

Article

Effect of Material, Number of Yarns, and Loop Length on Pressure, Stretchability, and Thermal Properties of Seamless Knitted Fabrics for Compression Textiles

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Abstract

Compression textiles have been widely applied in medical, sportswear, and daily usage, with single-jersey structures produced by circular knitting dominating the market due to their thinness and light weight. However, the presence of seams may compromise compression performance and wearer comfort. This study investigates the effects of yarn type, number of yarns, and loop length on pressure, stretchability, and thermal comfort of seamless punch-lace knitted fabrics and explores their potential application in compression textiles. The results show that yarn number is the dominant factor influencing fabric stiffness, stretchability, and pressure. Fabrics with increased yarn content demonstrate higher maximum load and compression pressure. Smaller loop lengths and additional reinforcing yarns improve dimensional stability and resistance to extension. Air permeability decreases with increasing yarn number due to increased fabric thickness and reduced porosity, while thermal conductivity increases and is positively associated with ventilation resistance, indicating a trade-off between heat transfer and breathability. Surface friction and roughness are significantly affected by yarn number, yarn type, and loop length, whereas water vapour permeability shows no significant relationship with the investigated variables. Overall, seamless punch-lace knitted fabrics demonstrate strong potential for compression applications, although careful design is required to balance breathability and thermal comfort.

Keywords: pressure; extension; thermal comfort; loop length; seamless knitting; compression textiles



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1. Introduction

Compression textiles have been widely applied in the medical sector for many decades as a first-line treatment for a range of venous diseases [1]. The underlying compression mechanism involves applying the highest pressure at the ankles to create a graduated pressure profile that gradually decreases toward the knees, thereby assisting blood flow upward toward the heart [2,3] and improving venous circulation in the lower limbs. Owing to their demonstrated benefits in medical contexts, compression textiles have increasingly been adopted in leisure, sports, and everyday wellness applications, such as travel socks [4]. Previous studies have suggested that sports compression garments (SCGs) can positively influence muscle fatigue indicators and perceived muscle soreness during post-exercise recovery [5,6], increase venous return and muscle blood flow, improve muscle oxygenation

during rest periods [7], prevent injury recurrence, and reduce symptoms of existing sports injuries [8]. However, inconsistent findings regarding the effectiveness of compression garments in enhancing sports performance and recovery have been reported across the literature [9,10]. These discrepancies may be attributed to limited consideration of garment-related factors, such as fabric properties, garment design, and construction, as well as heterogeneity in experimental protocols [4,10].

Circular and flatbed weft-knitting technologies are widely used in the production of elastic compression textiles [11,12]. However, both technologies typically produce garments with seams, which can lead to uneven pressure distribution and potentially compromise the effectiveness of compression therapy and wearer comfort. Single-jersey structures are commonly employed in circular knitting to produce lightweight compression stockings with plain colours. They are frequently used in medical compression stockings, where aesthetic requirements are relatively low. Circular knitting can produce stockings without side seams along the leg, although seams remain in other areas, such as the stocking head.

In sports applications, flatbed weft-knitted compression stockings are available in a variety of structures, including single and double jersey, interlock, rib, and spacer fabrics, often incorporating elastic yarns through inlay or plating techniques [12,13]. These structures offer greater visual variety, enabling diverse colours and patterns that enhance the attractiveness of sports apparel. However, they may also increase fabric thickness and weight, reduce breathability, and raise production costs. Consequently, single-coloured compression stockings continue to dominate the market. Despite this, the integration of graphical patterns into compression textiles using seamless knitting technology remains largely unexplored.

Seamless weft-knitting technology enables made-to-measure production, which is particularly advantageous for compression garments, where precise fit is essential for optimal performance. Recent advancements in the Shima Seiki SWG-XR seamless knitting machine have expanded the capability to produce graphical patterns, such as punch-lace knitted structures, offering new opportunities to enhance both the functionality and aesthetics of compression textiles. The yarn selection and structural design of textiles directly influence their pressure characteristics and fabric properties, thereby affecting garment efficacy, user comfort, and compliance. Various weft-knitted structures—including rib, single jersey, piqué, and inlaid knits—have been used in the construction of compression textiles [12,14]. Previous research has shown that plaited knit structures with larger loop lengths allow greater extensibility but produce lower compression [15]. Increased fabric thickness, stitch density, and fabric weight, together with reduced transverse elasticity, are associated with higher pressure [16]. Lower fabric thickness and weight contribute to improved comfort [14], while higher spacer yarn density enhances air permeability [17].

The research gap lies in the limited exploration of integrating graphical patterns into compression textiles while simultaneously achieving fully seamless compression garments using seamless knitting technology. In seamless knitting, punch-lace knitted structures can be utilised to create graphical patterns within the fabric. Our previous research demonstrated that the use of Cupro/Cotton/Polyurethane yarn exhibited the strongest positive impact on pressure by reducing fabric elasticity [18]. However, the highest pressure achieved in our previously developed samples was below 20 mmHg, which corresponds to Class 1 compression according to the German Standard RAL-GZ 387:2008 [19]. To increase the compression level of compression textiles, the present study investigates elastane yarn options, such as Lycra and spandex, and examines the effects of loop length, number of yarns, and yarn types on the properties of seamless punch-lace knitted fabrics. In addition to pressure and thermal comfort properties, this study also evaluates stretchability, water vapour permeability, and surface properties of the fabrics

to provide a more comprehensive assessment of their suitability for compression textile applications. The findings provide valuable insights for the design and development of compression textiles and contribute to advancements in textile-based compression apparel.

2. Materials and Methods

The experimental samples were designed to explore several structural and material parameters, including loop length, yarn type, and number of yarn ends. However, due to machine and yarn compatibility constraints in seamless knitting, these parameters were not varied in a fully balanced factorial design. Therefore, the results should be interpreted as comparative observations among the tested fabric configurations rather than as strictly independent effects of individual factors. Two levels of yarn number, four loop lengths, and four yarn types were selected for the fabrication of the knitted samples. In this study, loop length refers to the machine setting value used in the Shima Seiki seamless knitting machine to control stitch size, rather than a direct physical measurement in millimetres. Larger values correspond to larger loop sizes and a looser fabric structure. The experimental design and corresponding parameters are summarised in Table 1.

Table 1. Experimental sample parameters.

Factor	Level			
Yarn number	2	4		
Loop length	4.6	5.0	5.2	5.5
Yarn type	(A) 43D 69% Nylon 31% Lycra (Double low power)	(B) 90D 86% nylon 14% spandex (High Power)	(C) 94dtex 80% Polyamide 6.6 20% Lycra (100% Elongation)	(D) 25D 77% Nylon 23% spandex (High Power)

2.1. Knitting Materials

Four types of elastane-based yarns were selected from international suppliers. The yarn counts were chosen to ensure compatibility with the 18-gauge seamless knitting machine used in this study (Table 2).

Table 2. Yarn used in this study.

Yarn	Yarn Count	Material	Supplier
A	43D	69% Nylon 31% Lycra (Double low power)	Daiya FUKUSHOKU Co., Ltd., Japan
B	90D	86% nylon 14% spandex (High Power)	Sun Hing Elastic Covering Factory Limited, Hong Kong, China
C	94dtex	80% Polyamide 6.6 20% Lycra (100% Elongation)	W. Zimmermann GmbH & Co. KG, Weiler-Simmerberg, Germany
D	25D	77% Nylon 23% spandex (High Power)	Sun Hing Elastic Covering Factory Limited, Hong Kong, China

2.2. Fabrication of Knitted Samples

Seven seamless knitted fabric samples with various numbers of yarn, loop length, and yarn type were fabricated in a punch-lace knitted structure, and one knitted fabric in single jersey structure was produced as the control. All samples were knitted on an 18-gauge seamless knitting machine (SWG-XR, SHIMA SEIKI, Wakayama City, Japan).

The punch-lace structure was produced using two different yarns knitted simultaneously: the main yarn formed knitted loops on all needles, while the auxiliary yarn formed

knitted loops on two selected needles and float stitches across the remaining five needles in a repeating pattern. All samples were produced using identical knitting parameters and knitted in tubular form, with a height of 10 cm and a flat width of 6.5 cm when laid flat. Two specimens were produced for each fabric type. Each specimen was measured at three to six different locations depending on the test method, and the reported values represent the mean $\pm$ standard deviation of these measurements. The control fabric was produced without the punch-lace structure and served as a reference sample for comparison with the punch-lace knitted fabrics. As the control fabric also differs in yarn composition and yarn number from some of the punch-lace samples, the comparison should be interpreted as a general reference rather than a strict structural control. Details of the fabric composition and sample specifications are provided in Tables 3 and 4. A schematic diagram of the punch-lace knitted pattern is presented in Figure 1.

Table 3. Fabric component.

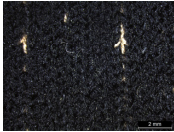
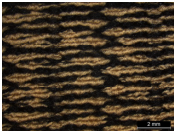
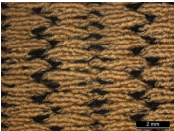
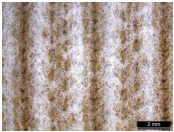
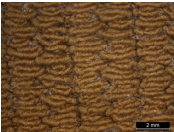
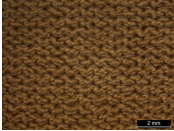
Fabric Component	L1–L3	S1–S2	S3
Main yarn (without float)	Yarn C	Yarn C	Yarn C
Auxiliary yarn (with float)	Yarn A	Yarn B	Yarn D

Knitting notations of punch-lace structure

Table 4. Sample specifications of punch-lace knitted specimens and control fabric.

Fabric Code	Yarn Number		Loop Length	Weight per Unit Area (g/m ²)	Thickness (mm)	Microscopic View of Fabric	
	Yarn A	Yarn B				Front	Back
L1	2		5.50	266.12	1.27		
L2	2		5.50	337.96	1.53		
L3	2		5.00	335.51	1.52		
L4	2		4.60	325.71	1.54		

Table 4. Cont.

Fabric Code	Yarn Number				Loop Length	Weight per Unit Area (g/m ²)	Thickness (mm)	Microscopic View of Fabric	
	Yarn A	Yarn B	Yarn C	Yarn D				Front	Back
S1		2	2		5.20	343.67	1.49		
S2		2	4		5.20	452.24	1.77		
S3			2	2	5.50	270.20	1.39		
Control			2		5.20	242.45	1.00		

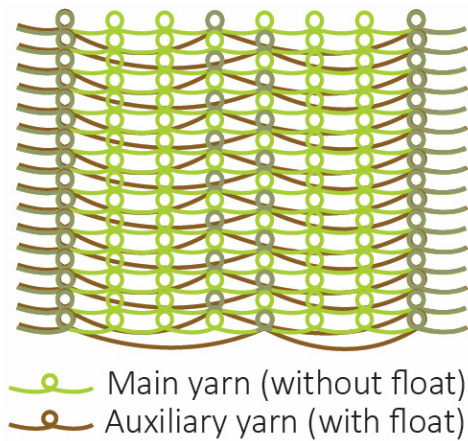


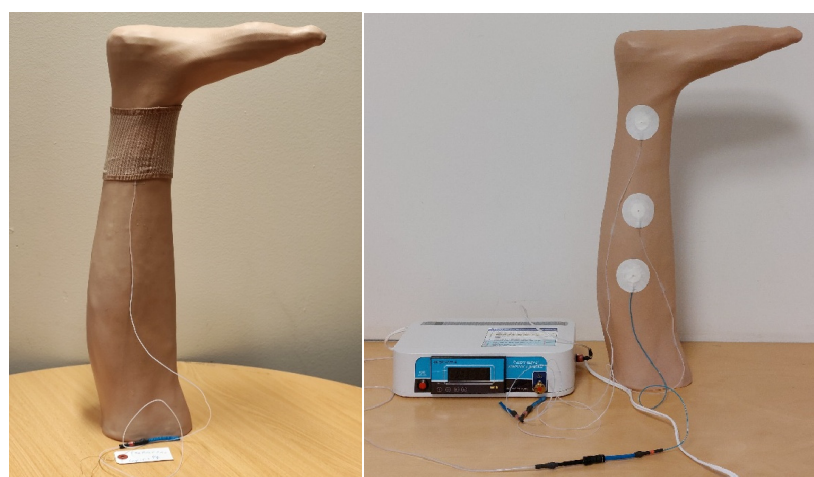
Figure 1. A schematic diagram of the punch-lace knitted pattern.

2.3. Evaluation of Fabric

The properties of the knitted samples were evaluated according to relevant textile standards (Table 5). The pressure exerted by the tubular knitted samples was measured using an AMI air-pack pressure sensor (AMI3037-SB-SET, SANKO TSUSHO Co., Ltd., Tokyo, Japan) at the ankle position, as defined in DS/CEN/TR 15831, using a 3D-printed leg mannequin. A thin sensor bladder with a thickness of 1 mm and a diameter of 20 mm was used for the measurements (Figure 2). The leg mannequin, with an ankle circumference of 21 cm and a calf circumference of 33.5 cm [20], was printed using a BigRep ONE printer with polylactic acid (PLA) and covered with a 1 mm thick Pevalen™ prosthetic cover (Embreis, Täby, Sweden). It should be noted that the surface characteristics and mechanical behaviour of the mannequin do not fully replicate those of the human leg, as human limbs exhibit variability in muscle distribution and tissue compliance. Therefore, the measured pressures should be interpreted as comparative indicators among the tested fabrics rather than exact representations of in vivo compression levels.

Table 5. Summary of test methods.

Property	Parameter	Device	Testing Standard
Thickness	Thickness under 4 gf/cm ² pressure	Thickness gauge (Model BC1110-1-04, AMES LOGIC Basic, USA)	ASTM D1777-96 (2019): Standard Test Method for Thickness of Textile Materials; ASTM International: West Conshohocken, PA, USA, 2019.
Pressure	Pressure	Leg mannequin with an AMI air-pack pressure sensor (AMI3037-SB-SET, SANKO TSUSHO Co., Ltd., Tokyo, Japan)	DS/CEN/TR 15831 Medical Compression Hosiery—Recommendations for Testing of Hosiery; European Committee for Standardisation (CEN): Brussels, Belgium, 2009.
Stretchability	Load, strain	Tensile tester (5566, Instron [®] , Norwood, MA, USA)	CEN. EN 14704-1:2005 Determination of the Elasticity of Fabrics—Part 1: Strip Tests; European Committee for Standardisation (CEN): Brussels, Belgium, 2005.
	Fabric growth	Tensile tester (5566, Instron [®] , Norwood, MA, USA)	ASTM D3107-07 (2019) Standard Test Method for Stretch Properties of Fabrics Woven from Stretch Yarns; ASTM International: West Conshohocken, PA, USA, 2019.
Air permeability	Ventilation resistance	Air permeability tester (KES-F8-AP1, KATO Tech Co., Ltd., Kyoto, Japan)	ASTM D737-18 Standard Test Method for Air Permeability of Textile Fabrics; ASTM International: West Conshohocken, PA, USA, 2018.
Thermal comfort	Water vapour transmission rate	Cup method in accordance with the standard	ASTM E96/E96M-16: Standard Test Methods for Water Vapour Transmission of Materials; ASTM International: West Conshohocken, PA, USA, 2016.
	Thermal conductivity	Thermal measuring unit (KES-F7 Thermo Labo II, KATO Tech Co., Ltd., Kyoto, Japan)	JIS L 1927:2010: Testing Methods for Cool Feeling of Textiles; Japanese Standards Association: Tokyo, Japan, 2010.
Surface	Surface roughness, surface friction	Surface Tester (KES-FB4-A, KATO Tech Co., Ltd., Kyoto, Japan)	JIS B 0601:2013: Geometrical Product Specifications (GPS)—Surface Texture: Profile Method—Terms, Definitions and Surface Texture Parameters; Japanese Standards Association: Tokyo, Japan, 2013.

**Figure 2.** Evaluation of the pressure of knitted sample L1 by AMI air-pack pressure sensor at the ankle.

Stretchability tests were conducted to assess fabric elasticity and recovery, which are critical for garment fit and durability. The maximum load at 50% extension was measured according to EN 14704. This parameter represents the force required to extend the fabric to 50% of its original length, where higher values indicate greater fabric stiffness. The specimen width and gauge length were both 50 mm, and the test speed was 50 mm/min.

Fabric growth after 50% extension was measured according to ASTM D3107. Measurements were taken before stretching and 10 s after tension release. A higher fabric growth (%) indicates a greater permanent deformation after removal of tensile stress.

Thermal properties, including thermal conductivity and water vapour transmission (WVT), were measured to evaluate wearer comfort. Thermal conductivity represents the rate of heat transfer through the sample due to a temperature gradient, while WVT assesses moisture permeability over a 24 h period. Ventilation resistance was measured according to ASTM D737-18 to evaluate the air permeability of the fabrics. Surface friction and roughness were measured according to JIS B0601 to assess surface irregularity and resistance to sliding, which are important indicators of fabric hand feel and comfort.

Prior to testing, all fabric samples were conditioned for 24 h at a temperature of 20 ± 1 °C and a relative humidity of $65\% \pm 5\%$. Two samples were produced for each fabric type. Each sample was tested three to six times at different locations, and the mean values were calculated and reported.

2.4. Statistical Analysis

The experimental data were analysed using Jamovi (version 1.6.15) software. Pearson correlation analysis was performed to examine the relationships among the measured variables. Multivariate analysis of variance (MANOVA) using Pillai's Trace was conducted to explore the effects of loop length, number of yarn ends, and yarn type on the material properties of the seamless punch-lace knitted fabrics. Multiple measurements taken at different locations on each specimen were used to capture spatial variability; however, these measurements do not represent fully independent experimental replicates. Prior to the analyses, the data were assessed for normality using measures of skewness and kurtosis, as well as histograms and normal Q-Q plots. The level of statistical significance was set at $p < 0.05$.

3. Results and Discussion

All quantitative results presented in the bar charts represent the mean values of the measurements, with error bars indicating the standard deviation (SD). The stress–strain curves shown in Figure 3 represent the typical tensile behaviour of the tested fabrics. The full Pearson correlation matrix of the measured fabric properties is presented in Table S1 in the Supplementary Materials.

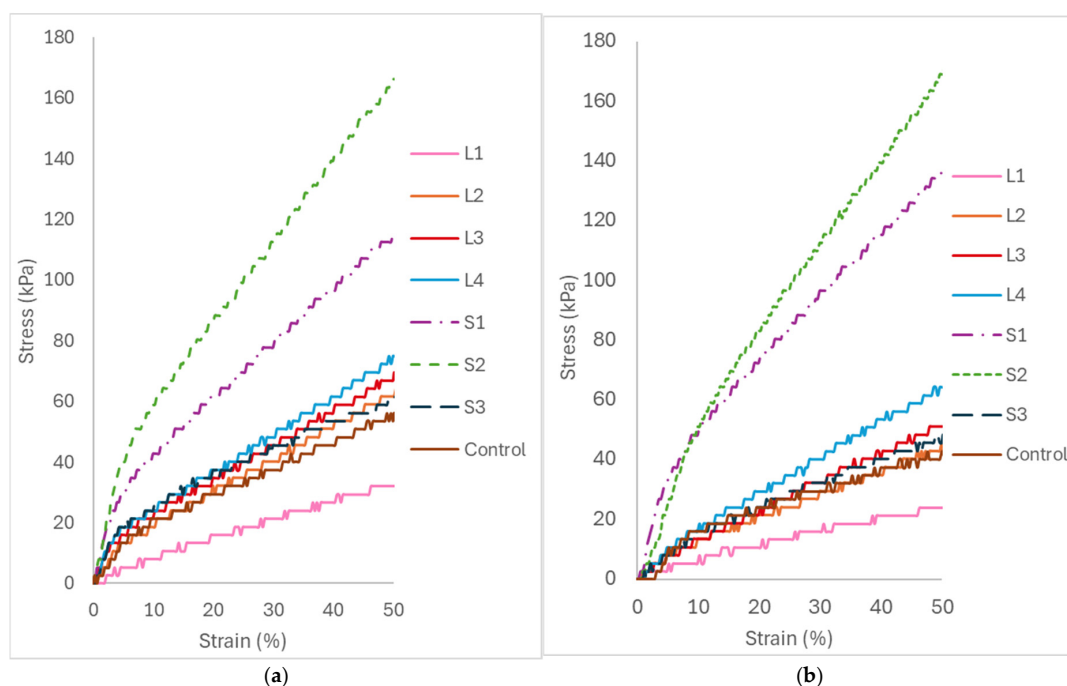


Figure 3. Tensile Stress–Strain curve of fabrics in the (a) weft and (b) warp direction.

3.1. Stretchability

MANOVA results indicate that the number of yarns has a significant effect on maximum load in both the weft (Yarn A: $F = 367.51$, $p < 0.001$, $\eta^2p = 0.96$; Yarn B: $F = 696.90$, $p < 0.001$, $\eta^2p = 0.98$; Yarn C: $F = 201.09$, $p < 0.001$, $\eta^2p = 0.94$) and warp directions (Yarn A: $F = 538.23$, $p < 0.001$, $\eta^2p = 0.975$; Yarn B: $F = 1062.55$, $p < 0.001$, $\eta^2p = 0.98$; Yarn C: $F = 141.77$, $p < 0.001$, $\eta^2p = 0.91$), whereas loop length and yarn type show no significant effects. A significant relationship was observed between fabric growth in the weft direction and loop length ($F = 26.55$, $p < 0.001$, $\eta^2p = 0.66$), as well as the number of yarn D ($F = 5.79$, $p = 0.026$, $\eta^2p = 0.29$). Fabric growth in the warp direction was significantly influenced by the number of yarn C ($F = 5.85$, $p = 0.025$, $\eta^2p = 0.29$). Pearson correlation analysis shows that maximum load in the weft and warp directions is almost perfectly correlated ($r = 0.99$, $p < 0.001$), indicating that they measure essentially the same property. Maximum load in both directions exhibits moderate negative correlations with the number of yarn A (Weft: $r = -0.54$, $p = 0.007$; Warp: $r = -0.55$, $p = 0.005$) and very strong positive correlations with the number of yarn B (Weft: $r = 0.91$, $p < 0.001$; Warp: $r = 0.95$, $p < 0.001$). Fabric growth in the weft direction is strongly positively correlated with loop length ($r = 0.77$, $p < 0.001$) and strongly negatively correlated with the number of yarn C ($r = -0.48$, $p = 0.019$). Fabric growth in the warp direction shows a moderate positive correlation only with fabric growth in the weft direction ($r = 0.42$, $p = 0.040$).

Tensile stress–strain curves (Figure 3) show that a steeper slope indicates a higher tensile modulus and greater fabric stiffness. A similar trend is observed in both the weft and warp directions for the punch-lace knitted fabrics. Regarding the effect of loop length, L4 has the smallest loop length and the highest tensile modulus, followed by L3 and L2. This suggests that, within the tested samples, fabrics with smaller loop lengths tend to exhibit greater resistance to extension in both directions. This observation is consistent with the pressure measurements, where L4 exhibits higher pressure than L3 and L2. These findings suggest that smaller loop lengths increase fabric stiffness and consequently provide higher compression to the wearer.

Considering the effect of yarn number, S2 and L2 exhibit higher tensile modulus than S1 and L1, respectively, in the weft direction. This suggests that the samples containing two additional ends of yarn C (S2 and L2) exhibit greater resistance to extension in the weft direction. In the warp direction, S2 displays a less steep stress–strain curve than S1 at low strain (up to approximately 10%), after which the curve becomes steeper. This behaviour may be attributed to the additional two ends of yarn C, which slightly reduce the initial fabric length in the warp direction after knitting. As the fabric extends beyond 10% strain, the additional yarn begins to restrict further extension, requiring greater force. With respect to yarn types, S3 exhibits a higher tensile modulus than L1 under the same loop length and also produces higher pressure. This suggests that the sample containing 25D 77% nylon 23% spandex (yarn D) exhibits greater elastic resistance and compression than the sample containing 43D 69% nylon 31% Lycra (yarn A).

Maximum load at 50% elongation represents the force required to extend the fabric to 50% of its original length; higher values indicate stronger and stiffer fabrics. Fabric S2 exhibits the highest maximum load in both weft (8.32 N) and warp (8.59 N) directions, followed by S1 (Weft: 5.90 N; Warp: 6.64 N). This suggests that samples containing 90D 86% nylon 14% spandex (yarn B) exhibit higher maximum load values in both weft and warp directions. Under the same loop length conditions, the addition of two ends of 94 dtex 80% polyamide 6.6 20% Lycra (yarn C) in S2 further strengthens the fabric structure, requiring greater force for extension in both directions.

Fabric growth represents the extent to which the fabric fails to return to its original length after extension. This parameter is critical for compression textiles, which are re-

peatedly stretched during wear; excessive growth may reduce pressure performance and shorten product lifespan. In the weft direction, fabric growth decreases from 7.14% in L2 to 2.86% in L4 as loop length decreases from 5.5 to 4.6. Stretchability in the weft direction is primarily governed by loop geometry (Figure 4b), as the knitted loop structure naturally facilitates extension. A smaller loop length results in a tighter structure, restricting yarn movement and stabilising the fabric, thereby improving recovery after extension.

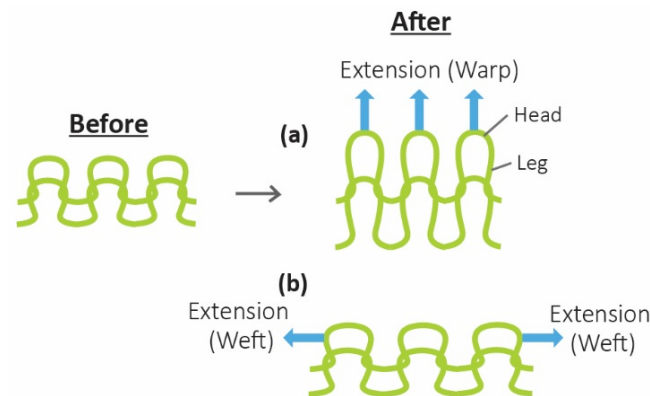


Figure 4. Loop movement during the extension in the (a) weft and (b) warp direction.

A similar trend is observed for L1 (12.32%) and L2 (7.14%), and for S1 (10.34%) and S2 (6.86%). The addition of two ends of yarn C in L2 and S2 reduces fabric growth compared with L1 and S1, respectively, in the weft direction. The additional yarn may restrict loop movement and contribute to improved recovery after extension.

In the warp direction, fabric L4 (8.04%) exhibits greater growth than L3 (1.7%) and L2 (6.38%), despite having the smallest loop length. This may be attributed to the extension mechanism in the warp direction, which primarily stretches the loop head and leg (Figure 4a). In tighter fabrics with smaller loop lengths, such as L4, the yarn experiences higher tensile tension for a given extension compared with looser fabrics such as L2, as the reduced loop geometry limits structural deformation and shifts the load to the yarn itself. This increases the likelihood of plastic deformation and incomplete recovery after extension.

3.2. Pressure

Pearson correlation analysis revealed that pressure is strongly positively correlated with the number of yarn B ($r = 0.85$, $p < 0.001$) and moderately negatively correlated with the number of yarn A ($r = -0.52$, $p = 0.010$). Pressure also shows very strong positive correlations with maximum load in both the weft ($r = 0.93$, $p < 0.001$) and warp directions ($r = 0.93$, $p < 0.001$). However, no significant correlations were found between pressure and loop length or yarn type ($p > 0.05$). MANOVA results further indicate that the number of yarn A ($F = 27.03$, $p < 0.001$, $\eta^2p = 0.66$), yarn B ($F = 46.25$, $p < 0.001$, $\eta^2p = 0.77$), and yarn C ($F = 8.28$, $p = 0.009$, $\eta^2p = 0.37$) significantly affect pressure. The pressure results observed in this study are consistent with the general trend in our previous study, where compression pressure was mainly associated with the number of yarns.

According to the German Standard RAL-GZ 387:2008 [19], compression levels are classified as Class 1 (18–21 mmHg), Class 2 (23–32 mmHg), and Class 3 (34–46 mmHg). Among the punch-lace fabrics shown in Figure 5, S2 exhibits the highest pressure at the ankle (26 mmHg, Class 2 compression), followed by S1 (23.17 mmHg, Class 2 compression), and L4 (21 mmHg, Class 1 compression). In terms of yarn number, both S1 and S2 produce higher pressures than the other fabric samples containing yarns A and D, suggesting that samples containing 90D 86% nylon 14% spandex (yarn B) tend to exhibit higher compression. The sample S2, which contains two additional ends of 94 dtex 80% polyamide

6.6 20% Lycra (yarn C), shows a higher pressure (26 mmHg, Class 2 compression) compared with S1 (23.17 mmHg, Class 2 compression). However, L2 shows a pressure level similar to L1, despite the addition of two ends of yarn C. This difference may be attributed to the varying yarn combinations in these fabric pairs. The addition of yarn C appears to enhance fabric pressure when combined with yarn B, but not when combined with yarn A.

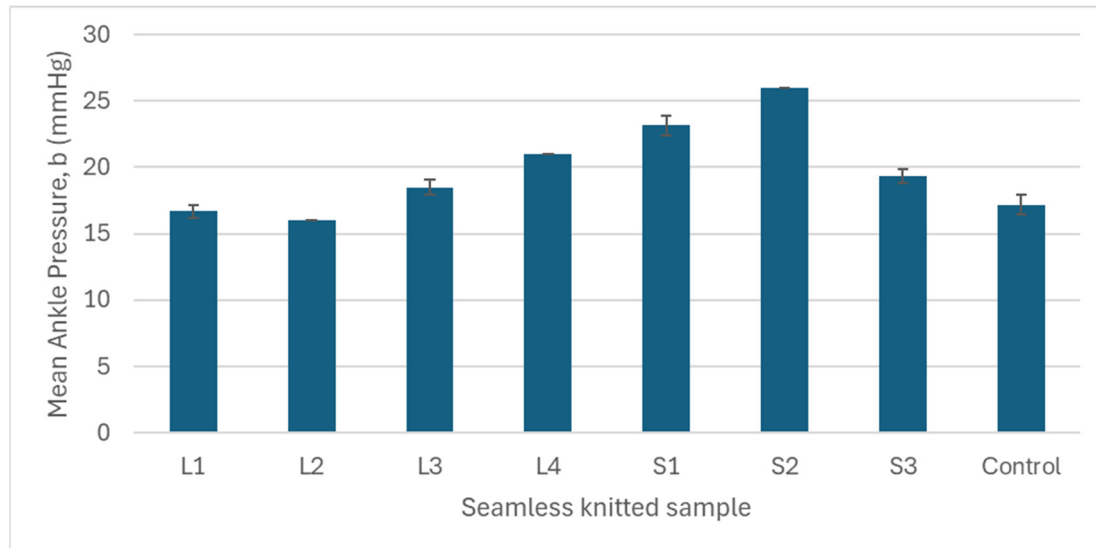


Figure 5. The pressure of the seamless punch-lace knitted fabrics and the control fabric.

Comparing S3 and L1, S3 (19.33 mmHg, Class 1 compression) exhibits higher pressure than L1 (16.67 mmHg, below Class 1 compression), suggesting that the sample containing 25D 77% nylon 23% spandex (high power; yarn D) produces higher compression than 43D 69% nylon 31% Lycra (double low power; yarn A). Notably, fabric S1 (23.17 mmHg) produces approximately 35% higher pressure than the control fabric (17.17 mmHg) under the same loop length, suggesting that the punch-lace structure incorporating two additional ends of 90D 86% nylon 14% spandex (yarn B) is associated with higher compression performance.

Similar to the trend observed for maximum load in both the weft and warp directions, measured pressure increases from L2 to L4 (Figure 5). A smaller loop length in L4 results in a tighter structure and higher fabric stiffness. Stiffness describes the material's resistance to deformation under an applied force, particularly when the fabric expands due to muscle movement during wear. Increased stiffness, therefore, leads to higher applied pressure on the body and may also be interpreted as a greater change in compression per change in limb circumference [21,22]. This explains the strong positive correlations between pressure and maximum load in both the weft and warp directions. Fabrics with higher stiffness require greater force to extend and consequently exert higher compression pressure on the wearer. Overall, several punch-lace knitted samples achieved Class 2 compression levels, indicating their potential suitability for moderate medical compression applications.

3.3. Air Permeability, Thermal Conductivity and Water Vapour Permeability

3.3.1. Air Permeability

For air permeability, lower ventilation resistance values indicate higher breathability and permeability. MANOVA results show significant effects of the number of yarns A ($F = 631.45$, $p < 0.001$, $\eta^2 p = 0.98$), B ($F = 126.76$, $p < 0.001$, $\eta^2 p = 0.90$), and C ($F = 93.70$, $p < 0.001$, $\eta^2 p = 0.87$), as well as yarn type ($F = 6.41$, $p < 0.05$, $\eta^2 p = 0.31$), on ventilation resistance, whereas loop length has no significant effect

As shown in Figure 6, the addition of two extra ends of yarn C in S2 and L2 results in higher ventilation resistance compared with S1 and L1, respectively. This suggests that samples containing additional yarn C exhibit lower air permeability, consistent with findings from our previous study [18]. This effect can be attributed to the increased fabric thickness and reduced porosity caused by the additional yarn, which restricts airflow through the fabric.

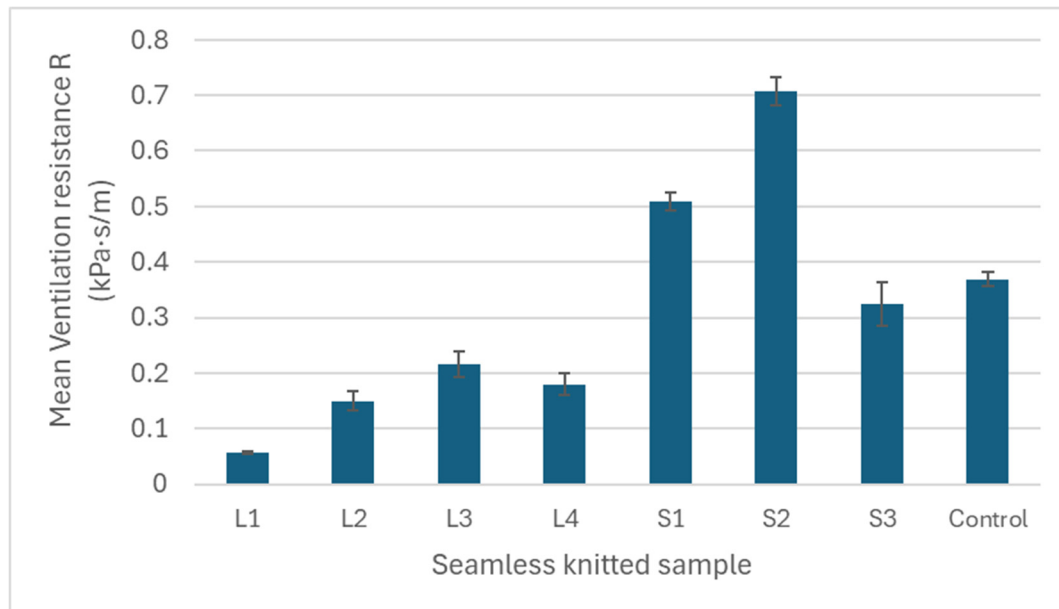


Figure 6. Ventilation resistance of the seamless punch-lace knitted fabrics and the control fabric.

Regarding yarn type, L1 exhibits lower ventilation resistance than S3 (Figure 6), suggesting that the sample containing 43D 69% nylon 31% Lycra (yarn A) exhibits better breathability than 25D 77% nylon 23% spandex (yarn D) in S3.

3.3.2. Thermal Conductivity

Pearson correlation analysis shows that thermal conductivity is strongly positively correlated with ventilation resistance ($r = 0.65$, $p < 0.001$). Among the seamless knitted samples, fabric S2 exhibits the highest thermal conductivity and ventilation resistance, followed by S1 and L3. This indicates that while S2 transfers heat more efficiently, it is less breathable. Thermal comfort in compression textiles is a multidimensional property that depends not only on heat conduction but also on air permeability, water vapour transport, fabric thickness, and fabric roughness. Therefore, higher thermal conductivity alone does not necessarily guarantee improved thermal comfort, and the overall comfort performance depends on the balance among these properties.

Similar to air permeability, MANOVA results indicate that thermal conductivity is significantly influenced by the number of yarns A ($F = 36.31$, $p < 0.001$, $\eta^2p = 0.72$), B ($F = 40.26$, $p < 0.001$, $\eta^2p = 0.74$), C ($F = 5.58$, $p = 0.03$, $\eta^2p = 0.29$) and D ($F = 7.23$, $p = 0.014$, $\eta^2p = 0.34$), as well as Yarn type ($F = 40.50$, $p < 0.001$, $\eta^2p = 0.74$), whereas loop length has no significant effect ($p > 0.05$). Thermal conductivity increases as the number of yarn C increases. For example, when the number of yarn C increases from two ends in L1 to four ends in L2, thermal conductivity increases, and a similar trend is observed between S1 and S2 (Figure 7). This behaviour can be mainly attributed to structural changes in the knitted fabric. The addition of more yarn ends increases the packing density of the fabric structure, thereby reducing the proportion of entrapped air. Because air has very low thermal conductivity and therefore acts as an insulating medium, reducing the air spaces

allows heat to transfer more efficiently through the fibre network. In addition, a higher yarn content increases the number of contact points between yarns, facilitating conductive heat transfer along the fabric structure. Consequently, thermal conductivity increases even though the overall fabric thickness increases, which is consistent with observations reported in our previous study [18].

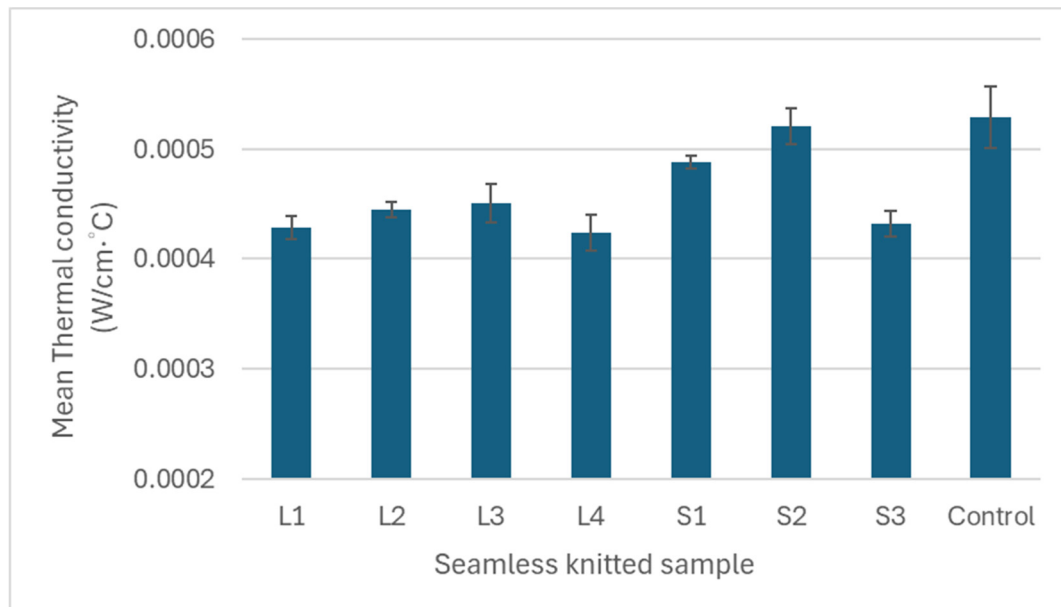


Figure 7. Thermal conductivity of the seamless punch-lace knitted fabrics and the control fabric.

With respect to Yarn type, L1 shows thermal conductivity values similar to S3, suggesting that yarns A and D have comparable effects on heat transfer. Since loop length does not significantly influence thermal conductivity, the higher values observed in S1 and S2 compared with L1 and L2 indicate that the inclusion of 90D 86% nylon 14% spandex (yarn B) contributes more to thermal conductivity than 43D 69% nylon 31% Lycra (yarn A). This difference may be related to differences in yarn composition, including the higher nylon content. Consequently, samples containing yarn B may dissipate heat more efficiently than those knitted with yarn A. However, overall thermal comfort depends on multiple interacting properties, including air permeability, water vapour transport, and fabric smoothness. Therefore, improved heat conduction should be considered together with these factors when evaluating the comfort performance of compression textiles. Overall, the findings suggest that yarn type and yarn quantity are important parameters associated with variations in fabric thermal conductivity.

Interestingly, the control fabric exhibits the highest thermal conductivity, comparable to that of S2. Although S2 and the control fabric share the same loop length, S2 has greater thickness (1.77 mm) and areal density (452.24 g/m²) than the control fabric (1 mm thickness; 242.45 g/m²). S2 also contains two additional ends of yarns B and C compared with the control. Despite these structural differences, the punch-lace fabric in S2 achieves a similar level of conductive heat transfer to the single-jersey control fabric. This suggests that the yarn combination used in S2 enables punch-lace knitted fabrics to achieve thermal conductivity levels comparable to those of the single-jersey control fabric. This finding highlights the potential of punch-lace knitted fabrics as an alternative to conventional single-jersey structures for compression textile applications. However, the overall thermal comfort of compression textiles depends on the combined effects of heat transfer, breathability, moisture management, and surface smoothness.

3.3.3. Surface Friction and Roughness

MANOVA results indicate that the number of yarns, yarn types, and loop length significantly influence the surface properties of seamless knitted fabrics in both the warp and weft directions ($p < 0.05$). In general, increasing the number of yarn C—from two ends in L1 to four ends in L2, and from two ends in S1 to four ends in S2—leads to higher MIU and SMD values in both directions, indicating increased surface friction and roughness (Figures 8 and 9).

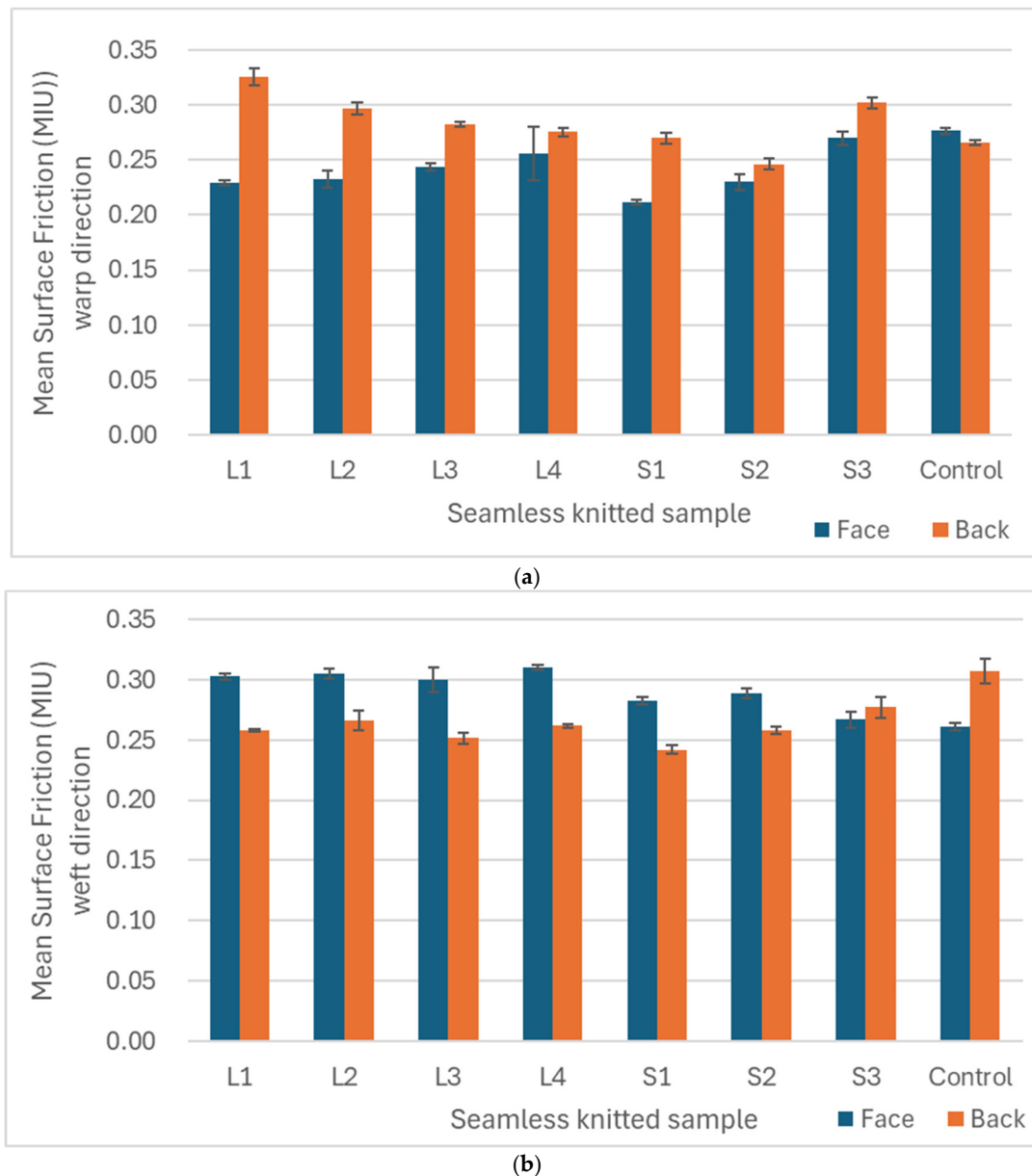


Figure 8. Surface friction (MIU) of seamless punch-lace knitted fabrics and the control fabric in (a) warp and (b) weft direction.

Among the samples, S1 shows lower MIU and SMD values on average across different directions and fabric faces, suggesting that this fabric exhibits lower friction and a smoother surface. Pearson correlation analysis further reveals that surface friction on the fabric back in the warp direction (MIU back warp) has a very strong negative correlation with ventilation resistance ($r = -0.79$, $p < 0.001$). This suggests that fabrics with lower air permeability tend to exhibit smoother surfaces in the warp direction.

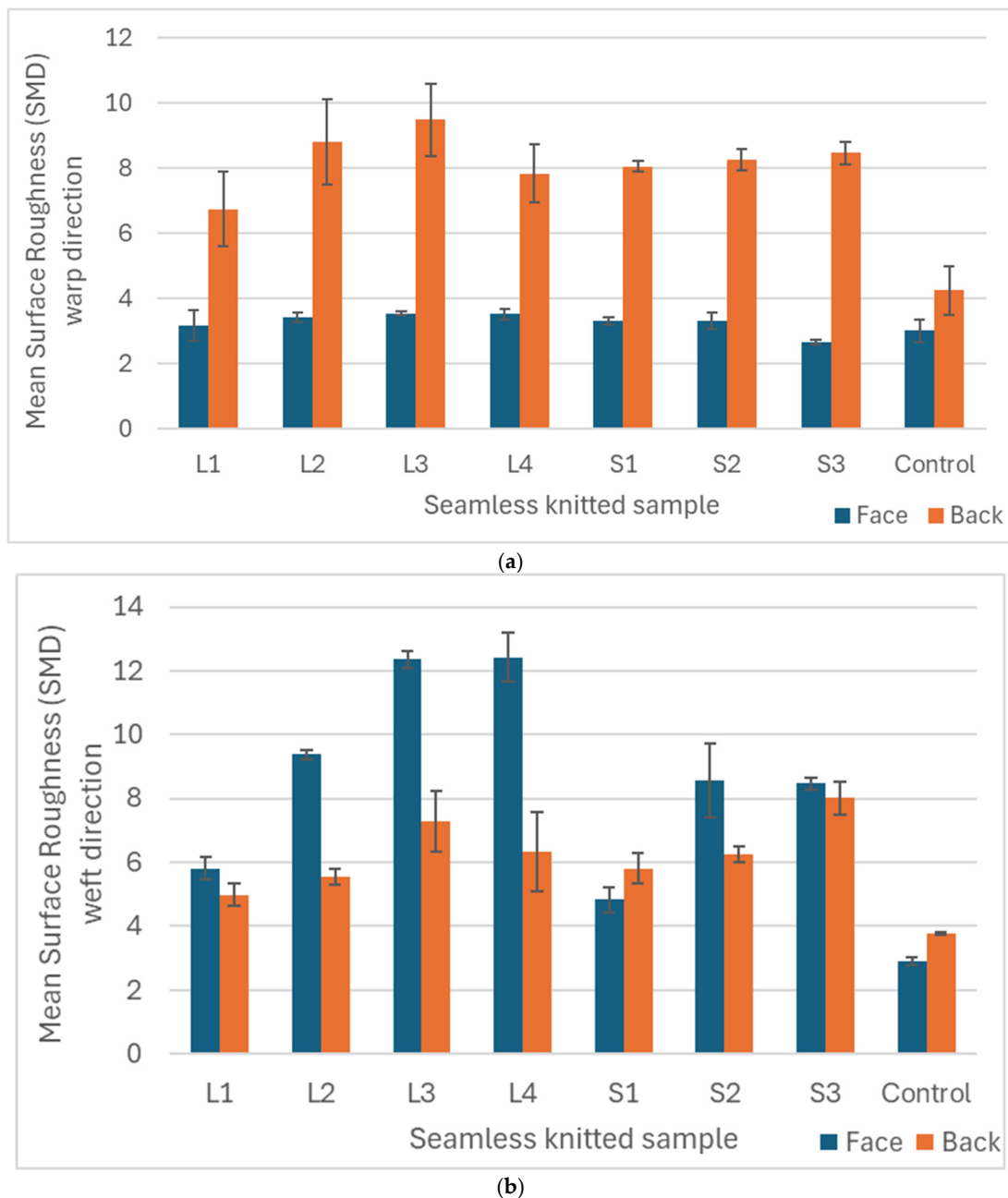


Figure 9. Surface Roughness (SMD) of seamless punch-lace knitted fabrics and the control fabric in (a) warp and (b) weft direction.

This relationship may be explained by the fact that smoother fabric surfaces are typically produced by tighter loop structures and finer yarns, often achieved using finer-gauge knitting machines. These conditions create a denser and more compact fabric structure with reduced pore size and porosity, which restricts airflow through the fabric and consequently lowers air permeability. Fabric smoothness is considered an important factor influencing wearer comfort and may have long-term implications for treatment compliance when used in medical compression applications.

3.3.4. Water Vapour Permeability (WVP)

Pearson correlation analysis shows no significant relationships between water vapour permeability (WVP) and loop length, number of yarns, or yarn type in this study ($p > 0.05$). As shown in Figure 10, all seamless knitted fabrics and the control fabric exhibit similar

WVP values. This suggests that factors beyond those investigated in this study may influence WVP, and further research is required to identify the key determinants of moisture transfer in compression textiles.

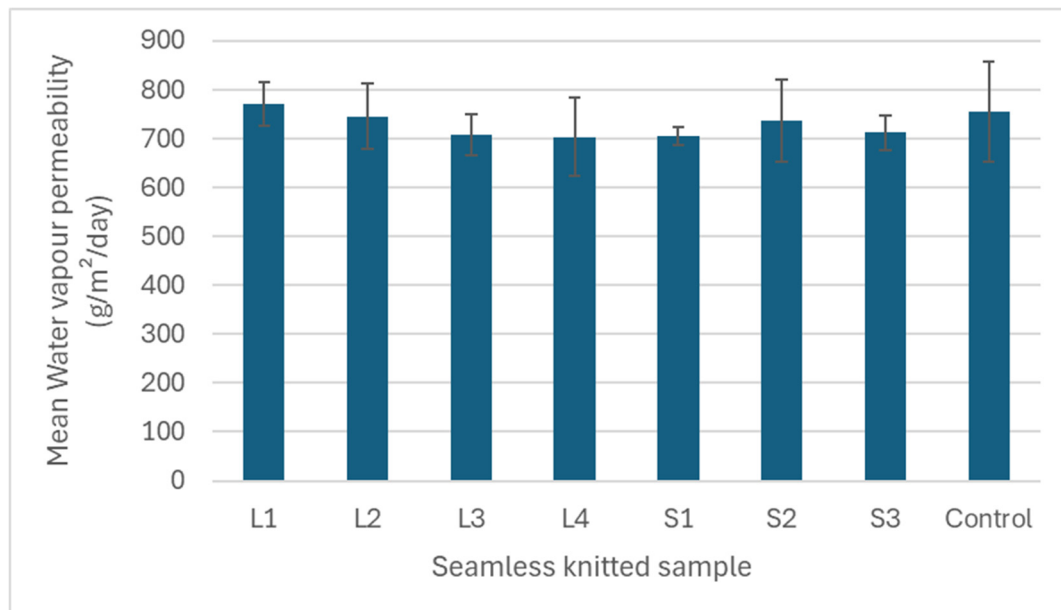


Figure 10. Water vapour permeability of seamless punch-lace knitted fabrics and the control fabric.

4. Conclusions

This study investigated the influence of yarn type, number of yarn ends, and loop length on the mechanical and thermal properties of seamless punch-lace knitted fabrics for compression applications. The results indicate that the number of yarn ends is the dominant parameter associated with variations in fabric stiffness and maximum load in both weft and warp directions. In contrast, loop length and yarn type did not show statistically significant associations within the tested samples. Smaller loop lengths and the inclusion of yarn C were associated with improved dimensional stability by restricting loop deformation.

Compression pressure is strongly associated with fabric stiffness and maximum load. Samples containing a higher number of yarns, particularly yarn B, exhibited higher compression levels, while tighter loop structures contributed indirectly through increased stiffness. Air permeability decreased with increasing yarn number, especially with the inclusion of yarn C, due to increased fabric thickness and reduced porosity. Yarn A exhibited relatively better breathability compared with yarn D. Thermal conductivity was also associated with yarn number and yarn type and showed a positive relationship with ventilation resistance, highlighting a trade-off between heat transfer and breathability. Surface properties were influenced by yarn number, yarn type, and loop length, with denser structures generally producing smoother surfaces but lower air permeability.

Among the tested samples, fabric S2 achieved the highest compression level and demonstrated favourable mechanical and surface characteristics; however, it also exhibited reduced air permeability. This highlights the inherent trade-off between compression performance and comfort-related properties in seamless knitted compression textiles. Therefore, the suitability of a given fabric configuration depends on the specific application requirements and the desired balance between compression, breathability, and thermal comfort.

However, due to the limited number of independent specimens, the results should be interpreted with caution and considered as comparative trends among the tested fabric configurations. Overall, this study demonstrates the potential of seamless punch-lace

knitted fabrics for compression applications and provides practical insights for the design of seamless compression textiles with balanced mechanical and comfort performance.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/textiles6020039/s1>, Table S1. Pearson correlation matrix of the measured fabric properties. Table S2. Surface Friction (MIU) of seamless punch-lace knitted fabrics and the control fabric. Table S3. Surface Roughness (SMD) of seamless punch-lace knitted fabrics and the control fabric.

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