Quantitative Assessment of Relationship between Pressure Performances and Material Mechanical Properties of Medical Graduated Compression Stockings

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ABSTRACT: Graduated compression stockings (GCSs) have been widely applied for prophylaxis and treatment of venous disorders. Their pressure performances and medical functions depend largely upon the mechanical properties of stocking knitted fabrics. In the present study, the multiple fabric mechanical behaviors of GCSs with different pressure levels and medical functions were examined by using Kawabata standard evaluation system. On the basis of pressure ranges advised by the European Committee for Standardization, the definitive quantitative relationships between pressure performances and key mechanical properties of GCS fabrics were developed and evaluated. The results show that GCS fabrics with different pressure performances produced significant differences in tensile, shearing, and bending properties ($P < 0.001$). GCS fabrics generating lighter pressure possessed higher values in tensile strain, tensile energy at a given force, and lower values in shearing stiffness and bending rigidity, while stronger pressure levels are produced by the GCS fabrics with higher resistance to the mechanical deformations. Pressure magnitude performances of GCSs are an integrative action performed by multiple fabric mechanical properties. The developed relationships between pressure levels and material mechanical properties provide a rational and practical approach for assessing and predicting pressure functional performances of GCSs. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 104: 601–610, 2007

Key words: quantitative assessment; compression stockings; compression performances; mechanical properties; relationships

INTRODUCTION

The potential impact of compression therapy on venous diseases has been demonstrated in numerous studies over the world during the last decade.[1] Graduated compression stockings (GCSs), as one of the essential potent compression therapeutic modalities, have been widely used for the prophylaxis and treatment of varicose veins, swelling, deep vein thrombosis, venous ulcer, lymphedema, etc., by providing controlled and ambulatory pressure on the lower extremity.[2–8]

Appropriate degree of external compression applied by GCSs is the crucial condition to achieve their satisfactory medical effectiveness. ''Pressure level'' has been recognized as a significant index in describing and assessing the pressure magnitudes performances, which is categorized according to the pressure exerted at the ankle region of human leg (i.e., the so-called B pressure).[9] Currently, there is little international agreement on the optimal level of compression.[10,11] Nevertheless, there is a general consensus that the medical functional performances of pressure levels depend largely upon the material properties of the knitted fabrics that the GCSs possess. Substantial clinical experiments have demonstrated that the physical presence of GCSs with different fabric elasticities produce different pressure profiles, which resulted in a variety of significant complex physical and physiological effects on vascular anatomic structures (e.g., diameter, cross-sectional area[12,13]) and venous hemodynamics (e.g., capillary filtration rate,[12] blood flow velocity[4,14]). Therefore, it is warranted to examine further scientifically the effects of material properties of GCSs on their corresponding pressure performances (especially pressure magnitudes), which may help us to elucidate the mechanisms of action behind compression effect so as to maximize the potential medical application of different pressure levels of GCSs.

In most of the existing materials studies relating to GCSs, the emphasis was placed on how the elasticity property (or stretch ability) of stocking fabric affects the pressure magnitudes or the efficacy of compression treatment. For instance, in earlier studies, by using Laplace's law and measuring the tension created by stretch, circular-knitted stockings designed with low-modulus yarn

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TABLE I
Basic Characteristics of Used Compression Stockings Samples

Pressure level	Specified ankle pressure (mmHg)[a]	Fibre content (%)			Thickness (mm)	Weight (g/m^2)	Suggested medical functions
		P	E	G[b]			
Light							
A1	10–14	80	20		0.41 ± 0.01	106.7 ± 21	Prevent varicose veins/thrombosis,
B1	12–16	83	17		0.28 ± 0.01	63.3 ± 15	relieve heaviness and fatigue
Mild							
A2	18.4–21.2	64	36		0.74 ± 0.02	246.7 ± 21	For curing mild varicosities, aching,
B2	18–25	75	25		0.36 ± 0.01	89.0 ± 18	swelling, initial varices during pregnancy
Moderate							
A3	25.1–32.1	73	27		0.75 ± 0.03	250.2 ± 15	For curing moderate varicose veins,
B3	20–30	74	18	8	0.97 ± 0.04	251.3 ± 23	edema, mild/moderate CVI
Strong							
A4	36.4–46.5	73	27		1.18 ± 0.02	376.3 ± 16	For curing serious varicose veins,
B4	30–40	50	15	35	1.45 ± 0.04	435.7 ± 39	severe edema/CVI, leg ulcer, lymphedema

Thickness and weight are given as mean ± SD. CVI, chronic venous insufficiency.
[a] mmHg = 133.322 Pa (Pa is the international system of units, [SI] unit for Pressure in N/m^2).
[b] P, polyamide; E, elastomeric yarn; G, gamma.

were found to deliver a more uniform skin pressure over a greater range of leg circumference than did high-modulus stockings.[15] The round-knitted GCSs with rubber components were shown to possess the best pressure performance in the prevention of edema symptom.[16] Horner et al. reported that the elastic tensile strength remarkably influenced the compressive effect of grading elastic stockings.[17] In recent studies, the elasticity of GCS materials was more popularly described and evaluated by using the concept of ''stiffness index.''[9,18,19] Stolk et al.[19] and Partsch[9] successively reported the testing methods for measuring dynamic and static stiffness indices. The aforementioned studies are all valuable attempts to assess the effects of elastic property of stocking materials on pressure function.

However, many studies in scientific textile research have shown that the quality of the end-use clothing products, and their functional performances during wearing, are ultimately determined by the mechanical behavior of fabrics.[20] During wear, pressure magnitude (or performance) produced by GCS is an integrated effect resulted from the multidimensional deformations of stocking knitted fabrics, which are closely related to their multimechanical properties, such as tensile, shearing, bending, compression, etc., rather than elasticity alone, although elasticity undoubtedly is of importance.

To date, few studies that investigate quantitatively the effects of material mechanical properties of GCSs knitted fabrics on their pressure performances have appeared. Moreover, the specific relationships between pressure levels and mechanical behavior of GCS fabrics have not been established.

Therefore, the present study is conducted to investigate comprehensively the effects of multiple mechanical properties of fabrics on the pressure magnitudes of GCSs, and to quantify the pressure ranges generated by the specific GCS fabrics. We also aim to establish the definite relationships between material mechanical properties and their corresponding compression level performances on the basis of the specification of pressure levels in terms of European Committee for Standardization. It is envisaged that our study could provide researchers, engineering designers, and manufacturers a useful reference in predicting and assessing pressure profiles of compression stockings, and which may even be helpful for other compression medical textile products.

MATERIALS AND METHODS

Compression stockings and basic characteristics

Two series (A and B) of eight different kinds of elastic compression stockings with diverse pressure levels, and manufactured in Germany and Italy, were tested and estimated in this study. Their compression was certified by ISO 9002 quality system according to the declaration of the manufacturers. Combining our elementary fabric structures testing,[21] the basic characteristics of tested GCSs samples are shown in Table I.

In Table I, the pressure that GCSs exert at the ankle level was measured and specified in millimeters of mercury (mmHg) by manufacturers, which is typically reported as a range owing to the small variations in pressure readings. To maintain consistency with our previous studies, the international unit for pressure ''Pa'' is employed in the quantitative analysis in this study.

From Table I, it is clear that the pressure level required is dependent on the severity of symptom, and the variation of compression ranges is related to the fabric physical structures (i.e., weight, thickness) and yarn components.

Assessed material mechanical properties

Systematic measurements and analysis in our correlative studies[21,22] have shown that, among numerous me-

TABLE II
Assessed Material Mechanical Properties of GCS Fabrics

Fundamental stress state	Properties	Symbol	Unit	Description[23–25]
Tensile	Tensile strain	EM	%	Extensibility or stretch, the percent of strain when a tensile load is applied. Higher values indicate that fabric is more stretchy
	Tensile energy	WT	gf cm/cm^2	The work done by the extension up to maximum force
	Tensile resilience	RT	%	A measure as the ratio of recovered energy per unit area to the energy of extending the fabric in the load-extension curve; or, the ability of a fabric to recover from stretch after the application of tensile stress. Higher RT value implies that the fabric has better ability to recover its original shape after the applied tensile stress is released
Shearing	Shear stiffness	G	gf/cm.degree	Fabric stiffness under a constant shear extension. Or the ease with which the fibres slide against each other resulting in soft/pliable to stiff/rigid structures. Lower values indicate less resistance to the shearing deformation
Bending	Bending rigidity	B	gf cm^2/cm	Stiffness per unit fabric width under bending deformation. Higher value indicates greater stiffness/resistance to bending motions

chanical properties, fabric tensile, shearing, and bending properties play more prominent roles in influencing the skin pressure functional performances of GCSs. In that, tensile energy (WT), tensile strain (EM), tensile resilience (RT), shearing stiffness (G), and bending rigidity (B) are the key mechanical properties significantly correlative to the skin pressure magnitudes (levels). Accordingly, these five mechanical properties related to three fundamental stress states (tensile, shearing, and bending) became the primary parameters used for assessing mechanical behaviors of GCS fabrics in this study. Table II lists the assessed mechanical properties and their corresponding scientific descriptions.

Measuring device and setting

The Kawabata Standard Evaluation System (KES-FB) (Kato-Tec Co., Japan) was used to examine objectively and assess the mechanical properties of GCS fabrics under standard measuring condition. The excellent repeatability, high accuracy, and sensitivity of this system have been validated by substantive textile surveys.[20] Table III illustrates the instruments and their settings used in testing.

Testing procedure

The whole process of the assessment testing was conducted in a laboratory with strictly controlled environmental temperature (T) at 21°C ± 1°C and relatively humidity (RH) of (65 ± 2)% (according to American Society for Testing and Materials D 1776 – 04). The fabric samples (swatches) with standard size of 20 cm × 20 cm were obtained directly from the tested GCSs hoses. Since ''pressure level'' is commonly classified in terms of skin pressure at ankle region, the mechanical properties of the lower leg segment of stocking hose, especially the ankle segment, were performed as the principal assessment.

Prior to testing, all fabric samples were conditioned in the above-mentioned standard laboratory for 24 h to minimize the instability of knitted fabric and to reach equilibrium with the standard T and RH values. In the formal assessment, unidirectional tests were performed to examine the fabric tensile, shearing, and bending properties in course direction and wale direction, respectively. Each test was repeated thrice for each direction. The means of the values along the two directions were adopted to express certain characteristics (i.e., EM, WT, RT, B, and G) of stocking knitted fabrics.

Assessment methods

Taking fabric property EM as the example, the specified pressure levels (including mean ankle pressure) of dif-

TABLE III
KES-FB Devices and Instrumental Settings for GCS Fabric Testing

Stress state	Devices	Instrument settings
Tensile	KES-FB-1	Extension velocity: 0.2 mm/s Processing rate: 2.5 s Maximum load: 50 gf/cm
Shearing		Rate of shearing: 0.417 mm/s Shear tension: 10 gf/cm Maximum shear angle: ±8.0
Bending	KES-FB-2	Rate of bending: 0.5 cm^{-1}/s Maximum curvature: ±2.5 cm^{-1}

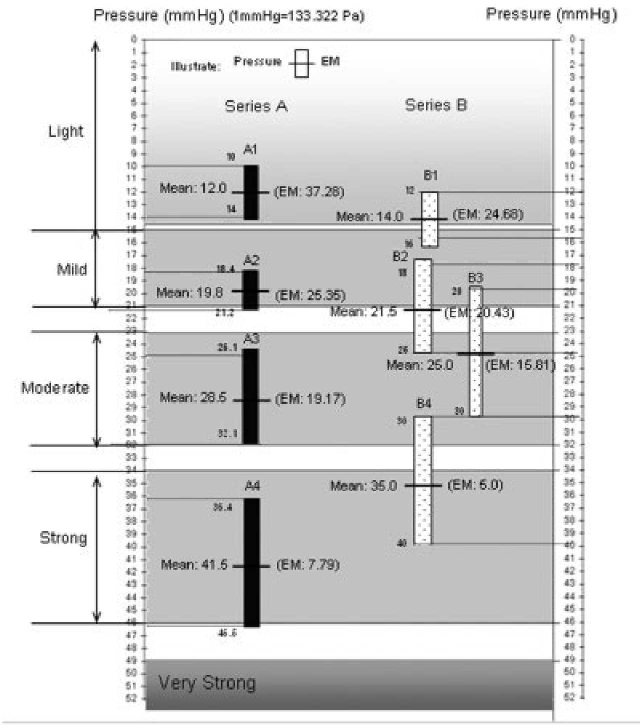

Figure 1 A schematic plot on quantitative assessment method of pressure levels and mechanical properties of GCSs.

ferent tested GCSs by manufacturers relative to their corresponding mean EM values of their ankle fabrics are plotted schematically in Figure 1, which also displays the pressure levels (i.e., light, mild, moderate, strong, very strong) advised by the European Committee for Standardization in shaded areas. On this basis, multiple regression equations were developed to establish quantitative relationships between pressure levels and material mechanical properties of GCSs. By means of the built equations and visualized curve-area figures, the ranges of pressure magnitudes produced by the GCS fabrics with certain mechanical properties were then predicted and assessed.

Statistics

Analysis of variance (ANOVA) method was used to identify statistically the significances of the differences on individual mechanical characteristics among GCS fabrics with different pressure levels. A P value of <0.05 was regarded as statistically significant.

RESULTS

General statistic assessment

Using ANOVA, the key mechanical indices of GCS fabrics at ankle segment between four different pressure levels and between two series of stockings, as well as the interactions between levels and series were statistically assessed and are presented in Table IV. It can be seen that the tested GCS fabrics possessed very significant differences in tensile, shearing, and bending properties among light, mild, moderate, and strong pressure levels ($P < 0.001$), especially in shearing property (with the highest F value). On the other hand, no significant differences were found in RT and B properties between the two series GCS fabrics. Meanwhile, except for G and B properties, within the same pressure level, the two series of stockings fabrics show similar tensile (EM, WT, and RT) properties. The results indicated that pressure level performances of GCSs are certainly closely related to the variations in tensile, shearing, and bending properties of stockings fabrics, and the GCSs used may reflect typically the mechanical properties of fabrics with different pressure levels.

Assessments of pressure magnitudes and mechanical properties of GCSs

Figure 2 shows the compression proportion distribution exerted by GCSs along the lower leg with reference to the compression profiles advised by European Committee for Standardization. It can be seen that the maximum skin pressure at ankle region with smallest circumference was divided into five different pressure levels according to the compression applied by GCSs, and decreasing up to the calf region with maximal circumference by the specific proportions. This forms the basis to assess the pressure levels and GCSs fabric mechanical properties.

Pressure magnitudes and individual mechanical properties at ankle region

Figure 3(a–e) illustrate the quantitative relationships between B-pressure (pressure levels) and the individual

TABLE IV
Comparison Analysis of Mechanical Properties of GCS Fabrics between Different Pressure Levels and between Two Series of Stocking at Ankle Region

Tested indices		*df*	Mean square	*F*	*P*
EM	Levels	3	1277.112	17.600	0.000
	Series	1	420.794	5.799	0.021
	Levels · series	3	61.966	.854	0.473
WT	Levels	3	87.357	18.832	0.000
	Series	1	38.021	8.196	0.007
	Levels · series	3	7.428	1.601	0.204
RT	Levels	3	799.107	11.195	0.000
	Series	1	78.618	1.101	0.300
	Levels · series	3	148.062	2.074	0.119
G	Levels	3	29.897	807.720	0.000
	Series	1	1.110	29.994	0.000
	Levels · series	3	2.095	56.601	0.000
B	Levels	3	0.276	104.217	0.000
	Series	1	0.001	.535	0.469
	Levels · series	3	0.052	19.557	0.000

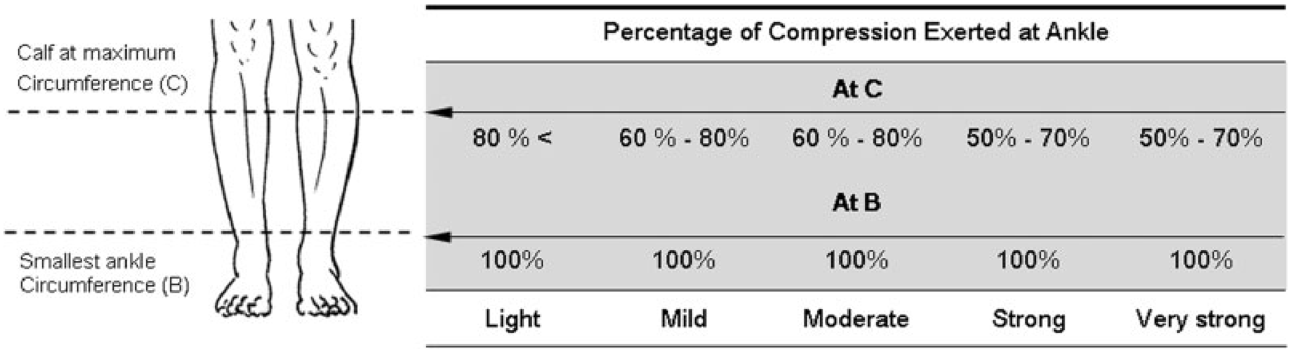

Figure 2 Compression profiles of graduated compression stockings.

key mechanical properties of tested GCSs. The corresponding multiple regression equations with satisfactory regression coefficients (R squares) and regression curves are also given.

Figure 3(a–c) show a similar pattern of a significant inverse correlation between fabric EM, WT, and RT properties with B-pressure magnitudes, indicating that the GCSs fabric with less tensile deformation (or extensibility) under certain tensile force would produce greater B-pressure or have higher pressure levels, and *vice versa*.

The pressure axis (x-axis) was divided into five sections in terms of pressure levels as advised by CEN (refer to Fig. 1). Based on it, the corresponding five sections in property axis (y-axis) can be obtained via logarithmic regression curves. The shaded bands (areas) relative to y and x axes were used to visualize the interactive correlations between certain pressure levels and specific fabric mechanical property.

For instance, in Figure 3(a), the rough ranges of fabric EM of GCSs with mild pressure (15—21 mmHg, i.e., 1999.83–2799.76 Pa) were from 21 to 28% under the standard loading condition (refer to Table I). For GCSs with strong pressure levels (34–46 mmHg, i.e., 4532.95–6132.81 Pa), the strain range is about 4–10%. In Figure 3(b), the fabric WT values in GCSs with mild and strong pressure levels ranged approximately from 7.6 to 5.6 (gf cm/cm^2), and from 2.7 to 1 (gf cm/cm^2), respectively.

Using the logarithmic regression equations, the fabric properties of GCSs with very strong pressure level can be predicted. Compared with light, mild, and moderate pressure levels, GCS fabrics with very strong pressure have very tiny extension range, and their maximum RT is only about 50%, while the GCS fabrics producing lighter pressure have the widest changing scope in extension and higher recovery (above 50%) [Fig. 3(a–c)].

By contrast, bending and shearing properties of GCS fabrics have positive correlations with B-pressure (or pressure levels), as shown in Figure 3(d,e).

It can be found that the values in bending rigidity (B) and shear stiffness (G) rise with increasing pressure levels. For instance, the B values in GCS fabrics with moderate and strong pressure levels ranged from about 0.10 to 0.26 (gf cm^2/cm) and from 0.31 to 0.69 (gf cm^2/cm), respectively. Their corresponding ranges of G values were from 1.5 to 2.5 (gf/cm deg) and 3.0 to 5.5 (gf/cm deg), respectively. These results indicated that GCS fabrics with higher pressure levels are more difficult to deform under bending and shearing forces, and they have better performances in dimension and shape stability than those with lower pressure levels.

For changing scope, tensile properties in EM and WT values displayed more even-proportioned variations among mild, moderate, and strong levels than those of bending and shearing properties in B and G values.

Pressure magnitudes and individual mechanical properties at calf region

The calf pressures applied by GCSs with different pressure levels were calculated with reference to the compression profiles advised by CEN. Figure 4(a–e) illustrate the relationship between pressure level performances and individual mechanical properties at the calf region. Since larger changing scope in compression gradient occurred at calf region (Fig. 2), overlapping hatched parts are seen among different pressure levels.

Figure 4(a,b) show that although the changing trends of the regression curves are in accordance with those at the ankle region, the scales of EM and WT values (y-axes) at calf region are all increased when compared with those at the ankle [Fig. 3(a,b)]. For instance, the calf pressure of GCSs with mild pressure level equaled to 60–80% of ankle pressure, and the upper and lower pressure limits of calf region were 1199.89–2239.81 Pa. According to the regression equations, the corresponding ranges of EM and WT values were 24–44% and 6.3–11.1 gf cm/cm^2, respectively. That is to say, for mild pressure level, the mean values of EM and WT properties at calf were higher than those at ankle by 38.8 and 31.8%, respectively. These results demonstrated that for the same pressure level, the fabric extensibility at the calf is greater than that at the ankle, but the resistance to deform at the ankle is higher than that at the calf, while the tensile recovery of the fabrics with the first four pressure levels still can be up to above 50% at the calf region [Fig. 4(c)].

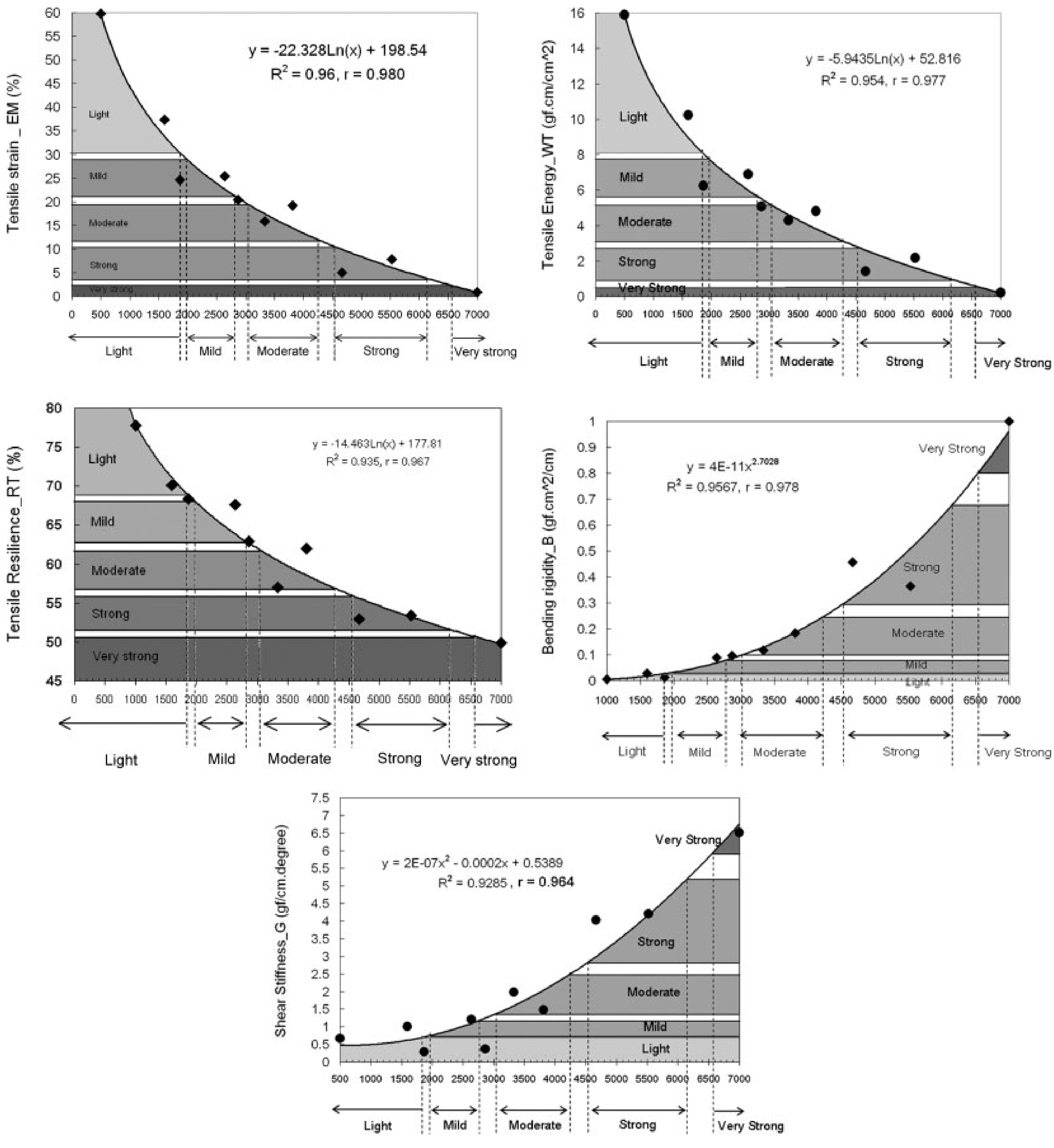

Figure 3 (a) Relationship between B-pressure and corresponding tensile strain property (EM) of GCS fabrics. (b) Relationship between B-pressure and corresponding WT property (WT) of GCS fabrics. (c) Relationship between B-pressure and corresponding tensile resilience (RT) of GCS fabrics. (d) Relationship between B-pressure and corresponding bending property (B) of GCS fabrics. (e) Relationship between B-pressure and corresponding shearing property (G) of GCS fabrics.

Figure 4(d,e) show the quantified relationships between calf pressure and bending (B) and shear (G) properties of GCS fabrics with different pressure levels.

It can be seen that the ranges of B and G values of GCS fabrics with strong and very strong pressure levels are obviously broadened. For instance, the range of B values in strong pressure levels at calf is from about 0.12 to 0.86 gf cm^2/cm, while at ankle the range of B is from about 0.31 to 0.69 gf cm^2/cm.

Compared with the ankle region, the sidelines among different levels [Fig. 4(a–e)] became less clear-cut at the calf region owing to overlaps. This feature became more

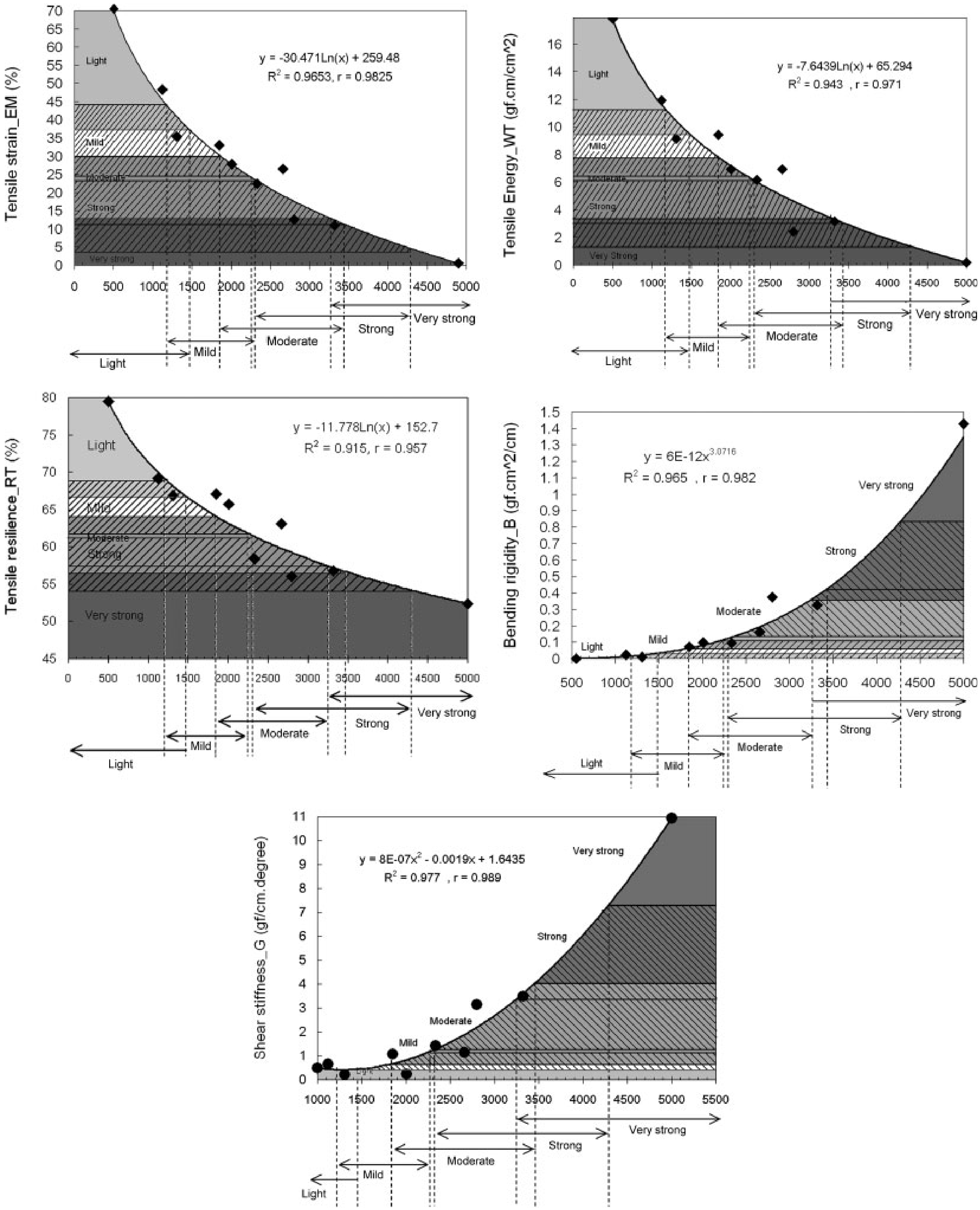

Figure 4 (a) Relationship between calf pressure and corresponding tensile strain property (EM) of GCS fabrics. (b) Relationship between calf pressure and corresponding tensile energy property (WT) of GCS fabrics. (c) Relationship between calf pressure and corresponding tensile resilience (RT) property of GCS fabrics. (d) Relationship between calf pressure and corresponding bending rigidity (B) of GCS fabrics. (e) Relationship between calf pressure and corresponding shearing stiffness (G) of GCS fabrics.

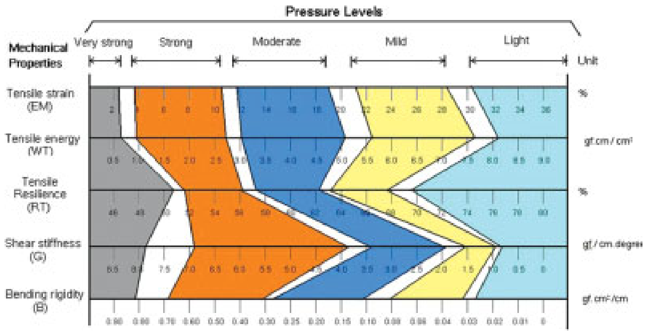

Figure 5 A summary plot of quantitative relationships between pressure levels and key mechanical properties of GCSs at ankle region. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

obvious in B and G properties, which implied that the differences in fabric mechanical properties at calf region were diminishing among diverse pressure levels.

Quantitative relationship between pressure levels and key mechanical properties of GCSs

Based on the above-mentioned analysis, a quantitative relationship between different pressure levels and key mechanical properties of GCSs was developed and is shown in Figure 5.

The five different pressure levels are represented by five different colors (Fig. 5). The five key fabric mechanical properties assessed are listed in the left column of Figure 5. At a certain pressure level, the corresponding specific values in fabric tensile, shearing, and bending properties are marked on the multiaxes by snake-lines. The final irregularly colored areas represent the main fabric mechanical properties that a certain pressure level possessed. For instance, for moderate pressure level, the rough ranges of EM, WT, RT, G, and B values at ankle fabrics were 11.9–19.3 (%), 3.1–5.1 (gf cm/cm^2), 56.9–62.3 (%), 1.8–3.3 (gf/cm deg), and 0.11–0.26 (gf cm^2/cm), respectively.

From Figure 5, it also can be seen that more even divisions of mechanical properties among different pressure levels occur in the EM-axis and WT-axis, which implied that tensile property of GCS fabrics is a remarkable criterion to differentiate or predict their pressure magnitudes. The way the data are expressed in Figure 5 allows us to realize that a reasonable combination of multiple fabric mechanical properties is also of critical importance to attain anticipated pressure level performances.

DISCUSSION

Compression itself is only one part of effective care provision. More attention should be given to the scientific evaluation and effective predetermination of pressure performances exerted by different compression materials, as well as a process that requires the integration of multidisciplinary knowledge and techniques to assess the true compression therapeutic potential of GCSs. In the present study, the GCSs fabric mechanical properties and their relationships with pressure functional performances were examined and assessed principally from the point of view of material science and medicine.

About pressure levels and mechanical properties

The present study has demonstrated that the fabric basic structures, mechanical properties, and a reasonable integration of multiple mechanical properties of stocking fabrics are closely related to pressure level performances and corresponding medical effectiveness of GCSs.

For instance, the fabrics of GCSs with light pressure level are thinner (about 0.35 mm in mean), lighter (about 85.0 g/m^2 in mean), and have lower resistances to extension, shearing, and bending forces and higher tensile recovery, while GCS fabrics with strong pressure level are thicker (about 1.32 mm in mean), heavier (about 406.8 g/m^2 in mean), and have higher resistances and lower RT. When the finished GCSs products made from these two kinds of fabrics are worn on a certain human leg, the fabrics would produce complicated deformations resulting from various intrinsic and extrinsic factors, such as the changes of leg surface curvatures, the motions of underlying anatomic structures, the variations of leg volume due to muscle contraction and relaxation exercises, and the changes of leg spacial dimensions due to knee flexion and ankle dorsiflexion, etc. GCS fabrics with higher pressure level would produce a larger recoil force to resist deformation, and thus ''high pressure'' would occur in the interface between stocking fabric and leg skin surface. The high pressure would be further transferred to the underlying tissues to cause physical and physiological changes, such as the internal volume of veins, arteries, and even lymph vessels, hydrostatic pressure, deep venous blood flow velocities, etc.[1] In clinical studies, GCSs with strong pressure level (34–46 mmHg, ~ 4532.95–6132.81 Pa) have been used to provide a safe and effective target level of compression therapy, to treat severe edema, chronic venous insufficiency, leg ulcer, lymphedema, etc.[27,28] In contrast, the GCS fabrics with less resistance would more easily deform with the leg form deformation, thus producing lower recoil force between stocking fabric inner face and skin surface. Additionally, the lower compressive force is dissipated by surrounding tissues during force transferring process. The GCSs producing light pressure, accordingly, would only exert influence on the structures near the surface of the skin, such as superficial venous system. For instance, the GCS with light pressure level (i.e., below 15 mmHg, 1999.83 Pa) is mainly used for daily leg health care and symptoms prevention. Meanwhile, since the tested

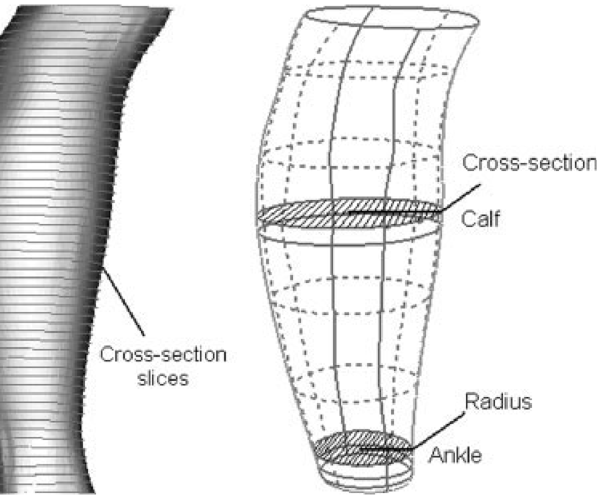

Figure 6 (a) A simulated human lower leg composing of numerous cross-sectional slices based on a prototype. (b) Geometric shape changes in cross sections of human leg.

GCSs in this study are all elastic fabrics with higher tensile recovery (up to above 50%), especially the fabrics with lighter pressure level, they would have better performances in ambulatory and sustained pressure than the compression bandages with short or no stretch.

The above-mentioned analysis indicates that the basic structural characteristics of GCS fabrics influence their multiple mechanical properties. Fabrics mechanical properties influence pressure level performances of the ultimate GCS products. The compression generated by the GCSs further exert different medical functional for specific leg diseases (symptoms). Therefore, the established quantitative relationships between pressure levels and materials mechanical properties possess theoretical and practical significance.

About assessment method

Since a complete uniform pressure objective testing method has not been applied in the compression hosiery industry worldwide,[10,11,29] the specified compression levels differ from one country or one brand to the other, resulting in difficulties to establish a specific accordant relationship between pressure level and GCS fabric property that is applicable to all compression hosiery manufacturers. This is the reason why the pressure ranges provided by European committee for standardization was employed as the frame of pressure level reference in the present study.

In addition, it should be noted that the quantitative relationships between pressures and materials are distinct from different positions located along the leg. A normal human leg may be regarded as an irregular cylinder cumulated by numerous cross sections layer upon layer [Fig. 6(a)]. The cross-sectional circumference (radius) of the ankle region is generally smaller than that of the calf [Fig. 6(b)].

Following Laplace's Law, when a fabric is applied with the same constant tension on a leg, the pressures achieved at the ankle will be higher than those exerted at the calf. The gradient compression of GCS is designed so that the highest pressure is exerted at ankle region, which then progressively decreases with increasing height along the leg. Therefore, specific quantitative relationships need to be developed to aim separately for the ankle and the calf, respectively.

From Figure 2, we found that pressures exerted at the calf have wider variation ranges for all pressure levels. For instance, if the ankle pressure is 20 mmHg, then the calf pressure ranges from 12 to 16 mmHg. This variation is closely related to anatomic structure and dimensional form of the calf. Larger circumference and shape changes in the segment from the ankle to the calf, and locomotion of underlying calf muscles (e.g., gastrocnemius, soleus), would make the covering stocking fabrics produce uneven or inconsistent multidimensional extension, shearing, and bending deformations, etc. (Fig. 7),[30] thus increasing the uncertainty of the calf pressures reading. In our established quantitative relationship between calf pressure and material properties (Fig. 4), the overlapping parts existed among different pressure ranges (*x*-axis) and their corresponding fabric mechanical properties (*y*-axis), which was in accordance with the practical wearing situations of GCS.

In the practical application of the quantitative relationships, the used leg model with definite three-dimensional size should be considered and clarified, such as mode materials, circumferences of key cross sections, testing positions, pressure sensors type and size, etc.

For the assessments of pressure-materials, some researchers have introduced the static and dynamic stiffness indices to evaluate the fabric elastic property and pressure performances by conducting wear trials *in vivo*.[9,19] These studies are all based on the concept of the stiffness index provided by European Committee

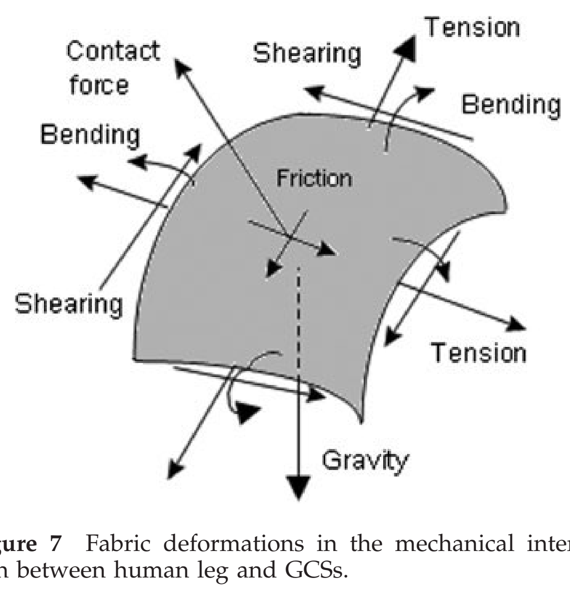

Figure 7 Fabric deformations in the mechanical interaction between human leg and GCSs.

for Standardization (CEN) (i.e., the increase in pressure per 1 cm increase in leg circumference, and expressed in mmHg/cm).[11] However, the test results produced by the two methods are largely influenced by the subjects themselves, such as body postures and movement velocities (lying, standing, walking,), muscle tensity, underlying tissue shift, etc., which are not easy to control exactly in different individuals. Furthermore, no other properties were considered except fabric elasticity. These testing were only suitable for clinical or laboratory assessments on a small scale, whereas the present study provides a reliable assessment approach with more extensive applications and high repeatability, which allows easy realization of unification or standardization of GCS products quality control. Meanwhile, the assessment outcomes can help designers and manufacturers to rationally predict pressure performances and therapeutic efficacy in terms of material properties before GCSs are actually produced, thus allowing effective and timely improvement of their designs and minimizing material and economic waste.

CONCLUSIONS

In the present study, five key materials mechanical properties related to three fundamental stresses (tensile, shearing, and bending) have been determined and assessed to characterize the mechanical behaviors of GCS fabrics. Multiple regression equations with satisfied *R* squares and the specified relationships between key mechanical properties and pressure level performances have been established, and an integrative illustrative pattern about their relations was constructed. Study results indicate that pressure level performances of GCSs are an integrative action performed by multiple fabric mechanical properties. GCS fabrics with different pressure level performances showed significant differences in tensile, shearing, and bending properties. GCS fabrics generating lighter pressure level possessed higher values in EM, WT, and RT at a given force and lower values in G and B, while the stronger pressure levels are produced by the GCS fabrics with higher resistance to the mechanical deformations. The used quantitative assessment method and the developed illustrative patterns provide correlative designers, manufacturers, and physicians in textiles and medical industries with a rational and practical reference for the assessment and improvement of pressure functional performances of GCSs and other pressure apparel productions for compression therapy.

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