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Comfort Properties of Medical Compression Stockings from Biodesigned and Cotton Fibers

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Abstract: Medical compression stockings (MCS) are special products with high stretchability, which are frequently used for physical therapy of varicosities, lymphedema, deep vein thrombosis and, post thrombotic syndrome. They support blood flow and muscle systems by applying pressure to the leg and are in contact with the skin closely. During long flights, body's working system changes due to the low air pressure and dry air, and use of low pressure compression stockings reduces long flight related symptoms of discomfort, swelling, fatigue, aching and tightness. Generally, synthetic yarns are used in compression stockings, and low air and moisture permeability as well as short lifespan are their main problems. From this point of view, the aim of this study has been to minimize the complaints related to the lack of comfort of compression stockings by developing new products using cotton and biodegradable Umorfil nylon 6 (Umorfil® N6U) fiber which has collagen peptid bonds in its structure. The results showed that not only the developed stockings have relatively better comfort related properties than the ones from conventional nylon fiber but also they exhibit sufficient pressure performance for travel stockings.

Keywords: Medical compression stockings, Umorfil N6U, Comfort, Class 1, Medical textiles

Introduction

The veins are the vessels that carry blood from the legs to the heart. The veins have a series of valves that open and close to allow the blood flow directly to the heart and to prevent the escape of blood back. If the valves within the veins do not work correctly, the blood can flow back and cause pooling in the legs. This pooled blood can raise pressure in the veins and affects limp health, resulting in conditions such as edema, varicose veins, hyperpigmentation, ulceration, phlebitis lymphedema and deep venous thrombosis (DVT) [1]. It has been demonstrated that increased risk of thrombosis is associated with prolonged air travel and exercise [2]. Compression therapy uses special type of compression stockings, such as travel stockings, which constricts the widening of veins by creating pressure on surface of the calves. These stockings help increase circulation and reduce the risk of swelling and clotting on a long flight [3].

According to an analysis reported, risk of venous thromboembolism is increased three-fold when travel duration increases. An increase of 18 % risk is reported per two-hour increase in duration [4]. In another study, 231 airline passengers aged over 50 years with no history of venous thromboembolism were randomly assigned to wear below-knee graduated compression stockings or no stockings in journeys lasting more than eight hours [4]. None of the passengers who wore the stockings had deep vein thrombosis, whereas 12 of 116 who did not wear stockings had asymptomatic deep calf vein thrombosis identified [4,5]. In addition, older passengers live this problem more than younger people do and consequently get greater benefit of wearing compression stockings, even during short-haulflights [6].

Medical compression stockings (MCS) exert pressure to the application area by releasing the kinetic energy stored on stretched elastomeric fabric at a decreasing gradient from the ankle towards the thigh. The applied pressure increases blood flow and prevents activation of clotting factors [7,8]. This varying degree of compression pressure propagate and regulate blood flow, keep the muscles in-line at the right position to mitigate the injury risk, gives relief to many of chronic venous disease patients and used for therapeutic purposes [9]. In addition, the ankle region is a most critical region since it is the predilection place for venous leg ulcers. The compression at this place should therefore be high enough to compensate the venous insufficiency [10]. In compression therapy provided by medical compression stockings, it is important to know the pressure profile, dosage of compression and pressure distribution since insufficient pressure will limit efficiency while too much pressure will result in reducing heart and lung functions, and perhaps will cause serious damage to health [1,11].

The degree of pressure provided by compression stockings is classified into several standards and, unfortunately, there is no single standard used worldwide [12-14], though in general, for those traveling long distances 15-20 mmHg compression level (medium/preventive level) is often prescribed for leg relief, mild varicose veins, or as a safeguard against DVT and swollen ankles during long-distance travel for those with no specific vascular problems [15,16].

Patients are not always willing to use medical compression stockings due to the difficulties they experience in putting the stockings on and discomfort feelings during long-time

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use, although the stockings have been proven to be an efficient compression therapy for preventing or healing venous diseases. Because of the extreme sensitivity of the skin, comfort characteristics of compression materials play a critical role in user compliance and healing [9]. According to the results of a study that was conducted to describe compliance rates of compression therapy with patients having chronic venous disease and also to describe frequent causes of non-compliance, the main reasons of non-compliance were found to be as follows: uncomfortable (49.4 %), too difficult to put on (34.5 %), skin problems (itching) (21.5 %), and unattractive (19.8 %) [17]. Skin irritation and related discomfort issues can be observed when using compression products.

The difficulty of putting on an MCS and uncomfortable feeling are closely associated with the friction of the stocking against human skin and fiber properties. The higher the friction between MCS and skin, the more difficult it is to wear the stocking. Perspiration during usage is another factor that leads to disturbance. The surface properties of the fabrics, fibre properties and, moisture at the skin-textile interface are important factors in determining usability and sensorial comfort of MCSs [18]. The water absorption and transportation capacity of such socks are also expected to vary with the textile construction as well as the fibre composition [19].

Compression stockings in the market are generally produced from nylon, and these products generally cause comfort related difficulties such as skin dryness and itching. In order to overcome such skin problems including varicose eczema and lymphorrhoea, use of cotton liners beneath compression hosiery is recommended to the patients [20].

Accordingly, the study was conducted to minimize the comfort related complaints of compression stockings by incorporating the innovative and biodegradable Umorfil Nylon 6 (N6U) fiber, which has collagen peptide bonds in its structure [21], and cotton into MCSs used during long flights.

Experimental

Materials

The travel stockings that could fit Tendon Circumference of 35-38 cm which meet preventive (i.e. mild) compression level requirements (15-20 mmHg) were designed and produced. The stockings were manufactured such that the ground yarns form the main body of stockings which is in touch with the skin and gives thickness and stiffness to the fabric whereas the inlay yarns generate compression, and their properties significantly reflect the compression behavior of fabrics. Accordingly, in the study, three different ground and inlay yarns were utilized in two different single jersey knitted fabric structures (Figure 1) to produce 18 seamless, knee-high, open toe compression socks.

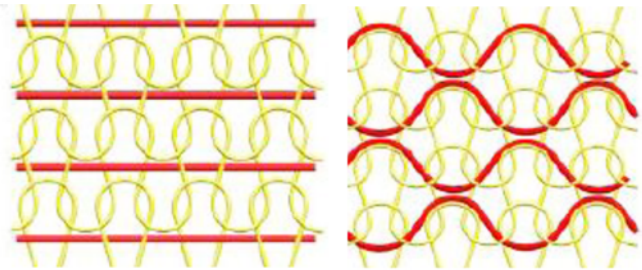

Figure 1. The single jersey fabric structures for the work [22]; (a) elastic yarns are as weft inlay stitch and (b) elastic yarns are as laid-in stitch.

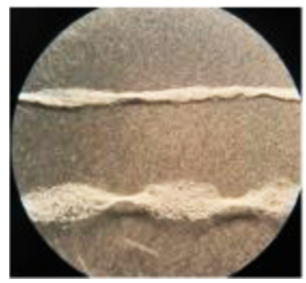

Figure 2. Umorfil® N6U and nylon filament yarns.

Figure 2 shows the longitudinal appearance of Umorfil® N6U and Nylon filament yarns employed for the study. N6U, which is a new kind of nylon 6, is produced by integrating the purified collagen peptide (amino acid) from waste fish scales with regular nylon 6 polymerization technology. Umorfil® N6U is a bionic nylon fiber with better moisture regain (in comparison to regular nylon), skin-friendly, deodorizing and, excellent color fastness properties [21].

The structural details as well as the coding of both the inlay (I) and ground (G) yarns are given in Table 1.

The samples were produced on a Merz CC4 II-8 Circular Knitting Machine with 28 gauge (E), 484 needles. The inlay and ground yarns were inserted in the fabrics at the constant

Table 1. Coding and content of the yarns

Yarn	Content*
G1	40/34×2 nylon 66 (two-ply)
G2	40/36×2 umorfil nylon 6 (two-ply)
G3	Ne 80/1 cotton
I1	310 dtex elastane / 22/7×2 nylon 66 (double cover, DC)
I2	285 dtex elastane / 22/7×2 nylon 66 (double cover, DC)
I3	285 dtex elastane / 33/24 nylon 66 + 80/1 cotton (double cover, DC)

*Filament yarn counts expressed in denier.

input tensions of 1,8 cN and 2,6 cN, respectively. In Table 2, the weight percentages (%) of the ground and inlay yarns in each stocking sample are also presented.

After the production, the stockings were subjected to washing (TS EN ISO 6330: 2012) with Primus RS18 18KG Industrial Washing Machine, and then they were ironed under commercial conditions using ALBA B04 industrial type press.

Test Methods

The input tensions of the inlay and ground yarns were kept constant during the knitting process. For comparative reasons, the elongation percentage values of all yarns were determined under a fixed load of 100 g using a Dinema DSC Touch 7-Black edition apparatus. Ten (10) cm length of each yarn was stringed to the Dinema apparatus that applied a load of 100 g by the help of its electronic system. Measured lengths of the yarns under the load were used for yarn elongation percentage calculations. The results are given in Table 3. Table 4, on the other hand, presents the fabric properties of the stockings at the ankle region where pressure values were recorded.

Water vapor permeability (ASTM E96-00), weight (ASTM D3776), stiffness (ASTM 4032) and thickness (ASTM D1776-96) of the stocking samples were measured in accordance with the relevant standards. Friction coefficients of the samples were determined using Frictor Fabric Friction Tester. Porosity of the samples were calculated in accordance with the equation (1) where P is porosity, m: fabric weight (g/cm^2), h: fabric thickness (cm) and ρ: fiber density (g/m^3).

$$P = 1 - \frac{m}{\rho \cdot h} \times 100 \qquad (1)$$

Pressure exerted by the stockings were tested using MST-Professional 2 Medical Stocking Tester to ensure that they meet the desired pressure level [23]. 3D construction mechanism of the tester provides observation of pressure at B, B1, C and D areas according to the desired size. The pressure measuring points for medical compression stockings (MCS) are shown in Figure 3 [11].

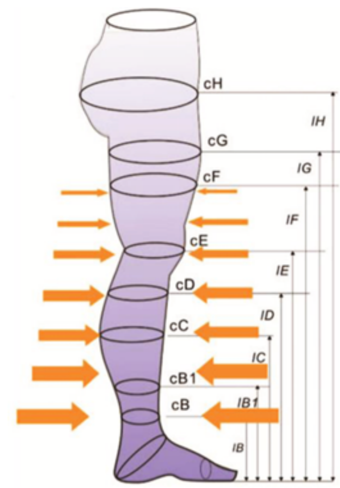

Figure 3. Pressure measurement points [11].

Minitab 17 package program was used to perform interaction relationship evaluation of the data obtained from full-factorial experiments.

Table 2. Weight percentages of the ground yarns to the inlay yarns

Sample	Structure SJ-A (G/I %)	Structure SJ-B (G/I %)
G1-I1	57/43	57/43
G1-I2	58/42	58/42
G1-I3	50/50	45/55
G2-I1	57/43	57/43
G2-I2	60/40	58/42
G2-I3	51/49	46/54
G3-I1	53/47	53/47
G3-I2	57/43	54/46
G3-I3	42/58	41/59

Table 3. Yarn elongation values of the samples

Yarn	Elongation (%) under 100 g
Ground yarns	
G1	27
G2	11
G3	268.75
Inlay yarns	
I1	242.25
I2	262
I3	293

Results and Discussion

Pressure Test Results

Pressure levels of the stockings at the ankle were recorded to be in the range of 11 to 20.1 mm Hg (Figure 4).

As was stated in the literature [24], the level of compression is largely determined by the materials and the construction method used. The compression stockings in which Umorfil Nylon 6 yarns were employed in the ground, irrespective of the knitting structure, tended to display higher pressure values, when compared to their counterparts. The pressure of the stockings whose grounds were knitted by a relatively finer yarn namely G3-Ne 80 Cotton, on the other hand, were slightly below than that of the other samples for both types of knitted structures. The results also revealed that the compression stockings having elastic yarns that are incorporated in the fabric as laid-in stitch (i.e. SJ-B) would exert higher pressure during wear than the SJ-A ones in which elastic yarns are as weft inlay stitch. All the pressure

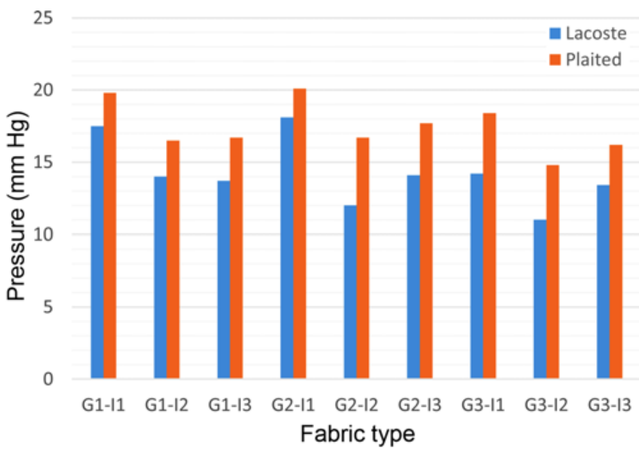

Figure 4. Pressure values of the compression stockings.

values recorded for the SJ-B stockings were higher than 15 mmHg. The pressure difference between the two structures (i.e. SJ-A, and SJ-B) appears to be largely governed by their differences in weight, thickness, and stitch density properties (Table 4, Figure 5C). This result was supported with the paired t-test (t=-6.030, sig. 0.000).

Furthermore, as the linear density of elastane of the inlay yarn was increased, thickness and weight as well as the pressure of the corresponding stocking tended to increase (Table 4 and Figure 5B). The elongation values of the yarns given in Table 3 may also have contributed to this very finding since the inlay yarns with coarser elastane are expected to result in lower extention in the corresponding fabric at a given tension, and in turn exert a higher influence on pressure. The samples from the I2 inlay yarn with finer elastane (285 dtex) showed the lowest pressure values in general. On the other hand, the stockings from I3 inlay yarns in which finer (285 dtex) elastane is covered by both nylon and cotton yarns did have higher pressure values than the ones with the I2 inlay yarn. This may be governed by the count as well as the material of the relevant cover yarns (i.e. I3) as both has an influence on the geometric and morphologic deformations in stitch structure, which in turn impacts the loop densities and contact forces thus varying the interfacial pressure generated during stretching. ANOVA results also implied that inlay yarn is a significant factor on the pressure values of the stockings (F=18.209, sig. 0.000).

Water Vapor Permeability Results

Appropriate moisture conditions should be kept for MCS wearer to prevent formation of dry conditions, that may lead to a skin vulnerable to cracking and, wet conditions that may lower the tissue tolerance to shear stress and friction. The clothing system plays an important role in moderating liquid and moisture to maintain a healthier micro-climate near the skin surface [25]. Two main factors that govern the water vapour transmission of textiles are fibre content and fabric geometry. Diffusion through air in fabric voids, diffusion through fibers and transfer of adsorbed water molecules along fiber surfaces are the ways in which water vapor is transferred through fabrics [26].

The results of our study showed that the water vapour permeability of the compression stockings were mainly

Table 4. Properties of the stockings

Sample	Thickness (mm)		Stitch density (cpcm×wpcm)		Weight (g/m^2)		Density (kg/m^3)		Porosity (%)	
SJ-	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
G1-I1	0.63	0.71	432 (18×24)	363 (16.5×22)	209	215.7	331.75	303.80	0.89	0.87
G1-I2	0.66	0.70	450 (18×25)	357 (17×21)	202.5	226.6	306.82	323.71	0.88	0.86
G1-I3	0.72	0.69	432 (18×24)	379.5 (16.5×23)	227.6	262	316.11	379.71	0.86	0.85
G2-I1	0.67	0.67	425.5 (18.5×23)	352 (16×22)	202	252.1	301.49	376.27	0.91	0.88
G2-I2	0.65	0.66	408 (17×249	371.25 (16.5×22.5)	207.2	235.1	318.77	356.21	0.90	0.88
G2-I3	0.68	0.73	375 (15×25)	336 (16×21)	227.5	270.3	334.56	370.27	0.88	0.85
G3-I1	0.62	0.63	350 (14×25)	290 (14.5×20)	165.1	199.5	266.29	316.67	0.92	0.91
G3-I2	0.57	0.59	315 (15×21)	315 (14×22.5)	160.1	188.1	280.88	318.81	0.93	0.92
G3-I3	0.62	0.71	350 (14×25)	280 (14×20)	201	207	324.19	291.55	0.91	0.89

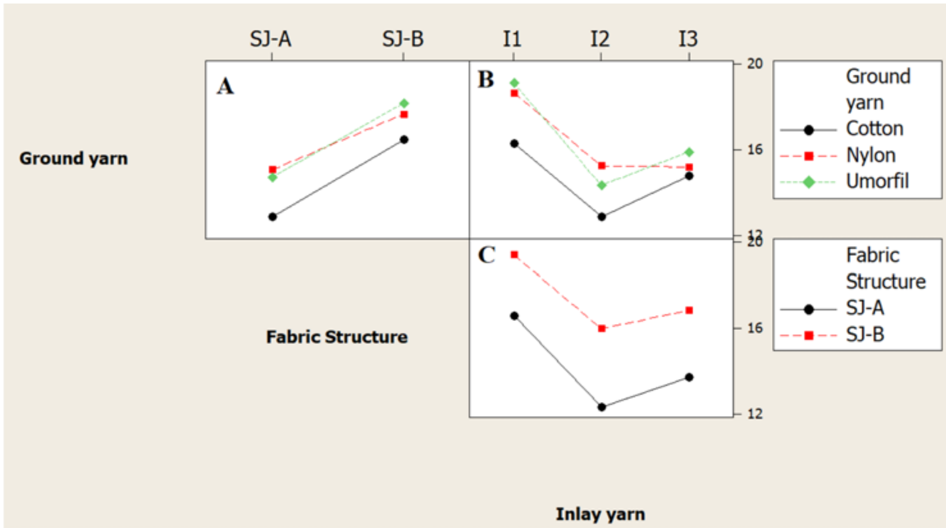

Figure 5. Interaction plot for pressure values.

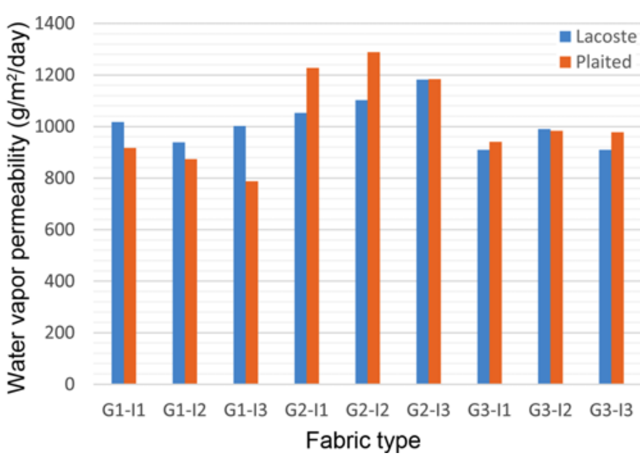

Figure 6. Water vapor permeability of the compression stockings.

governed by the fibers employed in the ground yarns, in particular by the superior moisture transfering ability of Umorfil fibers. Irrespective of both the fabric structure and inlay yarn properties, the stockings with Umorfil ground yarns (i.e. G2-I1, I2, and I3) demonstrated better water vapor transfer performance than the other samples (Figure 6, Figure 7A). ANOVA evaluation also supported this result, such that Umorfil stockings are significantly different from cotton and nylon ones (F=72.661, sig. 0.000). Furthermore, SJ-B fabrics with Umorfil ground yarns performed higher water vapor permeability than the corresponding SJ-A ones whereas there is not such a consistent pattern observed for the SJ-B samples from Nylon and cotton grounds. Moreover, according to paired t-test there is no significant difference between plaited and lacoste stockings (t=0.236,

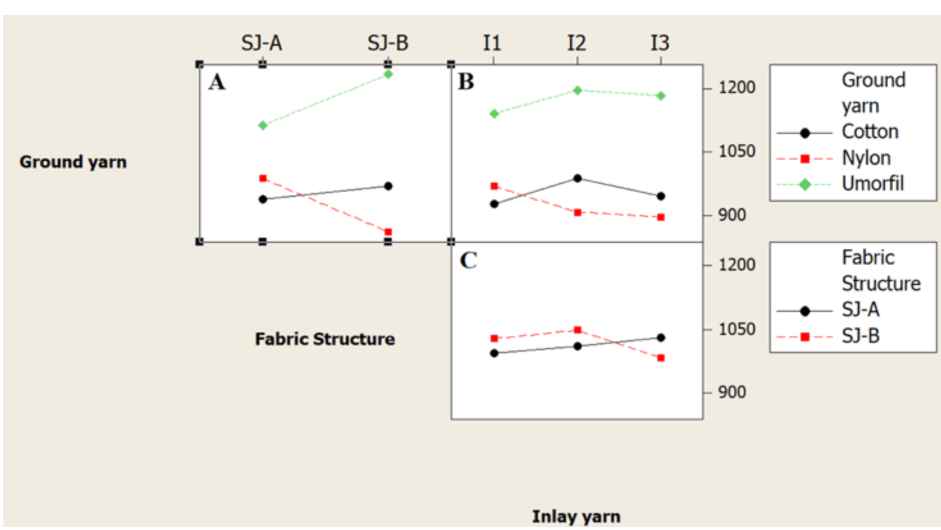

Figure 7. Interaction plot for water vapor permeability, g/m^2/day.

sig. 0.814).

Based on these findings, it may be concluded that the presence of more hairs on the spun structure of the cotton yarns, and comperatively bulkier structure of the conventional nylon yarns (Figure 3) might have had an impact on the interspaces among the yarns within the relevant structures, thus resulting in hinderance in water vapor passage, and that the fabric properties such as stitch density and porosity values affect the water vapor permeability of the compression stockings, which however, needs to be studied further.

Fabric Stiffness Results

Fiber, yarn and fabric properties such as inter-atomic and inter-molecular bonds, stiffness, stitch density in knitted structures, inter-yarn friction, etc. influence the performance of compression garments [27]. Liu *et al.* stated that the compression hoisery fabrics with higher stiffness and shear stiffness yielded higher pressure levels [28]. The data from the samples presented in Figure 8 and Figure 9 conform with the results of the researchers since the stocking samples that yielded higher pressures also had higher stiffness values. As may be seen from the interaction plots in Figure 9A, the stiffness of the stockings from Umorfil and Nylon ground yarns are consistently higher than that of the stockings with cotton ground. This result might be due to higher weight, thickness and density of the stockings from Umorfil and Nylon ground yarns as well as to the spun yarn structure of the cotton ground. Additionally, the tendency of an increase in the stiffness values of the stockings with I3 inlay yarns might be a result of the relatively coarser cotton yarns in their second cover (Figure 9B). ANOVA results showed that cotton inlay yarn significantly performed different from both coarse nylon (sig. 0.023) and fine nylon (sig. 0.047) ones. Despite the similar stiffness performances of Umorfil and Nylon stockings, the higher pressure values provided by the Umorfil ones can be considered as a positive effect that would facilitate wearers' leg movements, such as knee-bend and knee-extension.

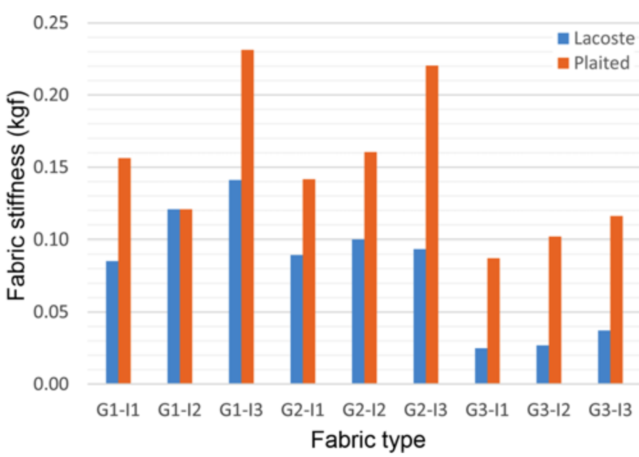

Figure 8. Stiffness values of the compression stockings.

The stiffness values of the samples revealed that the knitting structure is also an important parameter, and that the heavier and thicker SJ-B fabrics have higher stiffness values than their SJ-A equivalents for all ground and inlay yarn types. Finally, in that respect, the elevated pressure levels of SJ-B samples may be associated with their greater stiffness values. Moreover, paired t-test showed that the difference between the plaited and lacoste fabrics is statistically significant (t=-5.783, sig. 0.000).

Fabric Friction Test Results

Since the frictional characteristic of a fabric surface-that is mainly determined by fabric structure-influences comfort perception of stockings during wear, the fabric friction coefficients of the compression stockings ($\mu_{kinetic}$) under discussion were measured and are given in Table 8. The

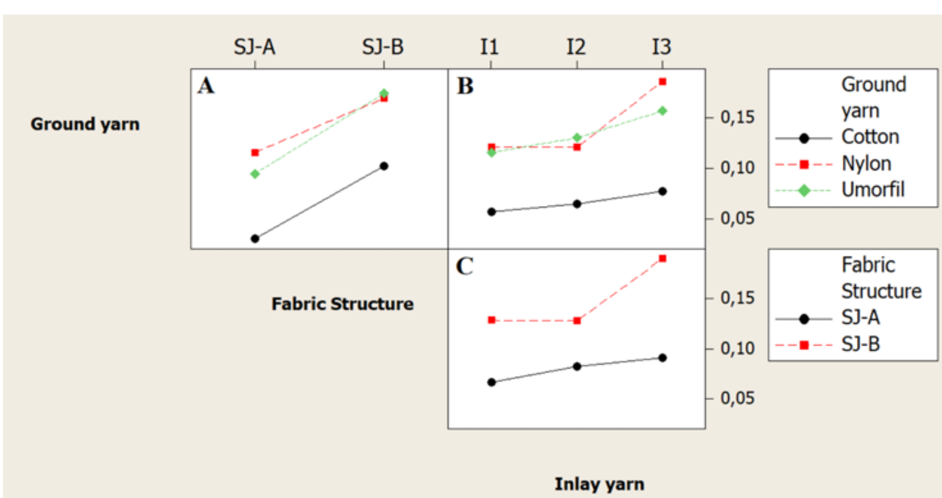

Figure 9. Interaction plot for fabric stiffness.

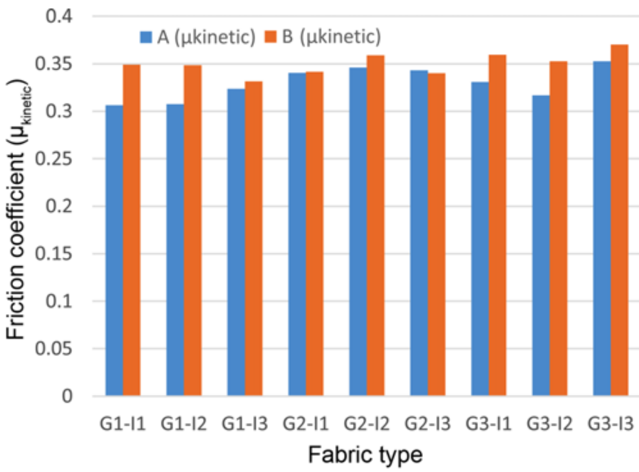

Figure 10. Fabric friction coefficient of the compression stockings.

greater the frictional coefficient of a stocking, the more difficult would it be to slide over the leg. On the other hand, comparatively lower frictional properties are expected to come from smoother fabric surfaces that would provide easiness in putting stocking on and off. However, this might result in the slippage of the stocking from the leg during wear.

Through investigating the effect of material properties and fabric structural characteristics on frictional properties of the samples, we concluded that the frictional properties of the samples were similar and the differences observed were mainly related to the fabric structure. The compression stockings with laid-in stitch elastic yarns (SJ-B) had higher fabric friction coefficients than the SJ-A ones with weft inlay stitch elastic yarns (Figure 10, 11). Overlapped stitches in the laid-in structure of SJ-B stockings might have resulted in relatively higher contact surface. As a final note, the paired t-test result revealed that fabric structure is an effective parameter on the friction properties of the stockings (t=-5.386, sig. 0.02).

However, it is worth mentioning that the samples containing cotton components in the ground and inlay yarns had the highest frictional coefficients (F=7.802, sig. 0.01), probably resulting from the rougher surface of the staple yarn structure.

Conclusion

It was the objective of this study to develop travel compression stockings with improved wear comfort properties. In doing so, the yarns from cotton and biodesigned Umorfil Nylon 6 were selected for the work as they have relatively better comfort related properties, but also are more eco-friendly than conventional nylon. However, the fibre preference posed the challenge of providing the required pressure values defined in the relevant standards with the stockings developed, though the problem was resolved such that the travel stockings with the necessary pressure performance as well as with improved wear comfort properties were designed and produced in two different knit structures. Below, some important findings of the study are given:

1. In parallel with studies on sustainable textiles, it was shown that biodesigned fibers such as Umorfil Nylon 6 can be used in travel compression stockings as an alternative to cotton and nylon.
2. For the SJ-B travel compression stockings with both the cotton and Umorfil Nylon 6 content, the compression pressure of 15-20 mmHg (medium/preventive level) was well satisfied.
3. Irrespective of both the knit type and the inlay yarn properties, the water vapour permeability of the travel

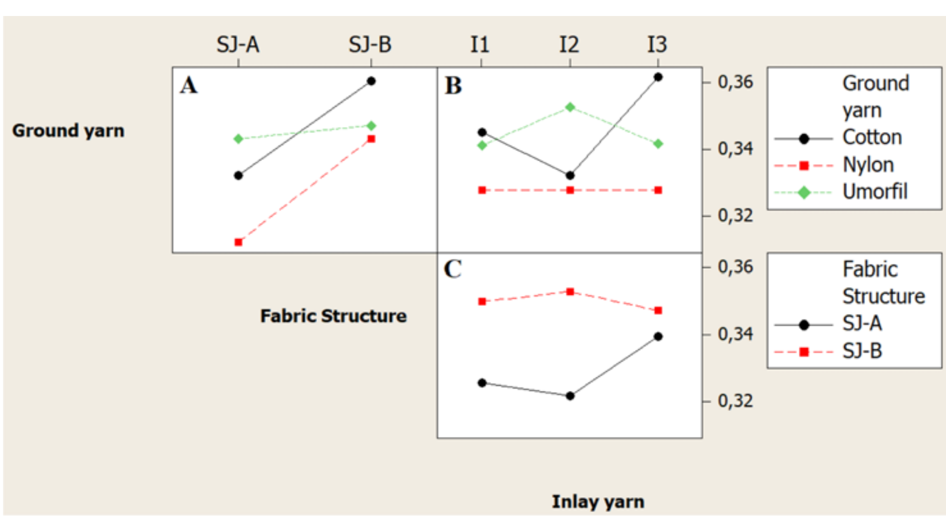

Figure 11. Interaction plot for fabric friction coefficient.

compression stockings were mainly governed by the fiber types employed in the ground yarns. In that respect, the stockings with Umorfil Nylon 6 content showed better moisture transfering ability than the others.

4. The frictional properties of the travel compression stockings, being an important property regarding the slippage of stockings over leg, was found to be mainly affected by the fabric structure, which was followed by fiber type.

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