Physiological Response and Comfort Sensory Perception towards Physical-Mechanical Performance of Compression Hosiery Textiles

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Abstract: The purpose of the present study is to determine the psycho-physiological effects of mechanical properties of compression hosieries (CHs) with different pressure levels and longitudinal gradient distribution profiles on the wearing comfort perception and blood circulation performance of the lower extremities in vivo. The mechanical properties of CHs (tensile, shearing, and bending) significantly influencing pressure level performances have been instrumentally estimated. Blood circulation as the main physiological parameter was investigated along the long and short saphenous veins and popliteal veins (PopV) of a total of 24 lower extremities of twelve female subjects by using Colour Doppler Ultrasound equipment in conjunction with four-hour subjective wear trials in a controlled environmental chamber. The study demonstrated that the mechanical properties of CHs fabric produced gradient variations along hosiery hose and among pressure levels. The skin pressures applied by CHs with four pressure levels significantly decreased the cross-sectional areas, and increased the mean flow velocities (VP mean) of the PopV by 15.70%, 29.80%, 31.30 % and 24.20%, respectively. Wearing comfort and acceptance degree significantly correlated with mechanical quality of CHs textiles. Light and mild compression by CHs provides the subjects more comfort sensory perception for long-term wearing period. The application of CHs textiles appears to be effective in preventing venous dilation and improving blood circulation in the lower extremities when wearers lack of physical activities. The fabrics with lower elasticity and higher bending rigidity properties produced higher pressure; while no significant differences in increasing blood circulation was found among mild, moderate, and strong pressure levels. An illustrative plot represents the integrative relationships between multiple materials mechanical properties, pressure performance, and resultant physiological responses and subjective comfort sensory perception, which provide a reference for product designer and physician in development and application of functional compression hosiery textiles.

Keywords: compression hosiery, mechanical properties, comfort perception, physiology, blood flow

1. Introduction

Compression hosiery (CH) with engineering designed gradient pressure and 3D fit construction has been one of important medical and healthcare textile products for prophylaxis and treatment of venous diseases in the lower extremities, such as fatigue, swelling, varicose veins, deep vein thrombosis (DVT), recurrent leg ulcerations, and lymphedema, etc [1-3]. During wear, the physical-mechanical stimuli induced by CH textiles trigger responses from various sensory receptors and induce resultant psycho-physiological variation, which affects the overall wearing comfort and health status of users. Immobilization, and prolonged standing and sitting may result in disruption of certain muscle fiber membranes, especially in the lower body musculature [4,5], thus reducing the effectiveness of the venous-muscle pump mechanisms and resulting in valvular incompetence, venous circulatory insufficiency and feelings of discomfort [6-8]. The most significant function of CHs is to provide gradient support and pressure on the cutaneous surface, underlying tissues and venous system of the lower extremities (e.g. the greatest pressure at the ankle, and then the thigh) by their limited and elastic stretch capability. However, to date the effects of compression hosiery

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with multiple material mechanical properties on pressure performances and corresponding physiological responses as well as wearing comfort perception have been not sufficiently studied, and relationships between different pressure levels and blood flow produced remain controversial. The compressive effects of hosiery on a lower limb were considered to depend largely upon the elastic tensile strength (stretch) of the garment and the circumference of the limb at different levels [9,10]. By conducting cylinder-elongation experiments and wear experiments, Morooka et al found that the compressive properties of different kinds of hosieries fabrics (compressive energy, compressive resilience, and fabric thickness) differ markedly according to the types and the sites of hose and posture while being worn [11]. The mechanical properties of hosiery fabrics directly influenced their pressure magnitudes and distributions as well as corresponding therapeutic efficiencies. The CHs with a compression force of 10-18 mmHg at the ankle, 2-8 mmHg at mid-thigh, are used in the prevention of deep vein thrombosis (DVT) [12-14]. Struckmann [15] examined the effects of CHs with low compression and high gradient, with the steepness of ankle/knee being 100:50 on the musculo-venous pump by using strain-gauge plethysmography (SGP), and stockings were found to elevate the maximal venous outflow by 27 %.

On the other hand, some researchers suggested that CHs with different pressure levels produced no significant differences in therapeutic effects. For instance, Mayberry et al [16] found that an exerted pressure of 30-50 mmHg at the ankle only produced a slight increase in venous flow in patients with deep venous insufficiency, and no significant improvement in ambulatory venous pressure in either the control or patient groups. Therefore, the present study is to elucidate the psycho-physiological effects of materials mechanical properties of CH textiles on blood circulation and subjective comfort perception during wear.

2. Materials and Methods

2.1 Subjects and Materials

Twelve healthy adult females were recruited with written consent to participate in this study, which has been approved by the university's ethics sub-committee for research on human subjects. All subjects were studied wearing all 4 pressure levels of CHs in random order following the control condition, as shown in Table 1.

2.2 Anthropometric Estimation

In order that individual subject wear the most fitting CHs for testing, the anthropometric parameters of the lower body were estimated and the measurement results are shown in Table 2.

2.3 Mechanical Properties Estimation

Systematic measurements and analysis in our correlative studies have shown that, among numerous mechanical properties, fabric tensile, shearing, and bending properties play more prominent roles in influencing the skin pressure functional performances of compression hosieries [5]. In that, tensile energy (WT), tensile strain, (EM), tensile resilience (RT), shearing stiffness (G), and bending rigidity (B) relating to three fundamental stress states (tensile, shearing, bending) became the primary parameters used for assessing mechanical behaviours of compression hosieries fabrics in this study. The fabric samples (swatches) with standard size of 20 cm × 20 cm were obtained directly from different regions of tested compression hoses and were assessed by Kawabata Standard Evaluation (KESF) (Kato-Tec Co., Japan) under an environmental controlled lab (temperature T: 20ºC ± 2 ºC, and relative humidity RH: 65 ±3%).

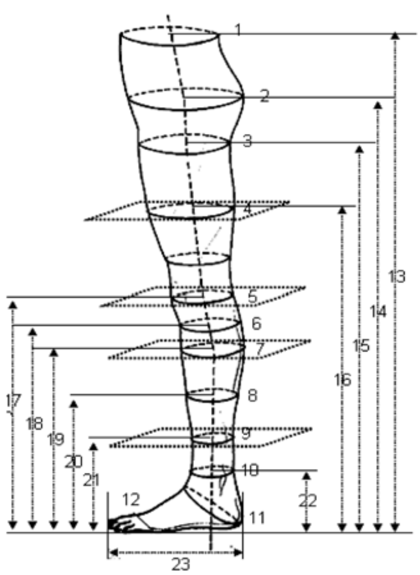
Table 1 Characteristics of studied hosieries

Compression levels of CHs used				
Levels	Light pressure (A1)	Mild pressure (A2)	Moderate pressure (A3)	Strong pressure (A4)
Pressures	(10-14 mmHg)	(18.4-21.2mmHg)	(25.1-32.1 mmHg)	(36.4-46.5 mmHg)
Fibre content	Polyamide 80% Elastomeric yarn 20%	Polyamide 64% Elastomeric yarn 36%	Polyamide 73% Elastomeric yarn 27%	Polyamide 73% Elastomeric yarn 27%
Thickness Mean ± s.d (mm)	0.41 ± 0.01	0.74 ± 0.02	0.76 ± 0.03	1.18 ± 0.02
Weight Mean ± s.d (g/m²)	106.7 ± 21	246.7 ± 21	250.2 ± 15	376.3 ± 16
Therapeutic application	To prevent leg discomfort, etc.	For curing mild varicosities, aching, welling, etc.	For curing moderate varicosities, oedema, etc.	For curing serious varicose veins, severe oedema, leg ulcer, etc.

* The pressure levels of CHs are categorized in terms of the pressures at the ankle region according to the European Committee for Standardization [17]. ° The pressure gradient of each type of CHs are identified in our related study [18].

Table 2 Anthropometric parameters of subjects' lower body

Circumference (cm)	Mean±SD
1 waist girth	73.2 ± 6.2
2 hip girth	92.3 ± 4.3
3 top thigh girth	55.2 ± 4.3
4 mid-thigh girth	45.2 ± 4.7
5 knee girth	35.9 ± 2.3
6 below knee girth	31.9 ± 1.3
7 greatest-calf girth	34.4 ± 1.8
8 below calf girth	27.5 ± 2.4
9 smallest ankle girth	20.8 ± 1.2
10 talus	22.5 ± 1.3
11 heel girth	28.8 ± 2.8
12 forefoot girth	22.8 ± 2.7
13 waist height	96.8 ± 5.7
14 hip height	80.2 ± 5.9
15 top-thigh height	72.1 ± 3.4
16 mid-thigh height	57.2 ± 3.9
17 knee height	42.9 ± 2.4
18 below knee height	37.6 ± 2.6
19 greatest calf height	27.8 ± 4.3
20 lower calf height	20.1 ± 2.3
21 smallest ankle height	12.1 ± 1.9
22 talus girth height	7.1 ± 0.5
23 foot length	23.3 ± 1.4



The testing parameters and corresponding instruments with settings were illustrated in Table 3.

Table 3 Materials properties and testing instruments

Properties	Parameters/Unit/Setting
Tensile	Tensile strain (EM) (%) Tensile Energy (WT) (gf. Cm/cm²) Tensile Resilience (RT) (%) Instrument/ setting KES-FB-1: Extension velocity: 0.2 mm/s; Processing rate: 2.5 s; Maximum load: 50 gf/cm
Shearing	Shear stiffness (G) (gf/cm.degree) Instrument/setting KES-FB-1: Rate of shearing: 0417 mm/s Shear tension: 10 gf/cm Maximum shear angle: ± 8.0
Bending	Bending rigidity (B) (gf.cm²/cm) Instrument/setting KES-FB-2 Rate of bending: 0.5 cm^{-1} Maximum curvature: ± 2.5 cm^{-1}
Surface	Coefficient of friction (MIU) Mean deviation of MIU Geometrical roughness (SMD) (µm) KES-FB4: Velocity: 1.0 mm/s Roughness contractor comp: 10gf
Construction	Weight (W) (mg/cm²) Thickness (T) (mm) Thickness at 0.5gf/cm²

A strip-biaxial tensile testing by using KES-G2 was also conducted to estimate relationships between tensile force and strain towards tested hosiery fabrics, which has been reported in our related study [19].

2.4 Pressure Profiles Physical Assessment

The pressure profiles applied by tested CHs were evaluated in vivo by using FlexiForceTM interface pressure sensors (Tekscan, Inc., Boston, USA) and a multichannel monitoring system in a climate-controlled chamber with temperature of 23 ± 0.5ºC and relative humidity of 65 ± 3%. Table 4 shows the pressure magnitudes and distributions by four kinds of tested CHs, and the more detailed descriptions about testing can refer to our retailed publication [18].

Table 4 Assessment of pressure profiles of CHs tested

Position	Pressure profiles of CHs tested along leg (Pa)			
At ankle	1089.4	1515.8	1763.1	2173.0
At calf	849.9	111.8	1596.9	2026.4
At thigh	547.9	526.2	683.3	769.1
Pressure gradient (Ankle/Calf/Thigh)	*100:78:50*	*100:74:35*	*100:90:39*	*100:93:35*
Pressure levels	Light (A1)	Mild (A2)	Moderate (A3)	Strong (A4)

2.5 Venous Function and Blood Circulation Assessment

The effects of mechanical properties of different tested CHs on venous function and blood circulation of the lower extremities were assessed in total of twenty-four lower limbs of twelve female subjects (21.18 ± 1.33 yr old, 159.82 ± 6.18 cm tall, weighed 52.45 ± 8.78 kg, BMI of 20.46 ± 2.33 kg/m²) in a laboratory with controlled T of 23°C ± 2°C and RH of 65 % ± 5%. The variations of cross-sectional areas (VA) and diameters (VD) were measured at mid-thigh region along the saphenous veins (LSV), the posterior knee along the short saphenous veins (SSV) and Popliteal veins (PopV), and mean and peak blood flow (PVmean, PVpeak) were tested at PopV by using color Doppler ultrasonographic scanning techniques with a 7.0 MHz linear-array transducer (Aloka SSD-1700 DynaView, USA) when subjects standing upright with feet spread evenly apart being with and without wearing CHs, as shown in Figure 1.

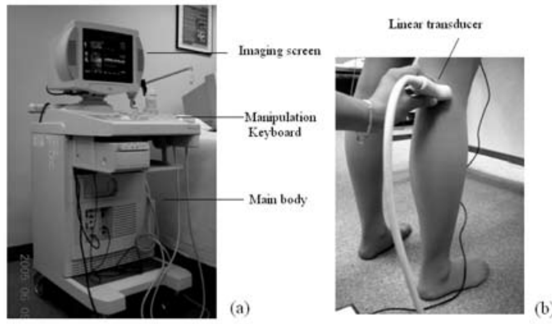


Figure 1 Color Doppler Ultrasound equipment and testing

The subjects were instructed not to engage in heavy physical work or strong exercise for 24 hours before the testing. After changing her street clothing into loose-fitting experimental wear, the subject took rest on a seat calmly for an acclimatization period of 20 min. The testing orders of CHs were randomized for each subject. A real-time ultrasound scanning was performed along the LSV and the SSV, to examine the anatomic structure and function. The Doppler examination was conducted three times during the 4 hours period (i.e. after wearing CHs for 1 min, 70min, and 170 min). The scanned images that were obtained through the hosieries were achieved with the application of a generous amount of non-irritant gel. To obtain optimal blood flow signals and images, the sample volume was positioned within the middle of vessel lumen, and its sample gate was set at 1mm. The angle between the direction of the Doppler wave and the vessel was maintained at approximately 60°.

Once the Doppler waveforms became stable, the images were frozen and the blood flow velocities were calculated.

2.6 Subjective comfort Sensory Perception

During the 4-hours physiological testing, the subjective comfort sensory perceptions towards different mechanical stimuli by hosiery textiles were estimated at different time points by means of questionnaires with multiple sensory items. Figure 2 presents the experimental protocol in this psycho-physiological study.

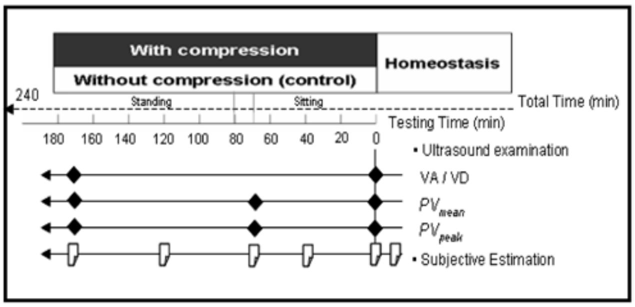


Figure 2 Psycho-physiological experimental protocol

Statistical analysis was performed using analysis of variance (ANOVA) method and t-test. Correlation analysis was performed with Pearson's correlation. Statistical significance was established when p was < 0.05.

3. Results

Figure 3 (a-e) illustrates the main mechanical properties of tested compression hosieries at three different gradient positions and with four different pressure levels. The pressure range along the hosiery hoses at each pressure level was marked with shadow. For instance, Figure 3-a shows that the range of EM values in light pressure level from ankle to thigh regions are from about 37 % to 69 %, and the EM values gradually decrease with the raising of pressure levels. The mechanical properties of compression hosieries significantly influenced the skin pressure profiles, which have been analyzed in our previous studies [5].

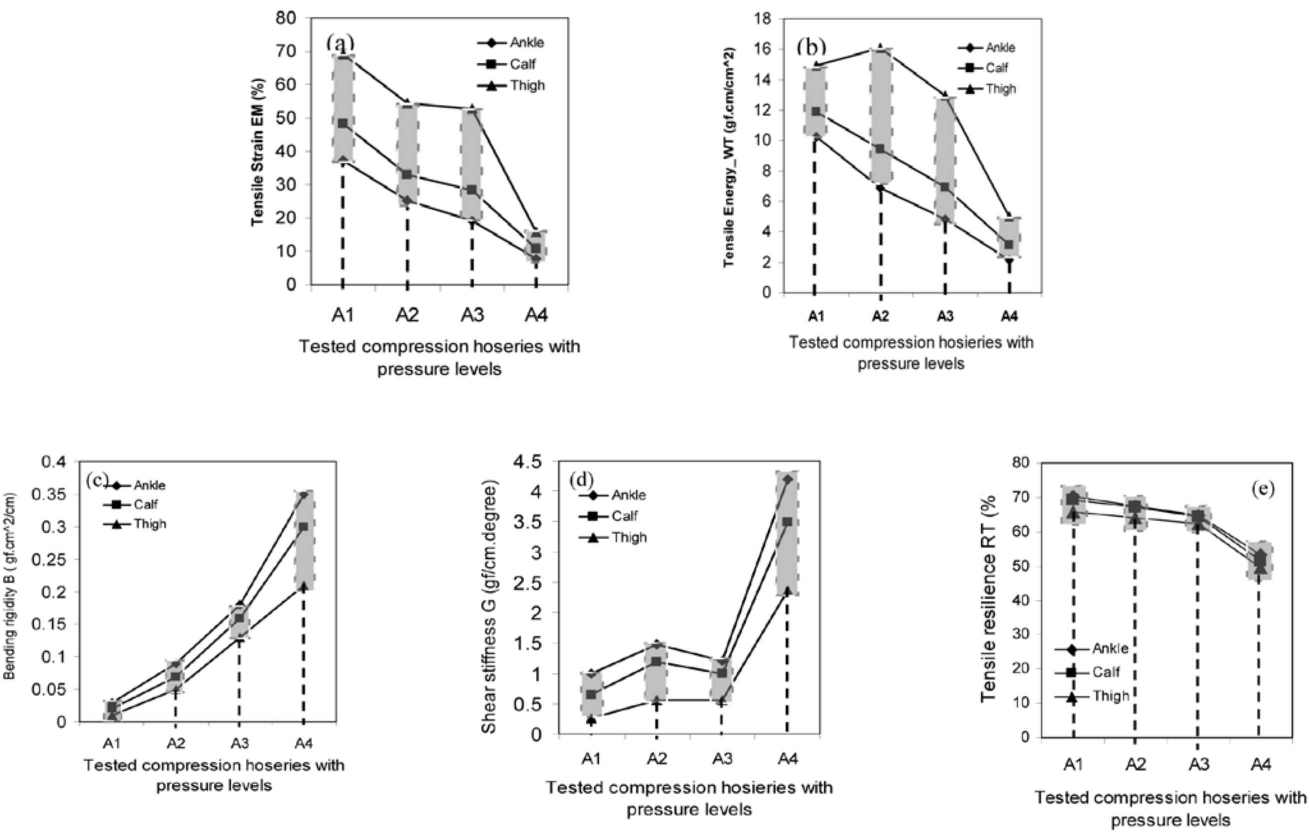


Figure 3 Mechanical properties of tested hosieries hoses with different pressure levels

Then, how about the physiological response and sensory perception towards the stimulation from the materials mechanical properties and skin pressure action? Venous diameters and flow velocities are normally considered to be the critical parameters to reflect the venous functions [20]. It was found that the cross-sectional diameters at the tested positions along the LSV and SSV significantly reduced under CHs compressions (P < 0.05), as shown in Figure 4.

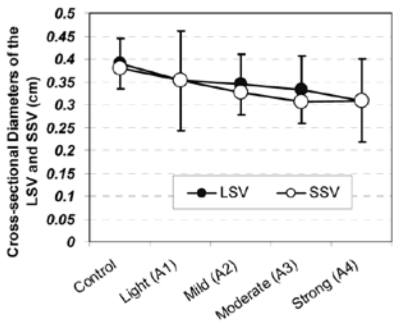


Figure 4 Variations in the mean size of the diameters (VD) of the LSV and SSV under different compressions by CHs

The PopV was selected as the typical testing point of the deep venous system. As shown in Figure 5, compressions by CHs significantly decreased the size of the VA of the PopV, but no significant differences existed among light, mild, moderate and strong pressures (P > 0.05). Venous flow velocity is an effective reflection of venous function, which can be influenced by the changes in the vessel diameter. The PVmean values were generally lower than the PVpeak values by about 40% on average as shown in Figure 6. While the compression significantly increased the PVmean and PVpeak values for all pressure levels (P < 0.05) compared with control condition. No significant differences were observed among mild, moderate and strong pressure levels. Figure 7 shows that except for CH with light skin pressure, the PVmean values were significantly increased after the 70 min and after 170 min under the application of CHs with pressure levels over the control condition.

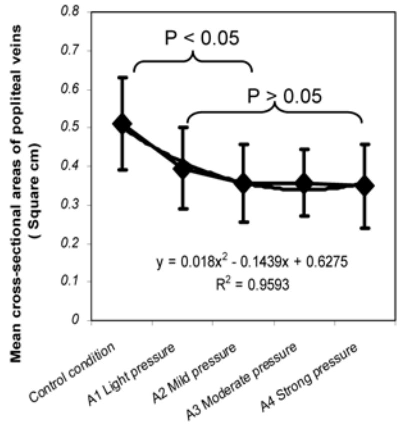


Figure 5 Variations of VAs in PopV among different compressions applied

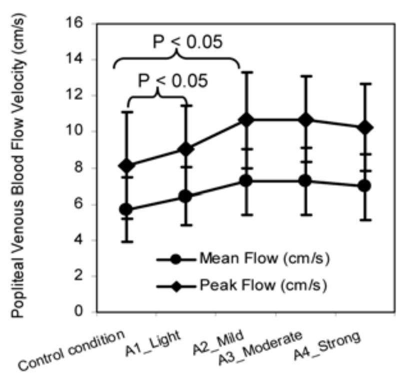


Figure 6 Variations of blood flow of PopV under tested compression conditions

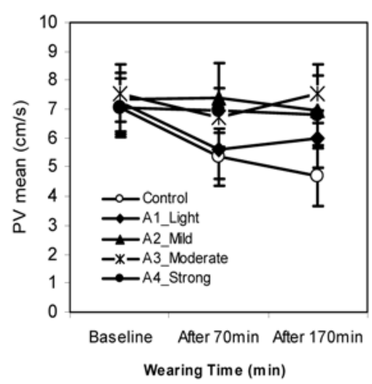


Figure 7 comparisons of the PVmean variations with time between the control condition and different skin pressures exerted

The wearing comfort perception has significantly correlation with the mechanical properties of the CH textiles as shown in Table 5. For instance, the pressure sensation closely related to fabric tensile, bending, shearing properties, and thickness; scratchy sensation is more markedly determined by bending, shearing, thickness and friction coefficient of fabric surface, etc.

The pressure comfort by different hosiery textiles was estimated by means of a questionnaire using a scale of 0-10 (where 0 stands for 'Extremely uncomfortable', 5 stands for 'neutral', and 10 stands for 'Extremely comfortable'). It was found that the hosiery with light and mild pressures obtained the higher pressure comfort rating than those with moderate and strong pressures. The average and maximum ratings towards the four pressure levels by CHs are: 6-7.5 (light pressure), 5-6.5 (mild pressure), 4-5.8 (moderate pressure), and 3.5-4.8 (strong pressure).

4. Discussion

The present study provides an insight into the effect of materials mechanical properties and skin pressure magnitudes (levels) and gradient distributions produced by CHs on the venous blood flow of the lower extremities as well as the comfort sensory perception, which allow us to explore further the compression mechanisms of action of the compression hosiery products in use.

The mechanical action of CHs fabrics and 3D construction (e.g. tensile, shearing, bending, surface properties, shape and dimension, etc.) not only influences the cutaneous surface deformation, the underlying soft tissues deformation and variations of venous system, but also stimulates the neurophysiological system to produce corresponding sensory perception. Thus, the integrative stimulation of compression hosiery textiles affects the general pressure functional performance, medical efficiencies (for healthcare), and wearing comfort, as illustrated in Figure 8.

In our previous related research, the quantified relationships between the materials properties and pressure levels have been developed [5].

Table 5 Correlation analysis between wearing sensations and material physical-mechanical properties

Wearing sensations	Mechanical-physical Properties								
	EM	RT	B	G	MIU	MMD	SMD	W	T
Easy in putting on	.763 *	--	-.852**	-.932**	-.787*	--	--	-.755*	-.896**
Stretchability	.868 **	.708*	-.812*	-.892**	.758*	--	--	.858*	.858**
Support feeling	-.809 *	-.717*	.920**	.978**	.789*	--	--	.877**	.929**
Sense of pressure	-.877**	--	.786*	.805*	--	--	--	--	777**
Easy in leg movement	.868**	.712*	--	-.867**	-.828*	-.715*	--	--	-.823*
Fetter feeling at ankle	-.851**	--	.741*	.729*	--	--	--	--	.744*
Satisfactory fit	.772*	--	-.892**	-.919**	-.711*	--	--	-.884**	-.871**
Snug feeling	-.760*	-.877**	.811*	.791*	.990*	.978**	.799*	.845**	.938**
Scratchy feeling	-.799*	--	.854**	.922**	.911**	--	--	.769*	.853**
Breathable	.781*	.830*	-.894**	-891**	-.934**	-.897**	-.752*	-.924**	-.978**
Overall comfortable	.838**	.799*	-.911**	-.956**	-.893**	-.830*	--	-.885**	-.972**
Acceptability	.825*	.877**	-.952**	-.962**	-.922**	-.885**	--	-.934**	-.983**

**: Correlation is significant at the 0.01 level (2-tailed); *: Correlation is significant at the 0.05 level (2-tailed).

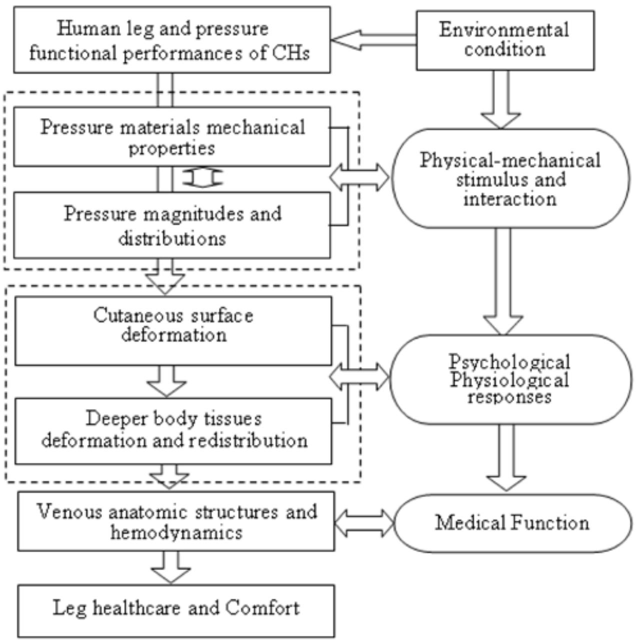


Figure 8 A summary plot of relationships between materials mechanical properties, pressure levels, venous functions, comfort sensation related to CH textiles

In the present study, we further investigated the relationships between mechanical properties of hosiery products and human body. Fabrics at ankle region and with higher pressure levels have higher values in bending rigidity (B) and shearing stiffness (G), which produce a larger recoil force to resist deformation, and thus "high pressure" would occur in the interface between hosiery fabric and leg skin surface. The higher pressure would be further transferred to the superficial and deep venous system resulting in the changes of venous cross-sectional diameters and areas. In medical study, venous flow velocity in the leg is an effective reflection of venous function, which is inversely proportion to the cross-sectional area (caliber) of the vessels to be filled [21], clinical significances of these effects depends upon the relationship between the intravenous hydrostatic pressure and the degree of external compression applied [22]. In this study, it has been found that compared with the control condition, the VA and VD values at the tested points were significantly decreased by the application of CHs, and the venous mean blood flow of the PopV were significantly enhanced by 15.70%, 29.80%, 31.30 % and 24.20% when subjects wearing four kinds of CHs with different pressure levels and mechanical properties after about 170 min. Meanwhile, wearing comfort is a fundamental to attain compression therapeutic efficiency. It has been found that the sustained external pressure stimulation by different CHs has induced wearers to generate different pressure comfort perception. Therefore, the quantitative investigation on inter-relationships between materials mechanical properties, pressure profiles, venous function, and comfort responses are extremely necessary.

Based on the present study, Figure 9 summarizes and develops an illustrative pattern on their interactive relationships. We can see that the four types of different tested hosieries were represented by four different colors. The five key fabric mechanical properties assessed are listed in the left column. For a certain type of compression hosiery, its corresponding specific mean values in fabric tensile, shearing, and bending properties at three different gradient positions along the hosiery hose are marked on the multi-axes by snake-lines. The final irregularly colored areas represent the main fabric mechanical properties that a certain type of tested CH possesses. The mechanical properties show gradient variations from ankle to thigh regions, e.g. for CH-A2, the rough ranges of EM and WT values from ankle to thigh fabrics were 25.3%-32.9%-54.6%, and 6.9-9.4-16.1 (gf.cm/cm2), respectively. The integrative mechanical action of CHs fabrics produced different skin pressure magnitudes and distribution, e.g. under the mechanical action of CH-A2 fabrics, the mean pressure with 1515.85 Pa produced on the skin surface at ankle region, and longitudinal gradient pressures distributed from ankle to thigh regions with 100:74:35 (Table 3), which further causes the parameters variations in venous system and comfort perception compared with the control. The way that the data is expressed in Figure 9 allows us to further understand the psycho-physiological responses induced by mechanical performance of CHs described in Figure 8.

In addition, the presence of CH fabrics provide sustaining pressure on the legs, which improve or maintain the venous blood flow of the lower extremities at a certain level for 170 min, compared with the control, which implies that the application of CHs textiles appears to be effective in preventing venous dilation and improving venous hemodynamics in the human lower extremities.

In practical wearing, the action of mechanical properties of compression hosiery fabrics and pressure function on venous system are also influenced by the body shape.

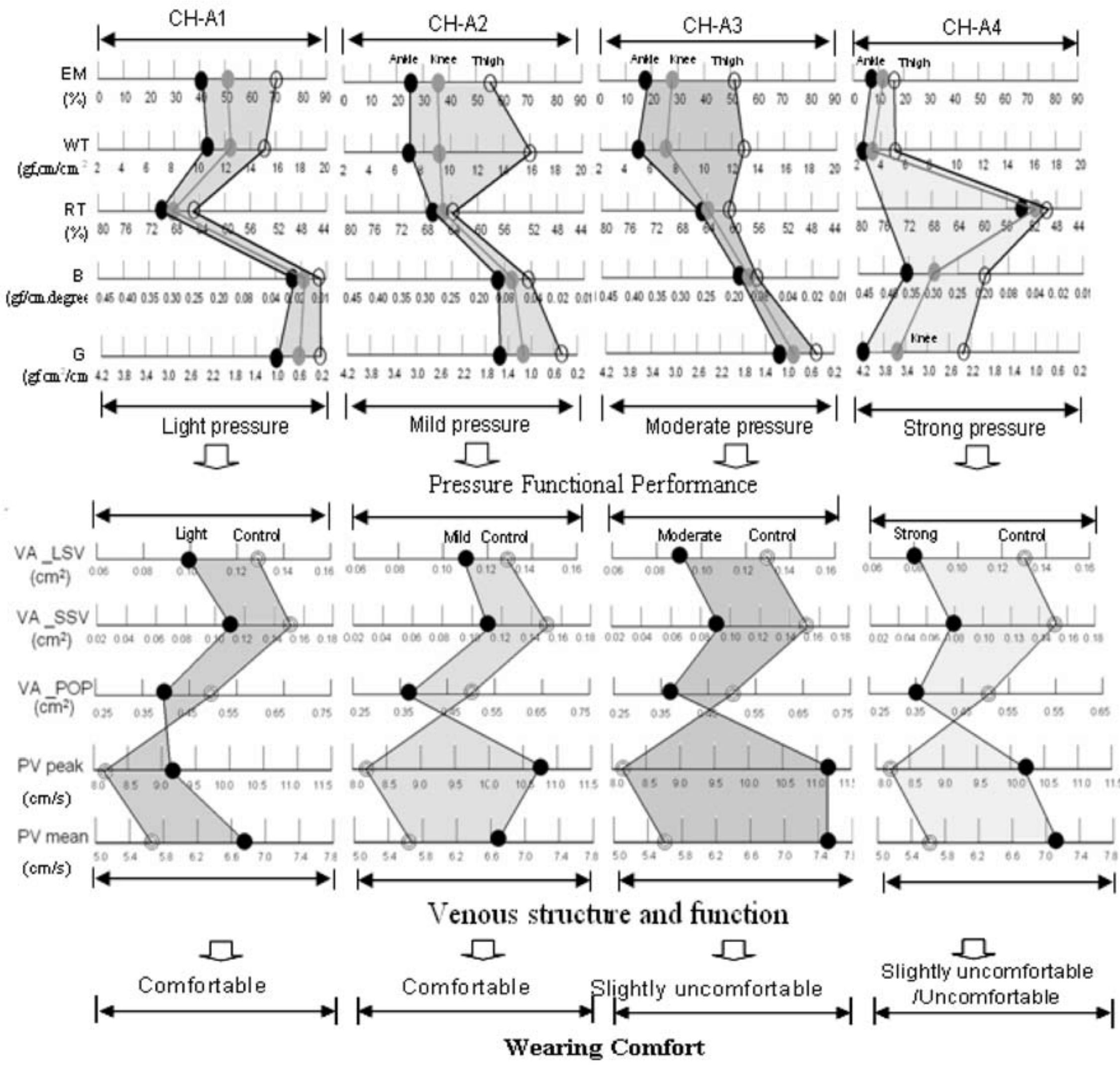


Figure 9 A summary plot of relationships between materials mechanical properties, pressure levels, venous function and comfort sensations related to CH textiles

The present study was conducted in twelve female subjects with specified body shapes as depicted in Table 2. In future study, more subjects need to be tested when wearing different compression hosieries to improve the established quantitative relationships between multiple factors, thus providing a reference for product designer and physician in the development and application of compression hosiery textiles.

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