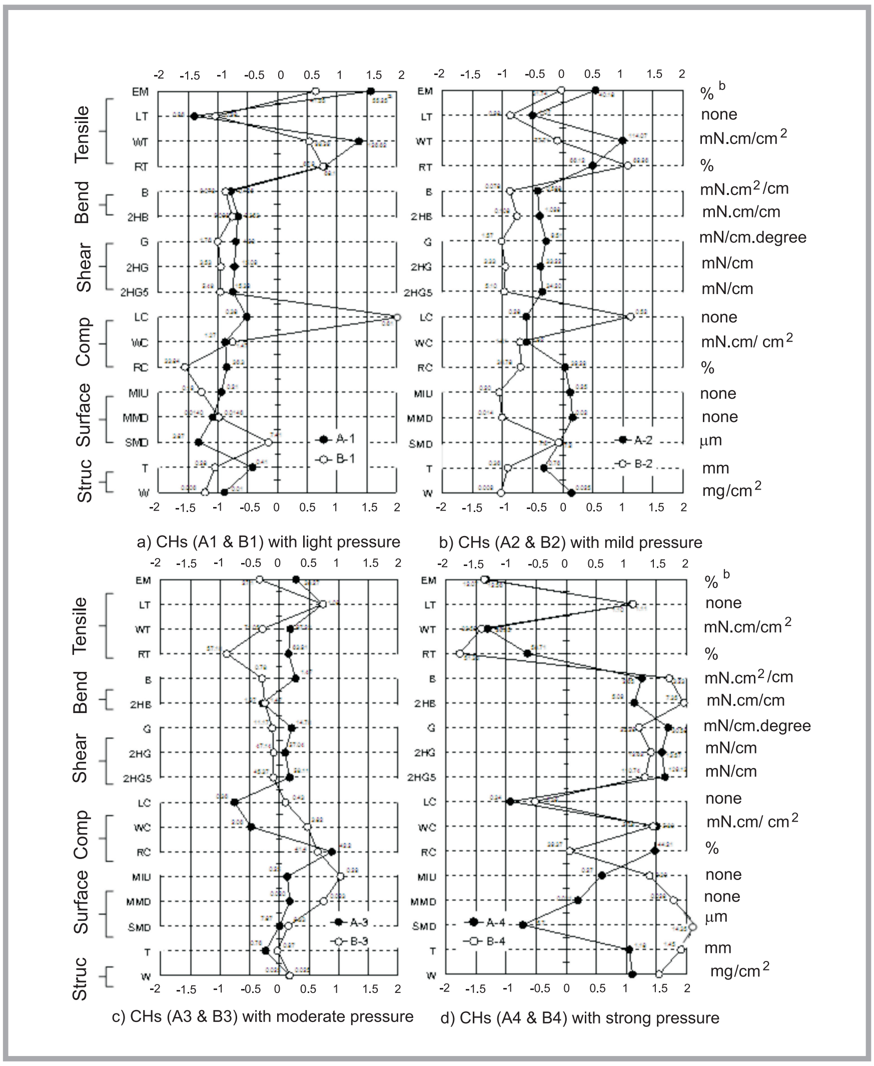


Figure 4. Comparison of the fabric properties of the two series of CHs.; —— : the measured mean values of Series A; – – – – : the measured mean values of Series B.



a) CHs (A1 & B1) with light pressure
b) CHs (A2 & B2) with mild pressure
c) CHs (A3 & B3) with moderate pressure
d) CHs (A4 & B4) with strong pressure

Figure 3. Comparisons of mechanical and surface properties for different CHs; a - the mean value in fabric wale and course directions, b - the corresponding practical unit.

peared in the compression energy (WC) indices (P = 0.008 < 0.01).

Comparative analysis of material properties of the two series of CHs

Utilising the same normalisation methods, ***Figure 3.a - 3.d***) shows comparisons of the results of material properties for CHs within the two series (A & B). It can be seen that a similar changing tendency appeared in the material properties of the two series of compression stockings: from chart (a) to chart (d); except for the tensile properties, the "snake" lines gradually moved from the negative (left) side to the positive (right) side of the "zero" axis. That is, an increase in the pressure levels of CHs results in an incremental trend in most of the test indices of material properties, which agrees with the results analysed earlier (see ***Figure 2***). However, some differences in material properties were found between the two series of hosieries despite having the same specified pressure levels.

At light and mild pressure levels (***Figure 3.a*** & ***3.b***), hosieries A1 and A2 had higher values of tensile strain (EM), tensile energy (WT) and compressional resilience (RC). Their bending values (B, 2HB) and sharing properties (G, 2HG, 2HG5) were also greater than those of the hosieries in series B, while hosieries B1 and B2 had significantly higher values of LC and lower values of T and W. These results indicate that hosieries B1 and B2 were thinner and lighter but had less extensibility than the hosieries in series A, while hosieries A1 and A2 were easier to stretch but had a better performance with respect to dimensional stability.

In chart (c), it can be seen that most of the values of the test indices were located near the "zero" axis. That is, their properties were closer to the average. Compared with B3, hosiery A3 has higher values of EM, WT, RT, RC, B and shearing properties, and lower values of LC, WC, T and surface properties, which means that hosiery A3 was easier to stretch, compress and had better resilience. Furthermore, it also had greater resistance to shearing and bending deformation than hosiery B3.

From the fourth chart (***Figure 3.d***), it can be seen that hosieries A4 and B4 had very close values of EM, LT, WT, LC and WC, meaning that they had a similar stretch and compressibility, but hosiery A4 had a relatively better tensile and compressive recovery (higher values of RT and RC); however, the most significant differences between them appeared in their fabric surface properties. Hosiery A4 was slicker, smoother and had greater shearing stiffness (G). Hosiery B4 was thicker, heavier and had higher bending rigidity (B). From the analysis above, it was considered that differences in material properties may exist between the two series of hosieries at the same level of compression.

Using ANOVA analysis and the intuitionistic "snake line" (***Figure 4***), the general differences between series A and B hosieries for all the indices of material properties tested were further quantified and summarised. Overall, significant differences ($P < 0.05$) in material properties between the two series of hosieries existed in the following testing indices: LC, RC, WC, WT. EM and SMD, which relate to compression, tensile and surface properties of the materials, respectively.

Under tensile, bending and shearing deformation, series A hosieries have better elasticity and dimensional (or shape) stability than those in series B (due to higher values of WT, RT, LT, B & G, and lower values of 2HB) (***Figure 4***). The hosiery fabrics of series A were fluffier, softer, and were easier to compress and recover under compression forces (e.g. lower values of LC and WC, and higher values of RC), which, to a great extent, was related to their thicker and heavier fabric structures, while the fabrics of hosieries in series B appeared to possess a stiffer and rougher handle (see ***Figure 4***).

Table 4. *Summary of the analysis of variances of material properties among the CHs with different pressure levels.*

Properties	Indices	Pressure Levels				P (Sig.)
		Light	Mild	Moderate	Strong	
Tensile	EM, %	48.40	35.96	32.69	12.31	0.023
	WT, mN.cm/cm^2	112.60	95.94	78.99	35.18	0.041
	RT, %	67.97	68.04	60.51	55.03	0.064
	LT, --	0.97	1.18	1.22	1.10	0.001
Bending	B, mN·cm^2/cm	0.10	0.39	1.18	2.94	0.006
	2HB, mN·cm/cm	0.20	0.59	1.37	6.17	0.006
Shearing	G, mN/cm·degree	3.43	5.59	12.94	27.93	0.009
	2HG, mN/cm	9.31	18.33	51.94	128.38	0.002
	2HG5, mN/cm	10.49	19.70	50.96	118.48	0.004
Compression	LC, --	0.49	0.40	0.40	0.36	0.741
	WC, mN·cm/cm^2	1.37	1.76	2.94	5.88	0.008
	RC, %	35.05	38.04	41.79	41.79	0.105
Surface	MIU, --	0.20	0.23	0.27	0.29	0.077
	MMD, --	0.01	0.02	0.02	0.02	0.157
	SMD, μm	5.64	7.68	8.10	10.02	0.362
Structure	T, mm	0.35	0.56	0.87	1.32	0.022
	W, mg/cm^2	0.01	0.02	0.03	0.04	0.026

Table 5. *Effects of different CH(s) on skin pressure magnitudes; a - R squared = .083 (Adjusted R Squared = .075), b) CH(s) with different pressure levels, c) CH(s) in two different series (A & B).*

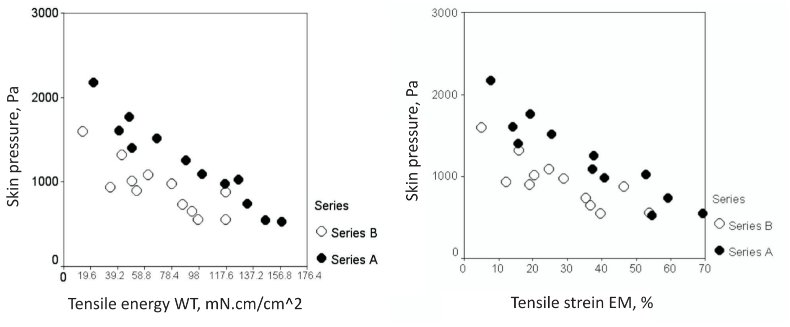
Source	Dependent variable: skin pressure (Pa)				
	Type III Sum Of Squares	df	Mean Square	F	Sig.
Corrected Model	45491944.472[a]	7	6498849.210	9.879	0.000
Intercept	800094088.299	1	800094088.30	1216.232	0.000
Levels [b]	26045427.804	3	8681809.268	13.197	0.000
Series [c]	10923722.269	1	1923722.269	16.605	0.000
Levels ·Series	8522794.398	3	2840931.466	4.319	0.005
Error	499963466.585	760	657846.667		
Total	1345549499.4	768			
Corrected Total	545455411.057	767			

Impacts of mechanical-surface properties on the skin pressure magnitude performance

Through objective measurement of skin pressure, we obtained skin pressure values, respectively, by applying eight different kinds of medical elastic compression hosieries. It was found that with an increase in the pressure levels of CHs, the skin pressures applied gradually increased. The average skin pressure proportions of light/mild/moderate/strong levels were 100:108:136:157. A detailed analysis of this is reported in our correlative paper [13]. Using the generalised linear model univariate analysis of variance, a quantitative analysis of the effects of pressure levels and series of CHs on skin pressure magnitudes was carried out (***Table 5***). It can be seen that significant differences in the skin pressure magnitudes existed among CHs at four different pressure levels ($P < 0.001$), and skin pressure magnitudes of the two series of hosieries also presented significant differences ($P < 0.001$). However, the levels and series interacted with each other significantly, i.e. significant differences in skin pressure levels existed among CHs within the same series ($P < 0.01$), and significant differences in skin pressure also occurred between the two series of

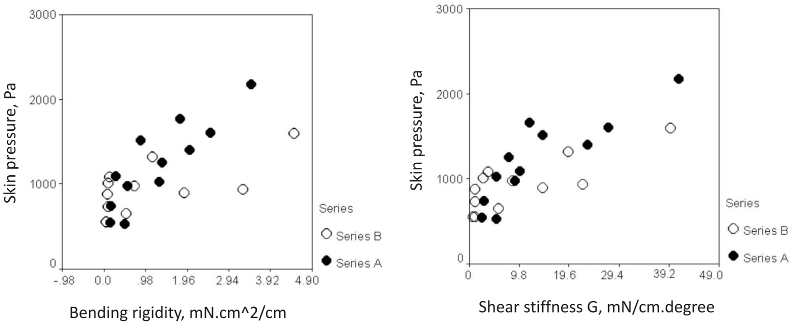
***Table 6**. Summary of material properties significantly correlated with skin pressure magnitudes; a. **.Correlation is significant at the .01 level (2-tailed); *. Correlation is significant at the .05 level (2-tailed).*

Properties/ Indices		Skin pressure (Pa)		
		Correlation Coefficient ^{a}	Sig. (2-tailed)	Asterisk^{a}
Tensile	EM	-0.660	0.000	**
	WT	-0.702	0.000	**
	LT	0.516	0.010	**
Bending	B	0.535	0.007	**
	2HB	0.527	0.008	**
Shearing	G	0.667	0.000	**
	2HG	0.615	0.001	**
	2HG5	0.643	0.001	**
Compression	LC	-0.476	0.019	**
Structure	W	0.496	0.014	*



(a) Correlation between WT and skin pressure

(b) Correlation between EM and skin pressure



(c) Correlation between B and skin pressure

(d) Correlation between G and skin pressure

***Figure 5.** Scatter plots of correlations between the key indices and skin pressure magnitudes.*

CH with the same specified pressure levels (P < 0.01). This result demonstrated that the material properties of compression hosiery fabrics did indeed have an extremely significant influence on their skin pressure performance.

By conducting correlation analysis with a two-tailed test of significance, the indices of material properties significantly correlated with the skin pressure magnitudes were quantified and are summarised in ***Table 6***. It can be seen that most of the indices of the mechanical properties of CH fabrics have significant correlations with skin pressure magnitudes, especially for tensile and shearing properties. The tensile energy (WT), with the highest correlation coefficient, and tensile strain (EM) have strong significant negative correlations with skin pressure magnitudes, meaning that CH fabrics with less tensibility under tensile forces would exert greater skin pressure. Shear stiffness (G) and bending rigidity (B) have a significant positive relationship with skin pressure magnitudes, indicating that fabrics with higher resistance to shearing and bending deformation would perform stronger pressure functions.

Figure 5.a & ***5.b*** shows that with the increase in WT and EM values, the skin pressure exerted by the two series of hosieries decreased correspondingly. The skin pressure readings for series A are generally higher than those for series B. The values for series A show a linear relationship between the skin pressure and tensile indices (i.e. WT and EM). From ***Figure 5.c*** & ***5.d***, we can observe that with a rise in the values of B and G, the skin pressure applied by the two series of hosieries increased. Compared with series B, the hosieries in series A produced a more pronounced, positive increase, as well as greater skin pressure values at moderate and high pressure levels.

The results above indicate that the CHs in series A would exert higher pressure during wear. These differences in pressure function between the two series were largely related to their differences in material properties, as shown in ***Figure 4***. However, some other possible influential factors should also be taken into account. The laboratory physical testing of the materials undertaken may not have simulated the practical wearing situation exactly. In ***Figure 1***, we have shown that some differences in hosiery shape existed between series A and B. The hose lengths of the CHs in series A were about 40 cm, which were shorter than those of series B by 20 cm on average. In the objective testing of the pressure, the average distance of the subjects from the anklebone to the groin was measured to be about 60 cm. That is, the original hose lengths of hosieries in series A were elongated in the longitudinal direction by approximately 50 % on average when worn, while very little elongation occurred in the hose length of CHs in series B. Hence, larger elongation in the wale direction occurred when CH was worn, and the superior elasticity of the fabrics of series A would be likely to enhance their general pressure function, thus producing more satisfactory pressure levels than those of series B.

In addition, the surface properties of the materials, especially geometric roughness (SMD) and the frictional coefficient (MIU), would also influence skin pressure magnitudes, although the statistical analysis results showed no statistically significant differences in the surface characteristics of CHs with different pressure levels (see ***Table 4***). In the pressure testing, the pressure sensor employed was a circular probe of 9.525 mm diameter and 0.127 mm thickness. A rough fabric surface would not completely and equably have contact with the probe surface, thus decreasing the measured interface pressure magnitudes between the skin and hosiery. From the materials testing and analysis results, we found that significant differences in SMD values existed between hosieries in series A and B ($P < 0.001$), and almost all values of SMD and MIU of series B hosieries were greater than those of series A, especially for CHs with high pressure levels (i.e. B4). This could also be one possible reason for the higher skin pressure of the CHs in series A.

Conclusion

The present study comprehensively evaluated the mechanical properties and surface characteristics of different compression hosieries which are popularly applied in the prevention and treatment of venous disorders of lower extremities in daily life and clinics. Quantitative analysis was conducted to study the effects of the material properties of CHs fabrics on their corresponding skin pressure performance in wear. It was found that significant differences in material properties existed for CH fabrics with different pressure levels. Tensile energy (WT), tensile strain (EM), shearing stiffness (G) and bending rigidity (B) are the key mechanical material indices significantly correlative to skin pressure magnitudes. The CH fabrics with higher pressure levels were rougher, stiffer, and less extensible, but they had better dimensional stability. Significant differences in tensile, compression and surface properties existed between the CH fabrics within series A and series B, although they experienced the same pressure levels. Linear relationships between the material mechanical indices tested and skin pressure magnitudes existed in the compression hosiery fabrics in series A, which can be attributed to their fabrics having smoother surfaces, better elasticity and dimensional stability. Through further analysis of the hose shape design and surface property, it is suggested that the less geometric roughness of the material surface and proper hose shape design may enhance the pressure performance of compression hosiery products in practical wear.

Acknowledgment

The author would like to thank the Research Grant Council (RGC) via project PolyU 5157/02 for supporting this research,

Reference

1. *Jones N. A. G., Webb P. J., Rees R. I., Kakkar V. V.; A physiological study of elastic compression stockings in venous disorders of the leg. British Journal of Surgery, 1980, 67; pp. 569-572.*
2. *A Abu-Own J. H. Scurr P. D. Smith C.; Effect of compression stockings on the skin microcirculation in chronic venous insufficiency. Phlebology, 1995, 10; pp. 5-10.*
3. *Weiss R. A., Duffy D.; Clinical benefits of lightweight compression: reduction of venous-related symptoms by ready-to-wear lightweight gradient compression hosiery”. Dermatol Surg, 1999, 25: pp. 701-704.*
4. *Ibegbuna V., Delis K.T., Nicolaides A. N., Aina O.; Effect of elastic compression stockings on venous hemodynamics during walking. Journal of Vascular Surgery, 2003, 37(2): pp. 420-425.*
5. *Kraemer W.J., Volek J.S., Bush J. A., Gotshalk L. A., Wagner P. R., Gómez A. L., Zatsiorsky V. M., Duarte M., Ratamess N. A., Mazzetti S. A., Selle B. J.; Influence of compression hosiery on physiological responses to standing fatigue in women”. Medicine & Science in Sports & Exercise,2000, 32(11); pp. 1849-1858.*
6. *Stylios G.; Textile objective measurement and automation in garment manufacture. Ellis horwood limited (1991).*
7. *Johnson G., Kupper C., Farrar D. J., Swallow R.T.; Gradded compression stockings: custom vs noncustom. Arch Surg, 1982, 117(1); pp. 69-72.*
8. *Ito N., Inoue M., Nakanishi M., Niwa M.; The relation among the biaxial extension properties of girdle cloths and wearing comfort and clothing pressure of girdles. Jpn. Res.Assn.Text.End-Uses, 1995, 36; pp. 102-108.*
9. *Finnie A.; Interface pressure measurements in leg ulcer management. British journal of Nursing, 2000, 9(6), p. 8.*
10. *Liu, R., Kwok, Y. L., Li, Y., Lao, T. T., Zhang, X., Dai, X. Q.; (2005). Objective Evaluation of Skin Pressure Distribution of Graduated Elastic Compression Stockings. Dermatologic Surgery (American Society for Dermatologic Surgery), 31 (6), pp. 615-624.*
11. *Liu, R., Kwok, Y. L., Li, Y., Lao, T. T., Zhang, X.; (2006). The effects of graduated compression stockings (GCSs) on cutaneous surface pressure along the path of main superficial veins of lower limb. Wounds - A Compendium of Clinical Research and Practice, 18 (6), pp. 150-157.*

Received 21.08.2007 Reviewed 08.07.2009