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Effects of Knitting Variables for Pressure Controlling of Tubular Compression Fabrics

Yu Shi, Rong Liu, Jingyun Lv

***Abstract*—**Compression textiles with ergonomic-fit and controllable pressure performance have demonstrated positive effect on prevention and treatment of chronic venous insufficiency (CVI). Well-designed compression textile products contribute to improving user compliance in their daily application. This study explored the effects of multiple knitting variables (yarn-machinery settings) on the physical-mechanical properties and the produced pressure magnitudes of tubular compression fabrics (TCFs) through experimental testing and multiple regression modeling. The results indicated that fabric physical (stitch densities and circumference) and mechanical (tensile) properties were affected by the linear density of inlay yarns, which, to some extent, influenced pressure magnitudes of the TCFs. Knitting variables (e.g., feeding velocity of inlay yarns and loop size settings) can alter circumferences and tensile properties of tubular fabrics, respectively, and significantly varied pressure values of the TCFs. This study enhanced the understanding of the effects of knitting factors on pressure controlling of TCFs, thus facilitating dimension and pressure design of compression textiles in future development.

***Keywords*—**Laid-in knitted fabric, yarn-machinery settings, pressure magnitudes, quantitative analysis, compression textiles.

I. Introduction

CVI occurs frequently in human lower extremities. Relevant clinical experiments demonstrated the effectiveness of compression stockings (CSs) in treatment of CVI such as chronic leg ulcers [1]. However, the application of CSs remains infrequent (35.1%) [2] due to high non-compliance of the users. The reasons come from different aspects such as insufficient knowledge on use of CSs, few recommendations from medical staff, wearing discomfort in application, and other sociopsychological factors [3]. For the existing ready-made commercial CSs, the limited size selections could also bring some dimensional discrepancy resulting in ill-fitting or side effects [4], [5]. Personalized CSs for ergonomic fit of the individual lower limb morphologies are highly needed.

Related studies investigated the influences of CSs materials, knitted patterns, and even machinery settings on the fabric properties and pressure performances of CSs. Bera et al. [6] indicated that inlay yarns showed significant effects on the fabric tensile properties. Liu et al. [7] and Zhang et al. [8] analyzed the impacts of laid-in structures and knitting parameters on fabric stretchability and clothing pressure performance under different testing conditions. Chattopadhyay et al. [9] demonstrated that the pressure exerted on rigid cylindrical tubes increased with reduction factor of the fabrics. Lozo et al. [10] further designed new CSs with specific pressure gradients by adjusting knitting parameters. Moreover, relevant statistical methodologies, such as multiple regression analysis, have been applied to establish fitting equations between the knitting variables and fabric properties [11], [12]. However, the quantitative correlations between the knitting settings and the correspondingly produced pressure values still need to be identified.

Therefore, this study investigated the key knitting parameters and their effects on physical-mechanical properties as well as pressure variations of TCFs when different elastic yarn materials and machinery parameters were applied. Through conducting parametric analysis and multiple regression model, quantitative relationships among multiple knitting variables, machinery settings, fabric properties, and pressure performances of the developed TCFs were established, which provide a practical reference for developing ergonomic-fit CSs in our future study.

II. Methodology

A. Sample Preparation

Three types of yarn design were proposed in this study. Table I and Fig. 1 (a) illustrate the physical-mechanical properties of the applied nylon double-covered Lycra® yarn with different linear densities as ground yarn and inlay yarns, respectively. The TCF samples were fabricated by applying 1×1 laid-in weft-knitted structures (Fig. 1 (b)) through three-dimensional seamless knitting machine (LONATI LA45 ME, Francesco Lonati, Brescia, Italy) set with four yarn feeders. The feeding controller (PYF), as one of the key machinery units, can adjust the amount of inlay yarns that are fed into the tubular fabrics. The higher the rolling velocity, the more inlay yarn materials are fed into the knitted tubular fabrics. Sizing motor, as another key unit, can control the needle bed positions for adjusting loop sizes of the TCFs. The greater the values, the larger or looser the knitted loops are. In this study, the stitch cam keeps a consistent value for producing the TCFs with identical knitting structures (i.e., 21.5 mm for the 1st and 3rd yarn feeders, and 20.5 mm for the 2nd and 4th yarn feeders). More details of the machinery settings and correspondingly produced fabric sample codes are shown in Table I. An ironing treatment was performed at the temperature of 100 °C for 10 seconds after fabrication process, to eliminate the internal loop stress and improve dimensional stability of the knitted TCF samples.

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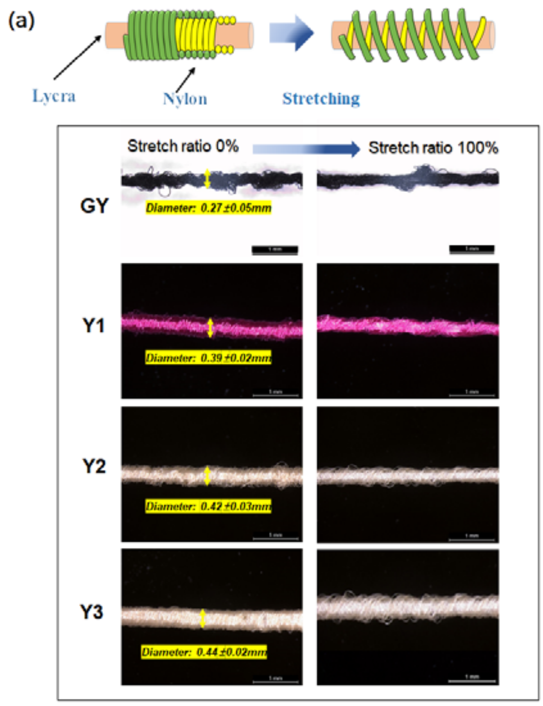
B. Experimental Method

The fabric densities were determined by using microscopic images obtained from Leica M165 C electronic device (Wetzlar, Germany) (Fig. 2 (a)) when fabric was placed at a natural relaxed status referring to the standard ASTM D1577-79. D_{course} and D_{wale} were used to indicate fabric course and wale densities, respectively, and D indicated the stitch densities of the fabric at a given area. The circumference (*Cir*) of each piece of tubular fabric sample was measured for three times at the place 1 cm away from the upper and lower welts and the middle position, respectively (Fig. 2 (b)) according to the standard ASTM D3774. Fabric thickness (h) was tested by using Vernier caliper based on the standard of ASTM D1777. The tensile behavior was investigated by the Instron 4411 uniaxial tension tester (CRE type, Fig. 2 (c)) according to the standard ASTM D4964. E_{course} and E_{wale} denoted Young's moduli along the course and wale directions of the tubular fabric, respectively, and ER_{course} and ER_{wale} denoted elastic recovery rates (%) along the course and wale directions, respectively. The produced interface pressure (P) beneath fabric tubes was tested by using Picopress@ (Microlab Elettronica, Italy) pressure probe on a wooden leg model with maximum girth at calf level of 32.2 cm (Fig. 2 (d)).

TABLE I
PHYSICAL AND MECHANICAL PROPERTIES OF THE YARN MATERIALS USED

Yarn	Code	Linear density of Lycra® yarn (Denier)	Linear density of nylon yarn (Denier)	Yarn diameter (mm)	Young's Modulus (MPa)
Ground yarn	GY	40	40	0.27 ± 0.05	0.90 ± 0.04
Inlay yarn	Y1	210		0.39 ± 0.02	1.12 ± 0.04
	Y2	280		0.42 ± 0.03	1.12 ± 0.01
	Y3	420		0.44 ± 0.02	0.40 ± 0.05



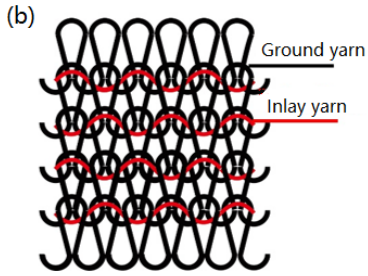


Fig. 1 (a) Characteristics of yarn materials, and (b) 1×1 laid-in knitted structure

TABLE II
SETTINGS OF KNITTING VARIABLES OF THE TCF SAMPLES

Sample code	Yarn combination		Machinery parameter	
	Ground yarn	Inlay yarn	PYF (m/min)	Sizing motor (mm)
A1	GY	Y1	600	700
A2	GY	Y1	650	700
A3	GY	Y1	700	700
A4	GY	Y1	750	700
A5	GY	Y1	800	700
A6	GY	Y1	850	700
A7	GY	Y1	900	700
A8	GY	Y1	950	700
A9	GY	Y1	1000	700
A10	GY	Y1	1050	700
A11	GY	Y1	1100	700
A12	GY	Y1	1150	700
A13	GY	Y1	1200	700
A14	GY	Y1	1250	700
A15	GY	Y1	1300	700
B1	GY	Y2	600	700
B2	GY	Y2	650	700
B3	GY	Y2	700	700
B4	GY	Y2	750	700
B5	GY	Y2	800	700
B6	GY	Y2	850	700
B7	GY	Y2	900	700
B8	GY	Y2	950	700
B9	GY	Y2	1000	700
B10	GY	Y2	1050	700
B11	GY	Y2	1100	700
B12	GY	Y2	1150	700
B13	GY	Y2	1200	700
B14	GY	Y2	1250	700
B15	GY	Y2	1300	700
C1	GY	Y3	600	700
C2	GY	Y3	650	700
C3	GY	Y3	700	700
C4	GY	Y3	750	700
C5	GY	Y3	800	700
C6	GY	Y3	850	700
C7	GY	Y3	900	700
C8	GY	Y3	950	700
C9	GY	Y3	1000	700
C10	GY	Y3	1050	700
C11	GY	Y3	1100	700
C12	GY	Y3	1150	700
C13	GY	Y3	1200	700
C14	GY	Y3	1250	700
C15	GY	Y3	1300	700
N1	GY	Y1	1150	500
N2	GY	Y1	1150	550
N3	GY	Y1	1150	600
N4	GY	Y1	1150	650
N5	GY	Y1	1150	700
N6	GY	Y1	1150	750
N7	GY	Y1	1150	800
N8	GY	Y1	1150	850

In this study, knitting variables (yarn-machinery settings) mainly included linear densities (yarn diameters) and feeding velocities (PYF feeding values) of the inlay yarns as well as the loop size adjustment (sizing motor values) of the knitted fabrics. The resultant physical (fabric stitch densities, circumferences, and thicknesses) and mechanical (Young's moduli and elastic recovery ratios) properties, and the generated pressure values exerted by the TCFs were analyzed. Pearson's linear correlation coefficient (ρ) with a range of $[-1,1]$ was applied to analyze the relation levels of yarn-machine settings with fabric physic-mechanical properties and pressure magnitudes. The greater the absolute value of ρ, the stronger the correlation was and vice versa. The negative and positive values represent negative and positive correlations between these variables, respectively [13]. The ρ is defined as:

$$\rho(\mathrm{X},\mathrm{Y})=\frac{\mathrm{cov}(\mathrm{X},\mathrm{Y})}{\sigma_X\sigma_Y}=\frac{E\left[(X-\mu_X)(Y-\mu_Y)\right]}{\sigma_X\sigma_Y}=\frac{E(XY)-E(X)E(Y)}{\sqrt{E(X^2)-E^2(X)}\sqrt{E(Y^2)-E^2(Y)}} \quad (1)$$

where X is the yarn-machinery setting value (i.e., linear density or feeding velocity of the inlay yarns, or size motor values); Y is the correspondingly produced fabric physical-mechanical property (fabric stitch densities, circumferences, thicknesses, Young's moduli, elastic recovery ratios, and pressure values); the *cov (X, Y)* is the covariance between X and Y; σ_X and σ_Y are standard deviations of X and Y, and $E(X)$ is the expected value of X.

Meanwhile, multiple linear regression model [14] was built to analyze quantitative relationships among knitting variables as shown in (2). The analysis of variance (ANOVA) for regression was conducted by using a statistical software (SPSS, version 23.0, IBM Corporation, USA). The coefficient of determination for the established fitting model is expressed by R-squared (R^2) as shown in (3):

$$Y=a_0+a_1x_1+a_2x_2+\ldots+a_nx_n+b \quad (2)$$

where Y indicates the predicted dependent variable (circumference or pressure of the produced TCFs), x_n denotes the independent variables (yarn-machine setting values and fabric tensile ratios), and a_n is the coefficient value corresponding to each independent variable, and b is the constant value.

$$R^2=1-\frac{SSE}{SST}=1-\frac{\sum_{i=1}^{n}(y_i-\bar{y}_i)^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2} \quad (3)$$

where R^2 is the R-squared, SSE is the residual sum of squares, which indicates the average of the squares of the residuals (predicted values-actual values), while SST is the average of the squares of the total sum, and y_i and $\hat{y}_i$ are the data before and after fitted.

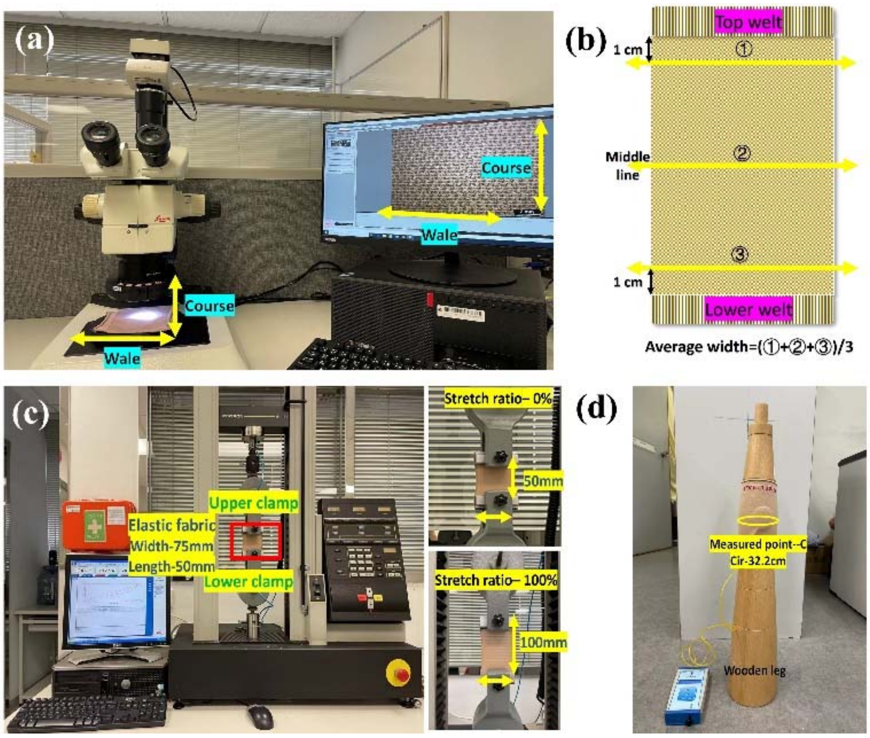


Fig. 2 Experimental investigations, (a) fabric density analysis, (b) fabric circumference test, (c) uniaxial Instron 4411 tension tester, and (d) fabric pressure testing

III. Results

Table III shows the results on the calculated ρ values. The effects of yarn-machinery settings on fabric properties and pressure magnitudes are presented in Fig. 3. It can be seen that the linear densities of the inlay yarns have negative correlation with fabric stitch densities ($\rho(D)$ = −0.58) but positive correlations with fabric circumference ($\rho(Cir)$ = 0.33) and tensile properties especially along the course direction ($\rho(E_{course})$ = 0.97, $\rho(E_{wale})$ = 0.72)). It is worthy to be noted that the types of inlay yarn showed weak correlations with the produced fabric pressure ($\rho(P)$ = 0.28). However, in the practical application, the involvement of fabric tension (T) and cross-sectional radius (r) of the applied body would make the effects of inlay yarn materials on pressure (P) to be more obviously according to the Laplace's Law ($P = T/r$).

Feeding velocities of inlay yarn showed the highly positive correlations with tubular fabric circumferences ($\rho(Cir)$ = 0.99) but highly negative correlations with fabric densities ($\rho(D) = -0.93$). That is, the amounts of inlay yarns fed into the fabrics can be controlled by revolving speeds of PYF, thus further varying fabric densities and circumferences. The produced pressure values of TCFs showed highly negative correlations with both feeding velocities of inlay yarns ($\rho(P) = -0.99$) and sizing motor settings ($\rho(P) = -0.95$). The increase of sizing motor values could reduce Young's moduli along course (E_{course}) and wale (E_{course}) directions of the TCFs.

Based on the above results, it is noted that when adopting the same inlay yarn materials and knitting loop structures, adjustment of the feeding velocities of inlay yarns contribute to varying fabric circumferences and elasticities to fit the applied body size (e.g., lower limb) and meet pressure dose requirement of compression textiles. For TCFs with defined dimensions, adjusting sizing motor to control loop sizes contributes to tuning pressure to a certain range of values for achieving required pressure gradient distribution.

TABLE III
THE CALCULATED ρ REFLECTING EFFECTS OF YARN-MACHINERY SETTINGS ON FABRIC PROPERTIES AND PRESSURE MAGNITUDES

(A) EFFECTS OF LINEAR DENSITIES OF INLAY YARN

Items		Mean ± SD	p (Sig.)	ρ
Physical property	D_{course} (stitches/cm)	17.31 ± 3.01	0.02	-0.36
	D_{wale} (stitches/cm)	24.38 ± 1.20	0.00	-0.78
	D (stitches/cm^2)	422.40 ± 74.18	0.00	-0.58
	Cir (cm)	20.26 ± 3.39	0.04	0.33
	h (mm)	0.64 ± 0.02	0.31	0.16
Mechanical (tensile) property	E_{course} (MPa)	0.63 ± 0.15	0.00	0.97
	E_{wale} (MPa)	0.34 ± 0.09	0.00	0.72
	ER_{course} (%)	89.10 ± 4.59	0.00	0.48
	ER_{wale}(%)	86.94 ± 3.55	0.06	0.30
Pressure	P (mmHg)	42.20 ± 10.34	0.09	0.28

(B) EFFECTS OF FEEDING VELOCITIES OF INLAY YARN

Items		Mean ± SD	p (Sig.)	ρ
Physical property	D_{course} (stitches/cm)	18.68 ± 2.72	0.00	-0.94
	D_{wale} (stitches/cm)	25.85 ± 0.64	0.00	0.85
	D (stitches/cm^2)	481.40 ± 59.27	0.00	-0.93
	Cir (cm)	18.91 ± 2.40	0.00	0.99
	h (mm)	0.64 ± 0.02	0.62	-0.13
Mechanical (tensile) property	E_{course} (MPa)	0.50 ± 0.02	0.17	-0.41
	E_{wale} (MPa)	0.30 ± 0.03	0.00	-0.87
	ER_{course} (%)	91.11 ± 1.63	0.00	-0.83
	ER_{wale} (%)	87.13 ± 3.26	0.48	-0.21
Pressure	P (mmHg)	36.08 ± 6.28	0.00	-0.99

(C) EFFECTS OF SIZING MOTOR SETTING (LOOP SIZES)

Items		Mean ± SD	p (Sig.)	ρ
Physical property	D_{course} (stitches/cm)	15.89 ± 0.26	0.00	0.97
	D_{wale} (stitches/cm)	26.95 ± 1.13	0.00	-0.94
	D (stitches/cm^2)	428.02 ± 11.71	0.01	-0.85
	Cir (cm)	20.70 ± 0.24	0.01	0.93
	h (mm)	0.65 ± 0.02	0.02	0.79
Mechanical (tensile) property	E_{course} (MPa)	0.54 ± 0.12	0.00	-0.89
	E_{wale} (MPa)	0.32 ± 0.13	0.00	-0.95
	ER_{course} (%)	89.66 ± 2.80	0.38	0.36
	ER_{wale} (%)	87.12 ± 3.77	0.21	0.50
Pressure	P (mmHg)	31.75 ± 4.95	0.00	-0.95

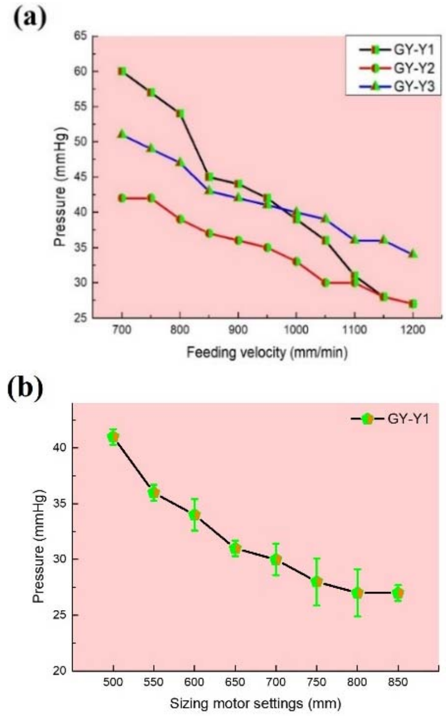


Fig. 3 Effects of machinery settings (a) feeding velocities and (b) sizing motor settings (loop sizes) on fabric pressure performances

To further analyze the effects of yarn-machinery settings on fabric circumference and the produced pressure values, the fitting equations, (4) and (5), were built as follows based on the developed multiple linear regression model:

$$Cir = 0.016 \times x_1 + 0.002 \times x_2 + 84.493 \times x_3 - 33.201 \quad (4)$$

where Cir is the circumference of tubular fabric (cm), x_1 is the feeding velocity of inlay yarn (m/min), x_2 is the loop size setting (mm), and x_3 is the yarn diameter of inlay yarn (mm).

$$P = -3.903 - 0.02 \times x_1 - 0.062 \times x_2 + 0.217 \times x_3 + 213.072 \times x_4 \quad (5)$$

where P is the pressure value of TCF (mmHg), x_1 is the feeding velocity of inlay yarn (m/min), x_2 is the loop size setting (mm), x_3 is the fabric tensile ratio (%) along course direction, and x_4 is yarn diameter of inlay yarn (mm). The results showed a good regression coefficient [15] between yarn-machine settings and fabric circumference (R^2 = 0.957) and pressure magnitudes (R^2

= 0.846), respectively.

TABLE IV
ANOVA FOR REGRESSION TOWARDS FABRIC CIRCUMFERENCES

		Sum of squares	Mean square	F	Sig.
ANOVA	Regression	990.715	330.238	485.021	**
	Residual	44.257	0.681		
	Total	1034.972			
		Coefficient	t-values	Sig.	R^2
Regression analysis	Constant	-33.201	-15.566	**	0.957
	Feeding velocity	0.016	31.914	**	
	Loop size	0.002	1.082	*	
	Yarn diameter	84.493	20.835	**	

*: $p < 0.05$; **: $p < 0.01$

TABLE V
ANOVA FOR REGRESSION TOWARDS FABRIC PRESSURE VALUES

		Sum of squares	Mean square	F	p
ANOVA	Regression	4766.788	1191.697	111.373	**
	Residual	866.701	10.700		
	Total	5633.488			
		Coefficient	t-values	Sig.	R^2
Regression analysis	Constant	-3.903	-0.558	0.578	0.846
	Feeding velocity	-0.020	-11.028	**	
	Loop size	-0.062	-9.395	**	
	Tensile ratio	0.217	6.718	**	
	Yarn diameter	213.072	14.996	**	

*: $p < 0.05$; **: $p < 0.01$

IV. CONCLUSION

This study analyzed the influence of knitting variables (yarn-machine settings) on fabric physical-mechanical properties and correspondingly produced pressure magnitudes of TCFs based on the experimental testing and multiple regression model. The results showed that feeding velocities of inlay yarns and sizing motor settings for controlling loop sizes significantly vary tension, circumferences, and pressure values of the TCFs. Although linear densities (yarn diameters) of inlay yarns presented weak correlations with the pressure magnitudes, the variations of fabric tension and cross-sectional radius of the applied body would influence pressure values in practical use, especially when applying TCFs made by inlay yarns with different linear densities. This study provides a practical reference for customizing knitting variable settings to control fabric dimensions and pressure levels for improving size fitting and pressure performance of compression textiles in practical applications.

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