Original Article

Designing compression of preventive compression stockings

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Abstract

The paper focuses on leg diseases and the application of preventive compression stockings in people who perform their working tasks in the standing position, pregnant women and recreational athletes. Specific amounts of compression classes from several significant European standards are shown. Structural properties of knitted fabric structure in the production of preventive compression stockings are given. Tubular elastic knitted fabric samples of uniform structure which are used in the production of preventive compression stockings and pantyhose were produced. The yarns used for knitting were PA microfilament yarns in the counts 40 dtex f 40 and 60 dtex f 60 and elastane yarn in the count 22/17 dtex f 7. Tubular elastic knitted fabric samples of the structure intended for preventive compression stockings were made on a single-bed hosiery knitting machine with a gauge of E32 and needle bed diameter of 100 mm (4″) with 400 needles. The samples were made in jersey plated and partially plated structure 1 + 1 at three loop sinking depths. The widths of the tubular knitted fabric samples were 98 to 113 mm. The produced samples were pulled onto rigid cylinders of the circumferences 240 to 790 mm and the compression measured by the Pico Press device was 1 to 24 hPa.

Introduction

The higher living standard has resulted in the increased use of stockings. The ever longer, more exhausting and demanding working days additionally burden the human body, which grows tired and sick more quickly. People who perform their work activities primarily in the standing or sitting position experience problems with venous outflow which can cause discomfort in the lower extremities, oedema or development of surface veins (varicose), Figure 1.[1,2] This is caused by disorders that lead to venous hypertension, usually due to damaged veins or incompetent venous valves.[3,4] In such cases, many people, without medical consultations, use light compression stockings to make their work activities and life easier. This is one of the reasons why the use of stockings is increasing.[5]

If the disorder is not detected and treated in time, venous insufficiency turns into chronic venous insufficiency, which is treated in various ways. Chronic venous insufficiency occurs due to venous obstruction, usually after deep vein thrombosis or significant venous reflux (retrograde venous flow) caused by incompetent venous

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Figure 1. Examples of leg conditions: (a) varicose veins and (b) lipodermatosclerosis.

valves. The pressure transfers onto the surface, deep and perforating veins, the venous blood pools in the periphery, which results in venous hypertension causing a complex pathophysiological activity and overflow of venous blood into surrounding tissues thus triggering inflammation and finally hypoxia. This is manifested by changes on the skin, from hyperpigmentation and lipodermatosclerosis to venous ulcerations of the lower leg.[6] Deep vein thrombosis is the most common risk factor for chronic venous insufficiency, followed by trauma, age and adiposity. Deep venous insufficiency occurs more often in women than in men, especially over age 50.[3]

Primary prevention of chronic venous insufficiency involves wearing preventive compression stockings accompanied by weight reduction and change in the daily behaviour by lowering the orthostatic load, that is, avoiding extended immobile standing or sitting. According to the degree of condition, compression therapy is practised for a minimum of 1 year. Stocking compression effectively treats and prevents the causes of venous insufficiency and postphlebitic syndrome and is indicated for all patients. Elastic bandages are applied at the beginning of therapy until oedema and ulcers stabilise. After that, compression therapy stockings are used. Stockings that achieve the compression from 15 to 30 mmHg are indicated for smaller varicose veins and mild chronic venous insufficiency.[5,6]

Standards for measuring hosiery compression

When measuring the compression that stockings exert on the leg, we measure the force with which a stocking presses the surface. In rigid-body mechanics, the ratio of force and surface on which the force acts is called stress, while in fluid mechanics, the ratio of force and surface is

pressure.[7,8] Blood pressure is measured in medicine and in practice it is still expressed in mmHg. Some designs of medical compression stockings aim to compress the tissue, but primarily also blood vessels in order to decrease their volume and thereby produce an effect on the blood pressure. The compression of these stockings is also measured in mmHg. This was the basis for determining the standards for classes of hosiery compression on the leg, the compression being expressed in mmHg. However, in technical sciences, pressure is measured in Pa (pascals) whose unit is N/m^2. The two main units used to measure hosiery compression on the leg are often stated on products or in research results.[9,10]

Many developed countries in the world have hosiery compression standards. In Europe, the most common are the German, French and English standard of compression hosiery regulation, but the American standard is used as well,.[11–13] The European Union countries also have the suggested common compression hosiery standards.[14] In all the given standards, hosiery compression on the leg is expressed in mmHg and is divided into classes or grades, which differ significantly between some standards, Table 1. Thus, according to the French norm, the smallest amount of compression hosiery is 10 mmHg, and the largest more than 36 mmHg. The smallest amount of hosiery compression in the German standard is 18 mmHg, and the largest over 49 mmHg. The first compression class measured according to the German standard roughly corresponds to the second class of the French standard, which causes significant implementation difficulties in different European countries. The given standards are mostly used to produce therapeutic medical compression hosiery.

Several different parameters had an impact on the establishment of these norms and their division into classes. According to the given classes of national norms,

Table 1. Hosiery compression classes in different (national) standards.

Class	Class name	Compression expressed in mmHg				
		DE	FR	UK	EU	USA
I	Light	18–21	10–15	14–17	15–21	15–20
II	Moderate	23–32	15–20	18–24	23–32	20–30
III	High	34–46	20–36	25–35	34–46	30–40
IV	Very high	>49	>36			>49
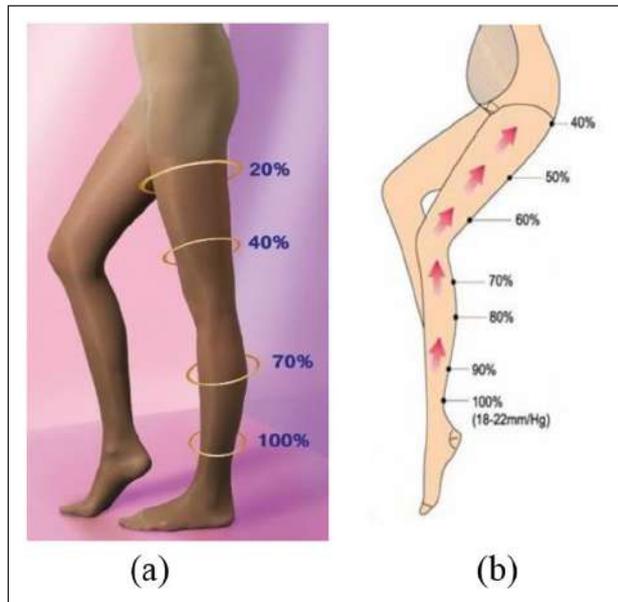
Figure 2. Preventive compression pantyhose: (a) everyday and (b) for pregnant women.[21]

doctors prescribe compression stockings for specific diseases.[2–4] Stockings that exert up to 20 mmHg (27 hPa) compression above the ankle usually belong to light or moderate compression and are often used without doctor consultation. These stockings are worn by recreational athletes, former professional athletes, but also pregnant women, Figure 2.[15,16] An experienced or recreational athlete will adjust hosiery compression to their activities without consulting a doctor. Many expectant mothers will happily consult a doctor on the use of preventive compression hosiery, especially after the second childbirth.[15,16]
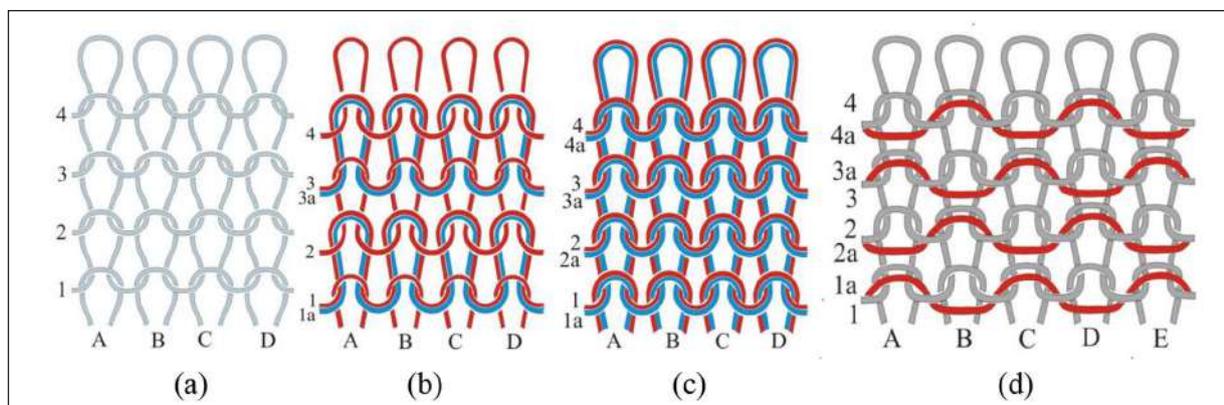
The design of preventive compression stockings

In the mid-19th century, in 1848 in England, William Brown used rubber threads to make the first elastic compression stockings, which were used for medical purposes.[5] After World War II, synthetic polymers (polyurethane) were used to make elastane threads (yarn) which are the basis for the production of elastic textile materials including compression stockings.[17,18]

The pressure that classic fine women's nylon stockings usually exert on the leg ranges from 1 to 6 mmHg (1–8 hPa; 1 mmHg = 1.33 hPa). These amounts are considered too small to be stated on the packaging. However, fine women's stockings with higher compression exert compression on the leg in the amount of 5 to 12 mmHg (7–15 hPa). They are usually used by women as secondary garments, most often on special occasions. People who spend the majority of their working life standing, such as dentists, surgeons, hairdressers, shop assistants, postmen, policemen, guides and mountain climbers use stockings with somewhat higher compression, typically 10 to 20 mmHg (13–27 hPa). These stockings enable them to do their jobs more simply, painlessly, diligently and for a longer time. Such stockings are often called preventive compression stockings and exert compression on the leg 5 to 20 mmHg (7–26 hPa).[5,17,18]

Preventive compression stockings usually come in three forms: knee-high stockings, thigh-high stockings and pantyhose. Depending on their purpose, all of these can have a full foot or a foot without the tip hugging the toes. Each part of a compression stocking is important and has its specific function. In the analysis of stocking compression on the leg, the most important is the structure of the material in the leg of the stocking, the other parts being less significant.[19–21]

Preventive compression stockings are most commonly made on specially constructed knitting machines. Certain constructional shapes and parts in the stocking differ significantly in their structures. The leg of a stocking is usually made in jersey, plain, partially plated 1 + 1, plated or basic inlaid structure 1 + 1 ('bent weft structure'), Figure 3. Numerous parameters have an impact on the application of a specific structure. The leg of a preventive compression stocking is commonly done in one structure. Only two yarns are used in such cases. The first yarn is the basic yarn, and the second is plating or the yarn that lays the weft in a bent way. With these two yarns, on certain parts of the leg, it is necessary to form a knitted fabric with different widths and amounts of elongation which will produce the desired compression on the leg. Different widths of tubular knitted fabric and its elongation are obtained by the regulation of loop sinking depth, that is, the length of yarn knitted into a course. With a smaller loop sinking depth, less yarn is knitted into a course resulting in a narrower knitted fabric of smaller elongation and higher compression. The increased loop sinking depth means more yarn is knitted into a course, knitted fabric width and yarn elongation are larger, which means lower compression.[22,23] Classic preventive stockings are usually made by combining polyamide (PA) multifilament and elastane bare, single and double-covered yarns in the counts of 20 to 70 dtex.[14,18,21,24]

Figure 3. Main jersey structures in the production of fine women's and preventive compression stockings: (a) plain, (b) partially plated 1 + 1, (c) plated and (d) basic inlaid 1 + 1 – 'bent weft structure'.

Table 2. Structure parameters of the designed and produced tubular elastic knitted fabric.

Structure	T_{tt} (dtex)	h_k	m (g/m²)	S_p (mm)	m_z (g/cm³)	D (l/cm²)	L_{PA} (mm)	L_{PA+} (mm)	L_{LY} (mm)
Plated 1 + 1	40	550	114	100	0.23	844	933	874	534
	40	700	97	105	0.20	634	1035	975	582
	40	850	89	106	0.18	520	1161	1105	645
	60	550	143	107	0.30	769	944	894	570
	60	700	125	110	0.24	600	1025	987	613
	60	850	118	113	0.21	502	1167	1129	674
Plated	40	550	154	98	0.31	942		902	621
	40	700	155	99	0.26	834		1011	685
	40	850	149	103	0.23	724		1120	623
	60	550	179	100	0.35	840		896	623
	60	700	178	105	0.30	737		1015	693
	60	850	174	110	0.27	649		1125	754

T_{tt}: count of basic yarn (dtex); h_k: loop sinking depth, dimensionless number in the computer programme; m: area mass of knitted fabric (g/m²); S_p: width of tubular knitted fabric (mm); m_z: volumetric mass of knitted fabric (g/cm³); D: number of loops per unit of area (l./cm²); L_{PA}: knitting of a polyamide or ground thread into a plain course (mm); L_{PA+}: knitting of a polyamide or ground thread into a course when knitted with an elastane thread (mm); L_{LY}: knitting of an elastane or plating thread into a course (mm).

Production of elastic tubular knitted fabric samples of preventive compression stockings

The goal of this paper is to link the length of yarn inserted into a course of a preventive compression stocking with the amount of knitted fabric elongation and compression on a rigid cylindrical surface. In compression stockings, knitted fabric structure in the leg changes every few centimetres, that is, every few tens of courses. Such conditions make it very hard to perform a good-quality knitted fabric analysis, measure elongation and compression on one part of the stocking. Therefore, tubular shapes of elastic knitted fabric were made, in the widths of 98 mm × 2 to 113 mm × 2 and length 400 to 800 mm. Each knitted fabric sample had a uniform structure. To make samples, polyamide (PA) microfilament yarns in the counts 40 dtex f 40 and 60 dtex f 60 were used as basic, while elastane single covered yarns in the counts 22/17 dtex f 7 were used for plating. PA yarns had the breaking elongation of 21.4% to 23.2% at the 0.5 cN/tex

preload and the elastane 32.9% at the 2 cN/tex preload.[25] Each yarn was used to make three groups of tubular knitted fabric samples with different loop densities at three different loop sinking depths. Further, for each yarn count and loop sinking depth, knitted fabric samples were made in a partially plated structure 1 + 1 (plated in every other course) and plated structure. The structures of certain knitted fabric samples are an integral part of a preventive compression stocking. Knitted fabric samples were made on a single needle bed hosiery knitting machine of E32 gauge, needle-bed diameter 100 mm (4″) which knitted with 400 needles.

The results of the knitted fabric structure analysis important for elongation and compression

Twelve primary samples of tubular knitted fabric were made in total, Table 2. The samples, which were made in the partially plated structure 1 + 1, have a PA yarn in each
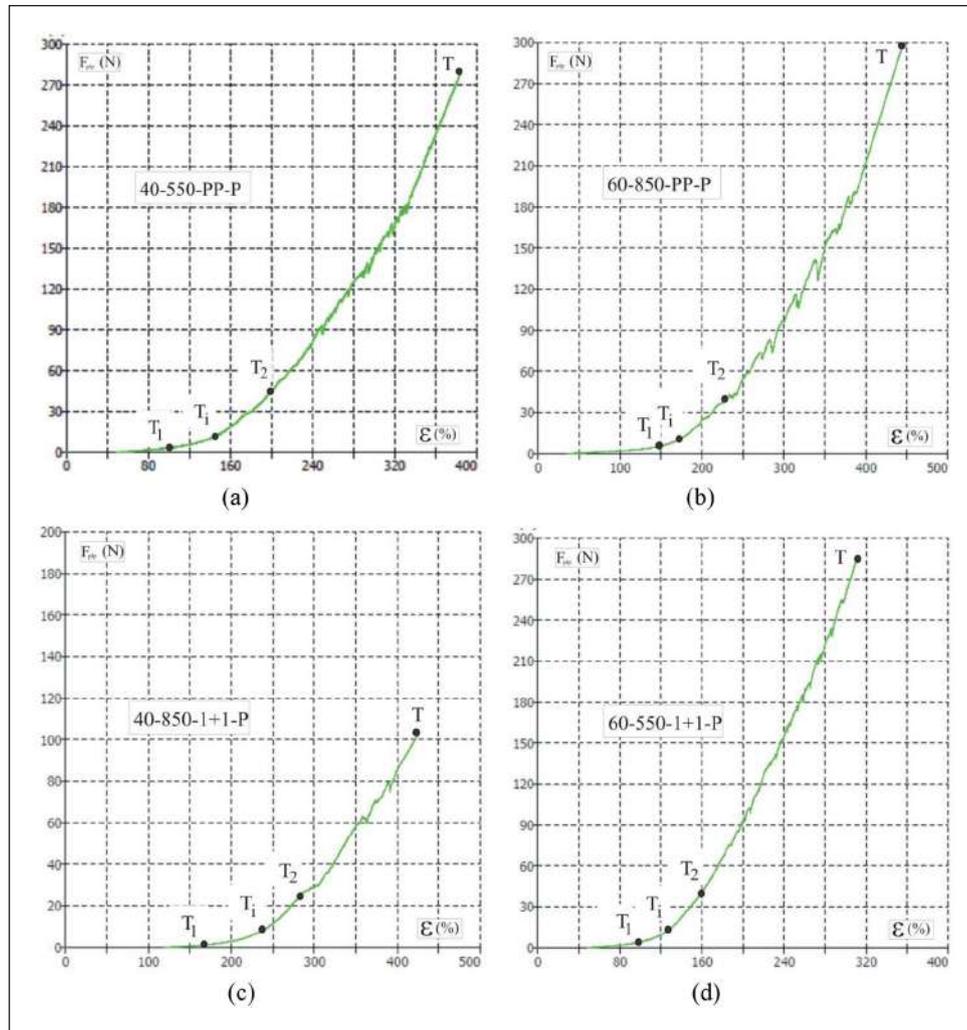
Figure 4. Force-elongation diagrams in the course direction of the structure of preventive compression stockings made with polyamide microfilament and elastane yarns: (a) plated knitted fabric, yarn count 40 dtex, loop sinking depth 550, (b) plated knitted fabric, yarn count 60 dtex, loop sinking depth 850, (c) partially plated knitted fabric 1 + 1, yarn count 40 dtex, loop sinking depth 850 and (d) partially plated knitted fabric 1 + 1, yarn count 60 dtex, loop sinking depth 550.

course and an additional elastane yarn in every other course. The mass of such knitted fabric ranges from 89 to 143 g/m^2, and the volumetric mass 0.18 to 0.30 g/m^3.[26,27] The plated structures contain both yarns in each course so the area mass is bigger and ranges from 149 to 179 g/m^2, and the volumetric mass 0.23 to 0.35 g/m^3. These two knitted fabric structure parameters alone point to two significantly different knitted fabric structures. It is important to note that with the increase of the yarn count number, the knitted fabric area density increases as well, whereas with the increase of the sinking depth it decreases. The width of the tubular knitted fabric ranges from 98 to 113 mm and is bigger in the partially plated than plated knitted fabric.[28] When elastane yarn is inserted into each course, longitudinal and transversal shrinkage is increased compared to the partial insertion, so the plated knitted fabric has a fuller structure and more loops per unit of area than the partially plated knitted fabric. The length of yarn knitted into a

course differs among the samples. The length of elastane yarns is significantly smaller than that of the ground PA multifilament. When the ground PA yarn is independently inserted into a course, 933 to 1167 mm is inserted, and when it is done with the elastane yarn, less is inserted, 874 to 1125 mm.[29] The length of elastane yarns knitted into a course is smaller in the partially plated than plated knitted fabric. These differences in the insertion of specific yarns into a course result from the use of tensile force regulation of certain threads to enable a normal knitting process and obtain a uniform knitted fabric structure.

Tensile properties of the produced knitted fabric in the course direction

Uniaxial tensile properties were measured according to the standard, which is used to determine maximum force and elongation using strip method.[30] The final research goal

Table 3. Elongation results of the partially plated 1 + 1 and plated knitted fabric of the structure of preventive compression stockings made with polyamide microfilament and elastane yarns.

| Yarn count	Structure	h_k	ε_e, (%)	$\Delta\varepsilon_e$, (%)	ε_i, (%)	$\Delta\varepsilon_i$, (%)	ε_p, (%)	$\Delta\varepsilon_p$, (%)	$\Delta\varepsilon_p - \Delta\varepsilon_e$ (%)	ε_t, (%)	$100 - \Delta\varepsilon_p$, (%)	$100 - \Delta\varepsilon_i$ (%)
40/40 +22/17	Partially plated 1 + 1	550	100	35	130	45	160	56	21	288	44	55
		700	120	36	170	51	200	60	24	332	40	49
		850	160	38	240	56	270	64	26	425	36	44
40/40 +22/17	Plated	550	100	26	140	36	200	52	26	384	48	64
		700	150	31	220	46	280	58	27	481	42	54
		850	180	36	240	48	320	64	28	500	36	52
60/60 +22/17	Partially plated 1 + 1	550	100	32	130	42	160	52	19	310	48	58
		700	120	34	150	42	180	50	17	357	50	58
		850	140	37	180	48	220	58	21	377	42	52
60/60 +22/17	Plated	550	100	31	130	41	160	50	19	320	50	59
		700	120	30	160	40	200	50	20	399	50	60
		850	150	34	170	38	230	52	18	445	48	62
a	b	c	d	e	f	g	h	i	j	k	l	m

h_k: loop sinking depth; ε_e: knitted fabric elongation or extension to the point T_1, area of elastic deformation (%); ε_i: knitted fabric extension to the vertex point (%); ε_p: knitted fabric elongation or extension to the point T_2, to the beginning of plastic area (%); ε_t: knitted fabric elongation or extension to the moment of tear (%); $\Delta\varepsilon_e$: share of elastic deformation in relation to total elongation (%); $\Delta\varepsilon_i$: share of elongation to the vertex point in relation to total elongation (%); $\Delta\varepsilon_p$: share of elongation to the beginning of plastic deformation in relation to total elongation (%); $\Delta\varepsilon_p - \Delta\varepsilon_e$: share between the points T_1 and T_2 (%); $100 - \Delta\varepsilon_i$: share between the breaking point and vertex (%); $100 - \Delta\varepsilon_p$: share between the breaking point and (T_2) (%).

Table 4. Dimensions of the (wooden model) legs for measuring stocking compression.[29]

Leg sizes		4	5	6	7	8	9	10	11	12	13	14
Circumference, cm	g_{max}	53	55	57.5	60	62.5	65	67	69.5	72	74.5	77
	f_{max}	48	50	51.5	53	55	57	58.5	60	62	64	65.5
	g	44	46	48	50	52	54	56	58	60	62	64
	f	41	42.5	44	45.5	47	48.5	50	51.5	53	54.5	56
	e	31	32.5	34	35.5	37	38.5	40	41.5	43	44.5	46
	d	28	29.5	31	32.5	34	35.5	37	38.5	40	41.5	43
	c	30	31.5	33	34.5	36	37.5	39	40.5	42	43.5	45
	b1	24	25.5	26.5	27.5	29	30	31.5	32.5	34	35	36.5
	h	28	29	30	31	32	33	34	35	36	37	38
	b-b	19	20	21	22	23	24	25	26	27	28	29
Height, cm	I-B						12					
	I-B1						20					
	I-C						31					
	I-D						39					
	I-E						45					
	I-F						60					
	I-G						72					

was to determine knitted fabric compression at a certain elongation in the course direction or transversely. Therefore, 50 mm wide and 200 mm long samples were cut out in the course direction from the knitted fabric. To achieve a large knitted fabric elongation, the initial gap between grippers of a tensile tester was 100 mm, preload 0.1 cN/cm and speed 100 mm/min. In order to make a force-elongation diagram, five samples were torn from each basic sample and the results are shown with the mean value, Figure 4.

In the analysis of the force-elongation diagram, four characteristic points were determined together with the areas related to the knitted fabric elongation and compression during use.[31] The first area encompasses the first linear section of the diagram that stretches to the beginning of elongation to the point (T_1). It is assumed to be the area of elastic deformation of the knitted fabric. In the measuring results, the amount of that elongation is labelled (ε_e) and it ranges from 100% to 180%, the data are given in Table 3, *column d*.
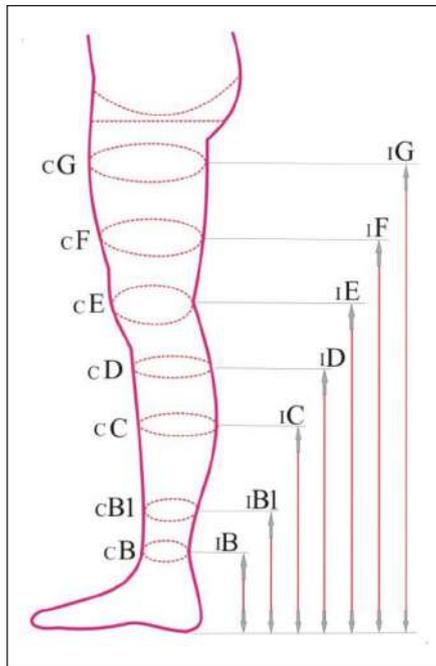
Figure 5. Positions for leg circumference measurement.[29]

The other point analysed in this research is maximum curvature point (T_i) which is the vertex of the force-elongation curve. At this point (T_i), the curvature radius of the force-elongation diagram is the smallest. The amount of knitted fabric elongation to this point is labelled (ε_i), given in *column f* and located in the area 130% to 240%. The third point which is of interest in this research is labelled (T_2) and represents the beginning of the second linear part of the force-elongation diagram and is also assumed to be the beginning of plastic (permanent) knitted fabric deformation. The data about elongation to this point (ε_p) are given in *column h* and range from 160% to 320%. The fourth point is registered at the maximum force at break of the knitted fabric (T), and the total elongation to this point is labelled (ε_t) and given in *column k*. As can be seen from the data: $\varepsilon_t > \varepsilon_p > \varepsilon_i > \varepsilon_e$. The amount of knitted fabric elongation to the measured maximum force at which the knitted fabric break occurred was registered on the dynamometer (ε_t), and the other three points $(\varepsilon_e, \varepsilon_i, \varepsilon_p)$ were calculated by a computer programme.[32] The minimum elongation at break was 288%, and maximum, 500%, which leads to the conclusion that the material in question has great or hyperelongation. Five specimens were torn per one knitted fabric structure and there were differences among them. By applying the 5% significance or the allowed practical error $p = 0.05$, certain analysed points were rounded to the nearest tens. Amounts and shares in relation to the amount of knitted fabric elongation at break are provided for each given point and sample.

The first area occupies the size from the beginning of elongation to the end of point (T_1) or the end of plastic

deformation at knitted fabric elongation. The share of this area in relation to total knitted fabric elongation is labelled $(\Delta\varepsilon_e)$, the results are given in *column e* and range from 26% to 38%. The second area which is interesting in this type of research includes the size from the beginning of elongation to the point (T_i) or the vertex of the force-elongation curve. The share of this elongation is labelled $(\Delta\varepsilon_i)$, and the results are given in *column g*. The third area occupies the length from the beginning of elongation to the beginning of plastic deformation or point (T_2), labelled as (ε_p) and given in *column h*. The share of this elongation is labelled $(\Delta\varepsilon_p)$, and the results are given in *column i* and range from 50% to 64% of the total knitted fabric elongation at break. The fourth area represents the total length of knitted fabric elongation from the beginning of elongation to the point of knitted fabric break or tear (ε_t), and the data for this area are provided in *column k* and are used to calculate certain elongation shares. The fifth area includes the length of elongation from the end of elastic to the beginning of plastic deformation of the knitted fabric, that is, the length between the points (T_1) and (T_2). The data are given in *column j* and range from 17% to 28%. We can also analyse the share from the point of curve vertex to the knitted fabric tear, which is given in *column m*, or the share of permanent deformation given in *column ℓ*. Significant for this research is the knitted fabric elongation to the point of permanent deformation or point (T_2).

Knitted fabric elongation and compression

By increasing the loop sinking depth from 550 to 850 control units, the knitted length of basic yarns into a course also increased from 874 to 1167 mm or from 2.19 to 2.92 mm per loop. Consequently, the knitted fabric elongation in the course direction or transversely increased to 288% to 500%. The produced elastic tubular knitted fabric has the width 98 to 113 mm or circumference 196 to 226 mm. On European market, the most common healthy leg circumferences above the ankle (position b-b) are 19 to 29 cm, where there are 11 sizes separated by the 1 cm gap, Table 4, Figure 5.[33] For the given sizes, crotch circumferences (position g-g) are 44 to 64 cm, and for plus-size people 53 to 77 cm. Measurements and circumferences of sick legs are significantly different and very often they are not the same in the legs of one person.[5,17,34]

The main compression of compression stockings is measured above the ankle (position b-b). Other compressions measured in particular places along the leg up to the crotch are compared to this compression. In the classic preventive and compression stockings, compression gradually decreases from the ankle (b-b) towards the crotch (g-g), typically 50% to 80%. The tubular elastic knitted fabric samples produced were pulled onto six rigid cylinders of different diameters on which knitted fabric

Table 5. The results of circumference, elongation and compression of partially plated tubular knitted fabric of the 1 + 1 structure of the preventive compression stockings made at three different loop sinking depths from PA microfilament yarn with the count of 40 dtex f 40 and elastane yarn with the count of 22/17 dtex f 7; knitted fabric elongation in the course direction – transversely.

Sample: PA 40 dtex f 40 + elastane 22/17 dtex f 7; DP 1 + 1

Cylinder circumference (mm)	$h_k = 550$; Op = 200 mm		$h_k = 700$; Op = 210 mm		$h_k = 850$; Op = 212 mm	
	ε (%)	K_c (hPa)	ε (%)	Kc (hPa)	ε (%)	Kc (hPa)
240	20	4	14	3	13	1
350	75	7	67	5	65	3
395	98	9	88	7	86	4
505	153	12	140	8	138	5
630					197	7
790					273	11

DP 1 + 1: label for partially plated structure 1 + 1, the second or plating yarn is inserted into every other course; h_k: loop sinking depth (550, 700 and 850); O_p: circumference of tubular knitted fabric (mm); ε: knitted fabric elongation in the course direction, transversely, (%); Kc: knitted fabric compression on a cylinder with a certain diameter/circumference (hPa).
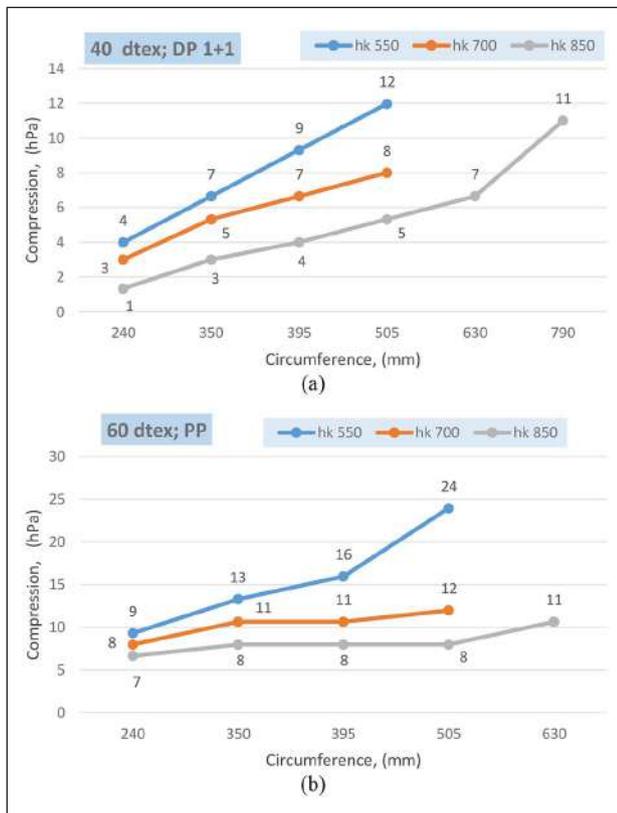
Figure 6. Diagrams of the amount of knitted fabric compression on a rigid cylindrical surface of different circumferences: (a) partially plated knitted fabric 1 + 1, basic yarn count 40 dtex and (b) plated knitted fabric, ground yarn count 60 dtex; h_k 550, hk 700, h_k 850 – loop sinking depth.

compression was measured using the Pico Press device.[35] Cylinder diameters/circumferences imitate leg circumferences in specific parts and in these measurements, they were: 75/240, 110/350, 125/395, 160/505, 205/630 and 250/790 mm. The produced tubular knitted fabric samples had different widths and were pulled onto cylinders of different diameters; the elongation was also different and consequently there were differences in the knitted fabric compression on the surface.

The knitted fabric samples made in partially plated structure 1 + 1 with the basic PA multifilament yarn in the count 40 dtex f 40 at the sinking depth of 550 units, had the circumference 200 mm, and were pulled onto the cylinders whose circumferences were 240 to 505 mm. The samples achieved the elongation 20% to 153% and compression 4 to 12 hPa (3–9 mmHg), Table 5. It was not possible to stretch the produced tubular knitted fabric sample onto a cylinder with the 630 mm circumference, since the beginning of permanent deformation in this kind of knitted fabric is achieved above 160%, (Table 3). The second group of samples made with the given yarn and structure had a larger sinking depth of 700 control units, and therefore a larger length of yarn knitted into a course. The circumference of this tubular knitted fabric sample was 210 mm. On the cylinders, the knitted fabric achieved the elongation 14% to 140% and compression 3 to 8 hPa (2 to 6 mmHg). The third tubular sample from this knitted fabric group was made at the largest loop sinking depth of 850, whereby the largest knitted fabric circumference and elongation ability were achieved. The sample was pulled onto the cylinders with the circumferences of 240 to even 790 mm, the achieved elongation was 13% to 273% and compression 1 to 11 hPa (1–9 mmHg), Figure 6(a). If we compare the compression results of these three groups of tubular elastic knitted fabric samples which were made at three different loop sinking depths, it can be concluded that the loop sinking depth of 850 control units is appropriate to make knitted fabric which lies closely on the leg under the crotch, where the circumference is around 500 mm, and the achieved compression 5 hPa, which is acceptable for

Table 6. The results of circumference, elongation and compression of the partially plated tubular knitted fabric of the 1 + 1 structure of the preventive compression stockings made at three different loop sinking depths from PA microfilament yarn with the count of 60 dtex f 60 and elastane yarn with the count of 22/17 dtex f 7; knitted fabric elongation in the course direction – transversely.

Sample: PA 60 dtex f 60 + elastane 22/17 dtex f 7; DP 1 + 1

Cylinder circumference (mm)	$h_k = 550$; $Op = 214$ mm		$h_k = 700$; $Op = 220$ mm		$h_k = 850$; $Op = 226$ mm	
	ε (%)	K_c (hPa)	ε (%)	Kc (hPa)	ε (%)	Kc (hPa)
240	12	5	9	3	6	1
350	64	8	59	7	55	4
395	85	9	80	8	75	5
505	136	15	130	9	123	5
630			186	12	179	8
790					250	15

Table 7. The results of circumference, elongation and compression of the plated tubular knitted fabric of the structure of preventive compression stockings made at three different loop sinking depths from PA microfilament yarn with the count of 40 dtex f 40 and elastane yarn with the count of 22/17 dtex f 7; knitted fabric elongation in the course direction – transversely.

Sample: PA 40 dtex f 40 + elastane 22/17 dtex f 7; PP

Cylinder circumference (mm)	$h_k = 550$; $Op = 196$ mm		$h_k = 700$; $Op = 198$ mm		$h_k = 850$; $Op = 206$ mm	
	ε (%)	K_c (hPa)	ε (%)	Kc (hPa)	ε (%)	Kc (hPa)
240	22	11	21	8	17	4
350	79	13	77	9	70	6
395	102	13	99	9	92	7
505	158	17	155	11	145	8
630			218	15	206	9

PP: label for (completely) plated structure, both yarns inserted into each course; PA: basic and the elastane, which is used for plating.

preventive compression stockings. By decreasing the loop sinking depth, compression increases to 8 or 12 hPa, which is, for the given leg circumference, acceptable in special occasions.

Tubular knitted fabric samples which were also made in the partially plated structure 1 + 1, but with a coarser ground yarn, that is, yarn in the count 60 dtex f 60, have a larger circumference ranging from 214 to 226 mm, so their elongation on the cylinders used to measure compression is lower, Table 6. The knitted fabric samples made at the sinking depth of 550 have the circumference of 214 mm and can stretch 12% to 136% and achieve the compression 5 to 15 hPa. Compared to the previous knitted fabric sample which was made with the ground yarn in the count of 40 dtex, the elongation in this sample is smaller, and the amount of compression on the same cylinders is larger. Therefore, coarser yarn means smaller elongation and larger compression will be achieved.

When the given yarns and sinking depths are used to make plated knitted fabric where two yarns, ground and plating, are inserted into each course, knitted fabric shrinkage after removal from the machine is larger compared to the partially plated knitted fabric and the obtained knitted fabric is narrower and of smaller circumference. Plated tubular knitted fabric made with ground yarn with the count of 40 dtex at the loop sinking depth 550 achieves elongation on the used cylinders 22% to 158% and compression 11 to 17 hPa (8–13 mmHg), Table 7. The compression 11 to 13 hPa can be applied above the ankle in lighter preventive stockings. Knitted fabric samples made at the loop sinking depths 700 and 850 can be pulled onto cylinders to 630 mm and achieve the compression of 4 to 15 hPa. The knitted fabric sample made at the loop sinking depth 700 achieves the compression on the 350 to 395 mm circumference of around 9 hPa which is appropriate for the area around and above the knee.

Among all of the knitted fabric samples analysed here, those made with basic PA yarn in 60 dtex in plated structure exert the largest compression on the surface, Table 8 and Figure 6(b). The samples made at the loop sinking depth 550 have the circumference 200 mm and achieve the compression 9 to 24 hPa or twice as large as the samples made in partially plated structure 1 + 1 at the identical loop sinking depth and the used ground yarn in the count

Table 8. The results of circumference, elongation and compression of the plated tubular knitted fabric of the structure of preventive compression stockings made at three different loop sinking depths from PA microfilament yarn with the count of 60 dtex f 60 and elastane yarn with the count of 22/17 dtex f7; knitted fabric elongation in the course direction – transversely.

Sample: PA 60 dtex f 60 + elastane 22/17 dtex f 7; PP

Cylinder circumference (mm)	$h_k = 550$; Op = 200 mm		$h_k = 700$; Op = 210 mm		$h_k = 850$; Op = 220 mm	
	ε (%)	K_c (hPa)	ε (%)	Kc (hPa)	ε (%)	Kc (hPa)
240	20	9	14	8	9	7
350	75	13	67	11	59	8
395	98	16	88	11	80	8
505	153	24	140	12	130	8
630					186	11

40 dtex. The compressions achieved by the tubular knitted fabric made at the loop sinking depths of 700 and 850 are appropriate to make above-the-knee part of the leg of maternity preventive stockings or preventive compression stockings intended for a recreational athlete.

The designed, produced and analysed samples of tubular elastic knitted fabric exert the compression 1 to 24 hPa (1–18 mmHg) on a rigid cylindrical surface. Certain knitted fabric structures can be used in the construction and production of preventive stockings in the region above the calf to the crotch. With the given samples, it is not possible to achieve the compression 10 to 25 hPa in the region located above the ankle and lower part of the calf. These knitted fabric structures can be obtained at smaller loop sinking depths. On the used machine of E32 gauge at the loop sinking depth 550 control units, 2.2 mm of yarn is used to form one loop. The construction of the machine allows operation at the loop sinking depths 200 to 1000 control units, where 1.5 to 4.5 mm of yarn is used for a basic loop. If the loop sinking depth is decreased to 250 to 500 units, the obtained knitted fabric is narrower and the desired compression achieved at a smaller elongation is 10 to 25 hPa. These loop sinking depths are used to make the stocking feet and leg around the ankle. In such knitted fabric, the thread input in a loop is small, knitted fabric is very compact and it is not simple for an experienced operative who performs knitted fabric analysis to tear and analyse yarn in this structure. Therefore, samples of these structures have not been analysed.

This paper focuses on basic samples of tubular seamless elastic knitted fabric intended for preventive compression stockings. The samples were made on a hosiery knitting machine of E32 gauge. To obtain larger knitted fabric compressions on a rigid cylindrical surface or leg, it is recommended to knit with coarser yarn on the machines of gauges E28 or E24.

Conclusion

PA multifilament yarns with a fineness of 40 dtex f 40 and 60 dtex f 60 and elastane yarn with a fineness of 22/17 dtex f 7 were used in the research to make knitted samples. With the mentioned yarns, tubular knitted samples were made in plated and partially plated structure 1 + 1 and in three depths of loop sinking depth. Based on the conducted research, the following conclusions are stated:

(a) The samples made in plated structures have two yarns in each row: base (PA) and elastane. The tubular samples are stretched in the course direction until the beginning of permanent deformation and pulled on rigid rollers of the range from 240 to 790 mm, which imitate the circumference on a certain part of the leg. Samples made with a base yarn of fineness of 40 dtex have an elongation of 17% to 218% with a compression of 4 to 17 hPa. Samples made with a base yarn of fineness of 60 dtex have a lower elongation of 9% to 186% and achieve a compression of 7 to 24 hPa.

(b) Tubular knitted samples made in a partially plaited structure of 1 + 1 have elastane yarn in every other row in addition to the base yarn. The elongation of these structures is higher than the plating and is in the range of 6% to 273%, achieving a compression of 1 to 15 hPa.

(c) Increasing the loop sinking depth also increases the length of the base yarn in one knitted row from 874 to 1167 mm for or an average of 2.19 to 2.92 mm per loop. At the smallest loop sinking depth and the used base yarn with a fineness of 60 dtex, the circumference of the samples of 200 mm and a compression of 9 to 24 hPa are obtained. However, with a partially plaited knit 1 + 1 and a fineness of the base yarn of 40 dtex, a knit of the same range was obtained, and a lower compression of 4 to 12 hPa was measured. At the greatest loop sinking depth, the greatest length of the yarn in one knitted row is achieved, from 1105 to 1129 mm, elongation from 6% to 273% and compression of 1 to 15 hPa.

d) The structures of the plaited knitted samples obtained with the smallest loop sinking depth achieve relatively high compression at low elongation, so they are suitable for making compression stockings that rests on the lower leg part (leg area from b to e). The structures obtained with the greatest loop sinking depth allow great stretching and a small compression, so it is recommended to use it on the upper leg (leg area from e to g).

(e) Knitting technologist needs three basic data to design a preventive compression hosiery: (1) the height of a particular part of the leg, (2) the circumference of the leg at the specified height and (3) the desired compression at the specified part of the leg.

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