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I-SCAN Method for the Assessment of Pressure Exerted by Textile Products

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Abstract
The capabilities of the I-SCAN (TekScan) system for pressure measurements were tested in in vivo and in vitro condition using hosiery articles at a pressure of 18-21mmHg, as declared by the manufacturers. For two types of knee-length socks with the same structure and slight difference in composition (polyamide/elastomer 78/22% and 64/36%) the pressure was measured on the ankle and calf in four positions (1-front, 2-inner side, 3-back, 4-outer side). The highest pressure values were found for the 1-front position and the lowest for the 2-inner side position. It was shown that there is a correlation between the in vivo and in vitro tests. The I-SCAN method allows to take measurements in various place and to create maps of the pressure distribution.

Key words: *textiles, pressure measuring, knitted structures.*

Introduction

The pressure exerted by textiles can cause an undesirable influence on the comfort and health of the user or act preventively (prophylactically) through the special design of products, e.g. hosiery. The specificity of hosiery used in compression therapy involves exerting certain pressure on the body. These products are characterized by varying degrees of pressure which should be maintained for a long period of use (about six months). The value of the pressure of the product is usually measured on rigid models in *in vitro* conditions, determining the average value of the pressure applied to the measurement circumference [1, 2]. The methodology for *in vitro* studies and requirements for compression products are given *inter alia* in suitable standards and test procedures [3 - 7]. Compression products which put pressure on the ankle of less than 18 mm Hg are classified as conservative (non-invasive) or resting. If the pressure on the ankle is greater than 18 mmHg, they are referred to as prophylactic/medical products and - depending on the value of the pressure applied - are classified into one of four classes of pressure [8].

Compression hosiery products are produced as flat or circular knitted textiles. The most popular are fashioned circular knitted products fully formed in the knitting process. The design and construction of the product should ensure suitable gradation of the pressure exerted on various parts of the limbs, where the greatest pressure should be exerted around the ankle, and the smallest on the calf or thigh. The range of the pressure exerted is the result of adequate product design taking into account the selection of the raw material, the type of stitch and take-up value of the elastomeric thread [9, 10]. Currently two types of yarns are used most often: basic yarn forming the stitch and additional yarn providing the flexibility of the product. Core yarns containing elastomer braided by polyamide or cotton fibres are most commonly used as the additional yarns. The whole hosiery product is made of the same stitch.

In the case of compression products the important aspects also include the stability of mechanical and use properties as well as esthetic, sensory and biophysical comfort [11 - 14]. Many works concerning pressure measurements are based on the cylindrical or conical models [15]. Research is also being done to take into account different factors that affect the value and distribution of the pressure, including, for example, the anatomy, the types of structures and finishes, and the methods used to test the pressure [16]. Therefore, despite the widespread use of stationary stands based on various rigid models, in recent years measurement systems have been developed with electronic sensors that allow to analyse the distribution of the pressure, for instance I-SCAN, FlexiForce - TekScan, USA [11, 17] and AMI 3037 - Co., Japan [18]. The big advantage of these systems is the possibility to use them not only in *in vitro* but primarily in *in vivo* studies. They allow to take measurements in any given place and to create a complex pressure distribution map which can be used for personalised product design with controlled pressure zones.

The aim of the preliminary research was to use the I-SCAN system for measurements of the pressure exerted by two hosiery compression products with the same pressure values, as declared by the manufacturers, in four different places on the ankle and calf in *in vivo* and *in vitro* conditions and to assess the capabil-

Table 1. *Characteristics of the properties of the knee-length sock's knitted fabrics.*

		I	II
Mass per unit area, g/m^2, [19]		111.5 ± 2	127.7 ± 2
Thickness, mm, [20]		0.44 ± 0.02	0.49 ± 0.02
Relative elongation, %, [21]		190 ± 2	202 ± 1
Relative elongation permanent after 1 min., %, [21]		15 ± 1	6 ± 1
Relative elongation permanent after 30 min., %, [21]		9 ± 1	2 ± 1
Elasticity after 1 min., %, [21]		44.7 ± 2	46.3 ± 2
Elasticity after 30 min., %, [21]		47.9 ± 1	48.3 ± 3
Air permeability, relaxed state, mm/s, [22]		2850 ± 14	2120 ± 14
Course density, cpc, [23]	ankle	30	23
	calf	21	18
Wale density, wpc, [23]	ankle	23	21
	calf	14	18

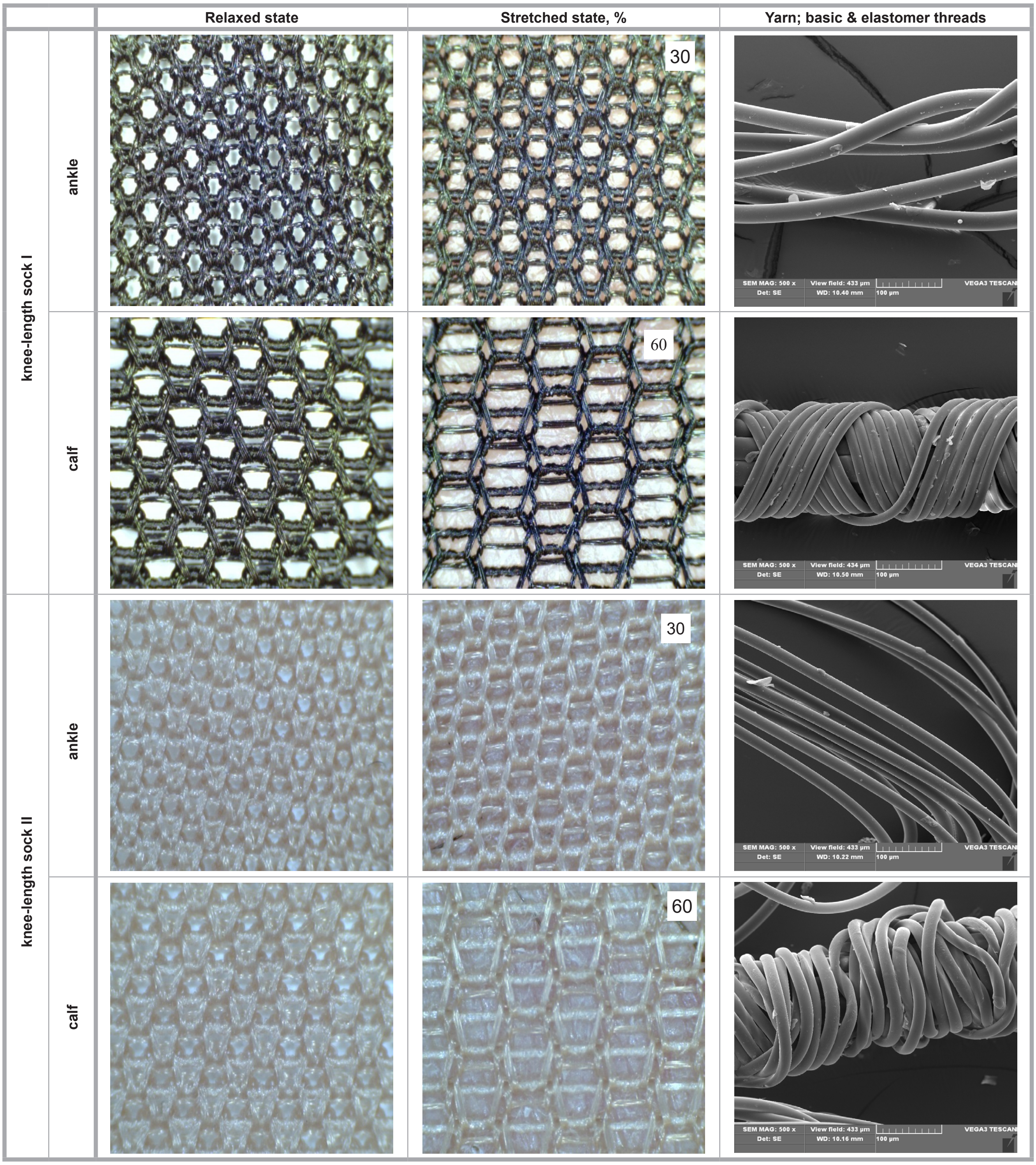

Figure 1. *Structures of the knee-length socks and yarns.*

ity of this system in terms of further study concerning pressure and textile scope.

Experimental

Materials

Tests were performed on hosiery products – two knee-length socks, with a class of pressure, declared by the manufacturer, of 18 - 21 mm Hg, feet size of 37 - 38 and outer circumference on the ankle and calf of 19 cm and 25 cm, respectively:

- knee-length sock I (I) 140 den - polyamide/elastomer, 78/22 %,
- knee-length sock II (II) 140 den - polyamide/elastomer, 64/36 %,

The structures of the knee-length socks in the relaxed and stretched state and a microscopic picture of the yarns are shown in ***Figure 1***.

A scheme of the knee-length sock's structure is shown in ***Figure 2***.

In the knee-length socks tested, the stitch is formed with basic thread and elastomer thread with a double braid. Elastomer threads form the mesh alternately every second wale and every second course of the knitted fabric. Characteristics of the properties of the knee-length sock's knitted fabric are shown in ***Table 1***.

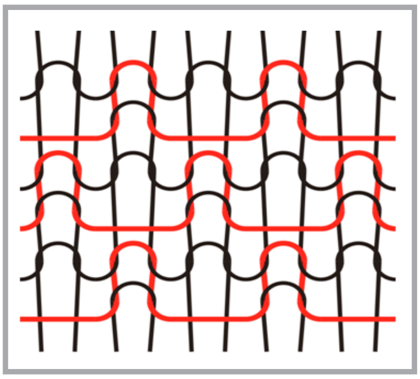

Figure 2. Locknit stitch structure (red colour – elastomer thread and black colour - basic thread).

The knee-length socks are characterized by a similar surface weight and thickness, wherein the value of these parameters for knee-length sock II are higher by 14.5% and 11%, respectively. The values of stitch density (wpc x cpc) for the ankle and calf amount to 690 and 294 for knee-length sock I and 483 and 324 for knee-length sock II, respectively. Both socks have the same stitch, but the analysis of yarn shows that the stitch in knee-length sock I is formed with 5-filament basic thread and elastomer thread with a regular double braid, and in knee-length sock II - 11-filament basic thread and elastomer thread with an irregular double braid (***Figure 1***). The air permeability value for knee-length sock I is higher by 34.4% than for knee-length sock II. The relative elongation values are similar, but higher permanent elongation was observed for knee-length sock I (by 60% after 1 minute and 77.8% after 30 min), with a lower percentage of elastomer. The values of elasticity are similar for both knee-length socks, being slightly higher for knee-length sock II (after 1 minute by 3.5%). The differences in properties of the socks result from the structure of the yarns and knitted fabrics.

Methods

I-SCAN system method

Pressure measurements were performed using an I-SCAN measuring system equipped with data acquisition electronics, sensors and software (TekScan, USA) (***Figure 3***). A flexible thin film sensor 5027 was used with a measurement area of 7.78 cm^2 (2.79 × 2.79 cm) and total number of measuring points equalling 1936 (248/cm^2). The principle of measurement sensors is based on measuring the electrical resistance that is inversely proportional to the pressure.

The thickness of the sensor (0.625 mm) did not induce further stretching of the knee-length socks tested.

Before the measurements, sensor calibration was carried out each time according to the manufacturer's guidelines [24]. Additionally the sensor was applied to each of the four points of measurement without the knee-length sock, where there was no indication of pressure.

Measurements were performed for the ankle and calf on a rigid plastic model (*in vitro* test) and on the left leg of a volunteer (*in vivo* test). The volunteer was a healthy woman who was 164 cm tall with a BMI (Body Mass Index) of 29.8, performing a long-term sedentary job.

For proper selection of the size of the knee-length sock, the circumferences of the left leg were measured. The measuring points are strictly defined and correspond to international standards [25]. In the case of the volunteer's limb, the smallest circumference of the ankle was 25 cm, and the largest circumference of the calf was 40 cm.

The same knee-length socks that were used in the *in vivo* tests, were also used in the *in vitro* ones. The model of the artificial leg at the ankle and calf had the same dimensions as the volunteer's leg.

In both the *in vivo* and *in vitro* tests, the sensor was placed at four points of measurement on the ankle and calf (***Figure 4***), indicated as follows: 1 - front, 2 - outer side, 3 - back, 4 - inner side.

Pressure tests were performed under normal climate conditions (20 ± 2 °C, RH 65 ± 4%). Before the test, the knee-length socks had been acclimated for 24 hours under the same conditions. During the study, the volunteer remained standing/motionless and was relaxed with regular breathing. Measurements were performed 10 minutes after putting on the knee-length socks. Each of the measurements was recorded as a 24.8-second video film showing the actual distribution of pressure exerted by the knee-length socks. 15 measurements for each of the four points of measurement were taken, without any breaks between them. The difference in the pressure value between measurement 1 and 15 was in the range of 0.5 - 1.0 mm Hg. Studies carried out by Veraart et al [26] showed that measurements taken after 5, 10, 15, 25 and 30 minutes after putting on stockings do not affect the pressure value.

Statistical analysis was carried out with the use of Statistica 8, StatSoft software [27], involving analysis of the Pearson correlation, basic statistics, and analysis of linear regression and variance.

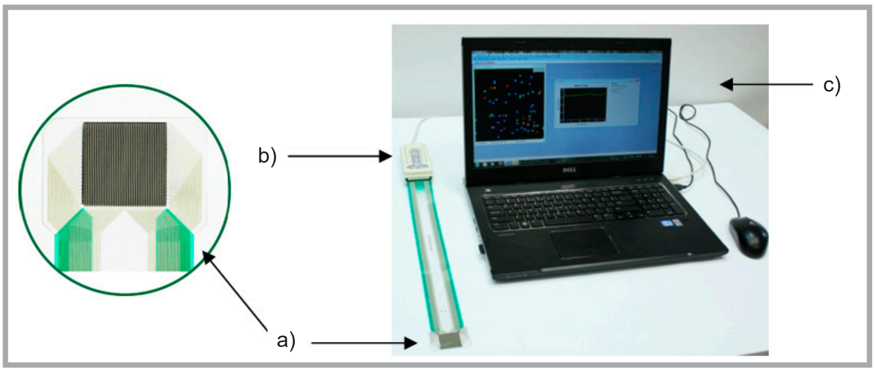

Figure 3. I-SCAN system: a) thin film sensor 5027, b) Evolution Handle EH-2, c) computer with I-SCAN software.

Results and discussion

Determination of pressure values at the four points of measurement

Figure 5 shows an example of images of the actual pressure distribution recorded at the four points of measurement on the ankle for knee-length sock II (*in vivo* test).

Figures 6 and ***7*** show a comparison of the average pressure values at the four points of measurement on the ankle and calf (*in vivo* and *in vitro* tests).

The highest values of pressure exerted on the ankle and calf (*in vivo* test) were observed for the 1-front measurement point. Lower values were found for the 3-back measurement point on the ankle and calf, respectively 20.9% & 21.3% (knee-length socks I) and 15.2% & 34.4% (knee-length socks II) (***Fig-***

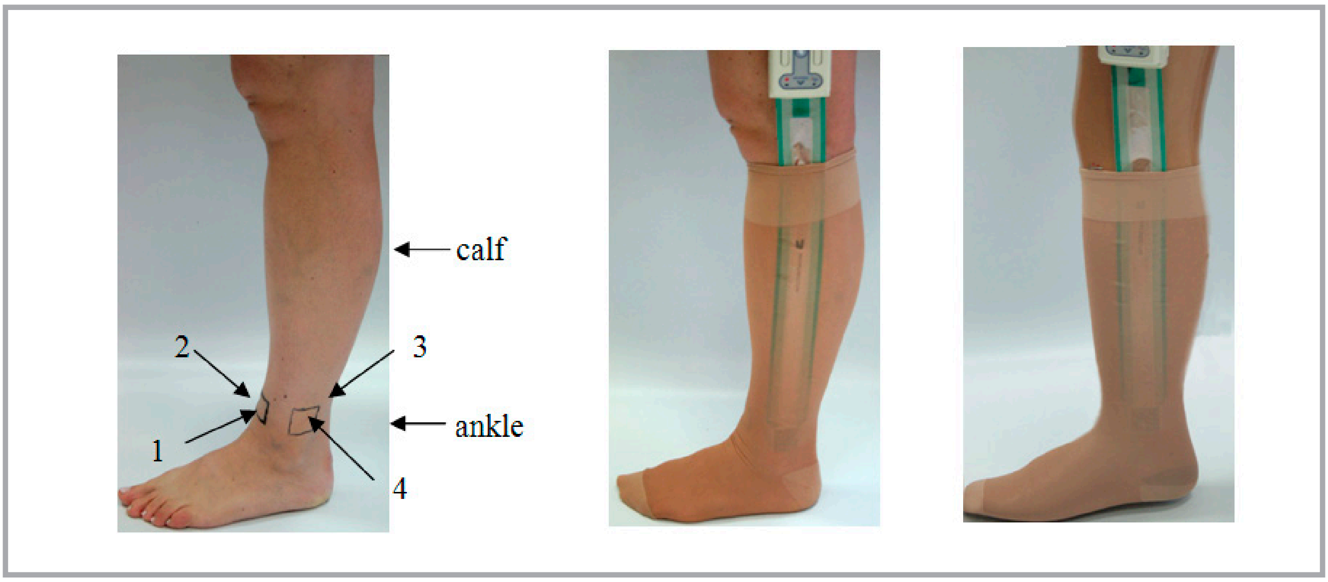

Figure 4. *Scheme of the pressure testing: a) the points of measurement (1 - front, 2 - outer side, 3 - back, 4 - inner side), b) in vivo test, c) in vitro test.*

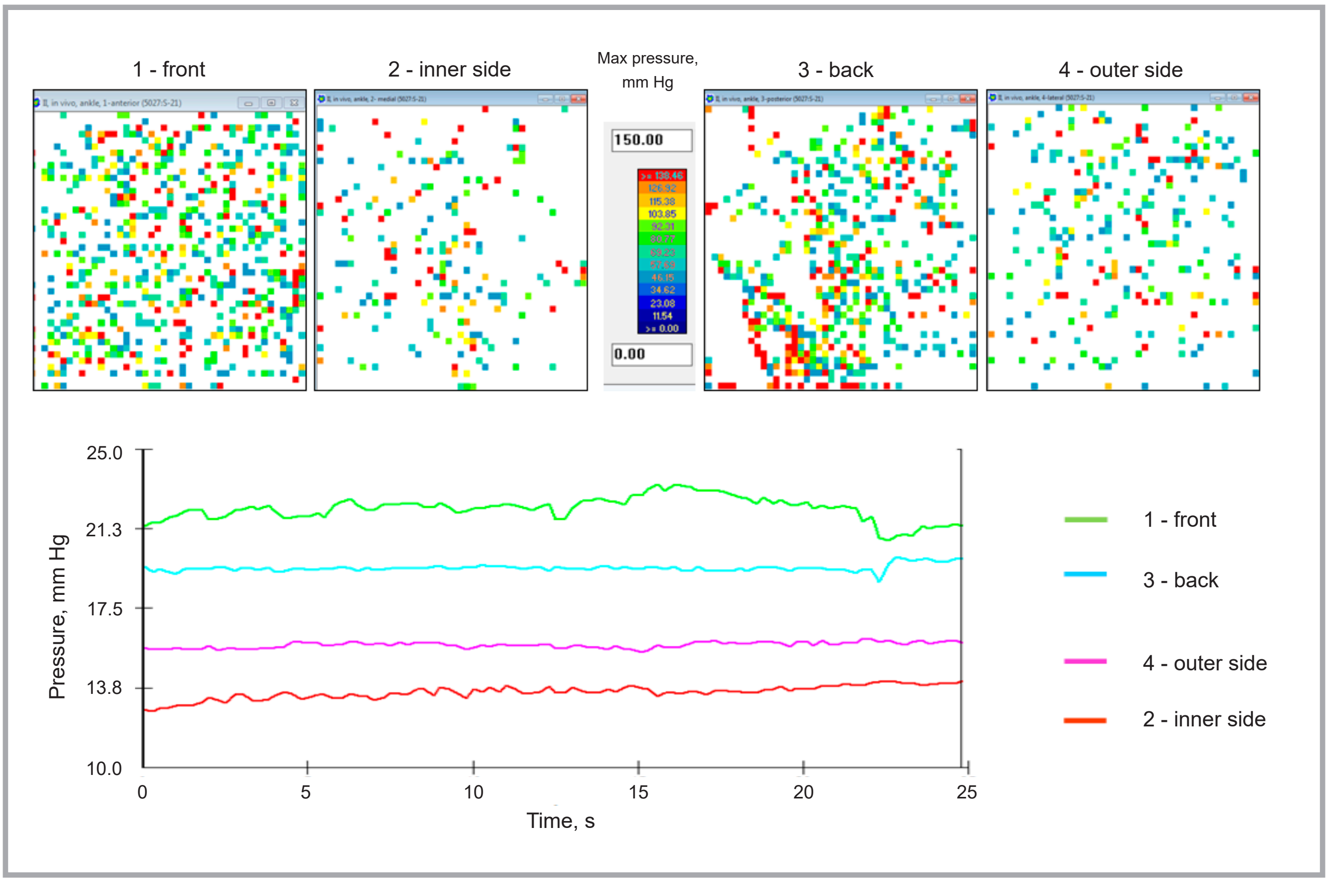

Figure 5. *Pressure distribution for knee-length sock II (in vivo test).*

ure 6). A similar situation was observed for the *in vitro* test, wherein the differences are much greater for the ankle, respectively 51.5% (knee-length socks I) and 59.6% (knee-length socks II) (***Figure 7***). The smallest pressure values in both test conditions were found for the 2-inner side measurement point (***Figures 6*** and *7*). In comparison with the 1-front measurement point on the ankle and calf, the differences were, respectively, 65.8% & 59.3% (knee-length socks I) and 48.2% & 53.9% (knee-length socks II) for the *in vivo* test and, respectively, 75.2% & 40.5% (knee-length socks I) and 65.6% & 33.0% (knee-length socks II) for the *in vitro* test. For the *in vivo* test the pressure for the ankle at the 2-inner side measurement point amounted to 50.7% - 43.5% and 67.6% - 58.0% of the average pressure declared by the producer for knee-length socks I and II, respectively. Analysis of the results shows that there are significant differences in the value of pressure between the measurement points. A similar correlation was observed by Liu et al. [17]. The authors

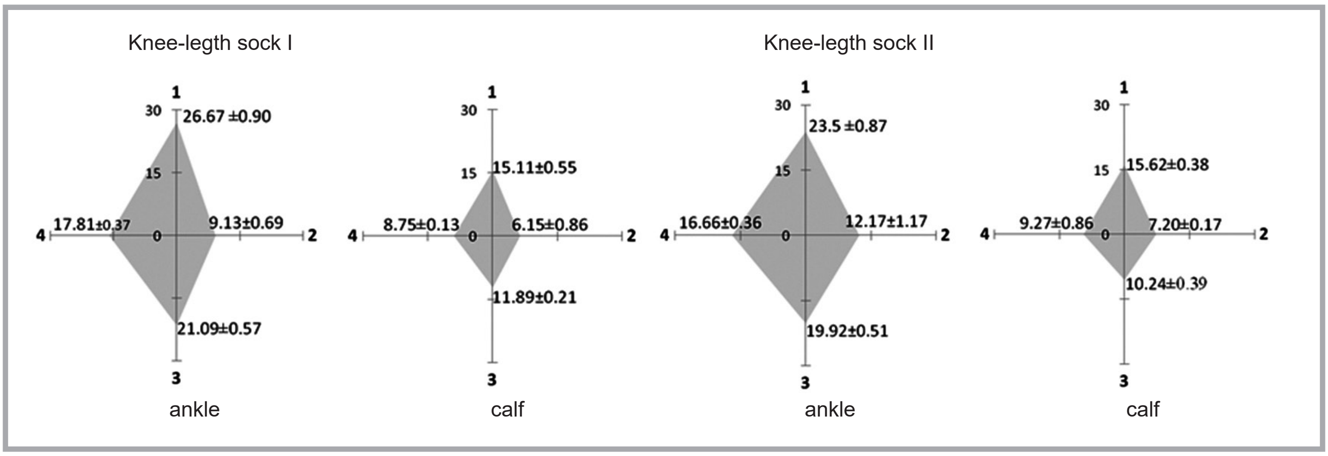

Figure 6. *Comparison of the average pressure values (mm Hg) at the four points of measurement (1 - front, 2 - outer side, 3 - back, 4 - inner side) on the ankle and calf for in vivo tests.*

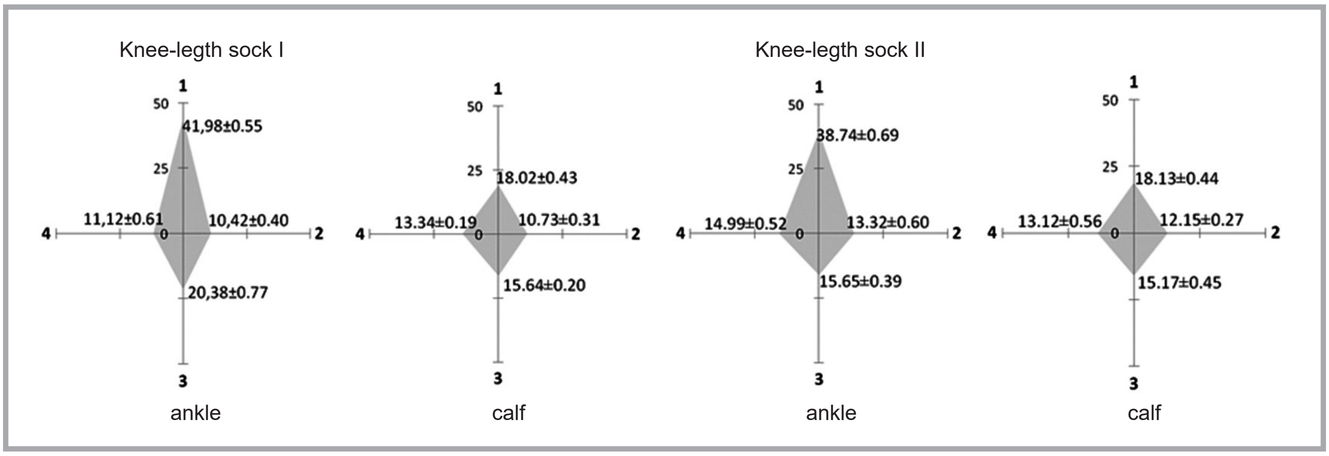

Figure 7. *Comparison of the average pressure values (mm Hg) at the four points of measurement (1 - front, 2 - outer side, 3 - back, 4 - inner side) on the ankle and calf for in vitro tests.*

Table 2. *Average pressure values on the ankle and calf for the in vivo and in vitro tests. M – the average pressure values calculated from 15 measurements for each of the four measurement points, Mp - the average pressure values calculated from all measurements (4×15) for the ankle and calf, SD - standard deviation, SV - coefficient of variation.*

	Knee-length sock	Plece measurement	Ankle		Calf	
			M ± SD, mm Hg	SV, %	M ± SD, mm Hg	SV, %
in vivo	I	1	26.67 ± 0.90	3.37	15.11 ± 0.56	3.70
		2	9.13 ± 0.69	7.51	6.15 ± 0.86	13.98
		3	21.09 ± 0.57	2.70	11.89 ± 0.21	1.77
		4	17.81 ± 0.37	2.12	8.75 ± 0.13	1.48
		Mp	**18.67 ± 5.90**	**31.61**	**10.48 ± 3.43**	**32.73**
	II	1	23.5 ± 0.87	3.70	15.62 ± 0.38	2.43
		2	12.17 ± 1.17	9.61	7.20 ± 0.17	2.36
		3	19.92 ± 0.51	2.56	10.24 ± 0.39	3.80
		4	16.66 ± 0.36	2.16	9.27 ± 0.86	9.27
		Mp	**18.06 ± 3.59**	**20.26**	**10.58 ± 3.17**	**29.96**
in vitro	I	1	41.98 ± 0.55	1.31	18.02 ± 0.43	2.39
		2	10.42 ± 0.40	3.84	10.73 ± 0.31	2.89
		3	20.38 ± 0.77	3.78	15.65 ± 0.20	1.28
		4	11.12 ± 0.61	5.48	13.34 ± 0.19	1.42
		Mp	**20.98 ± 13.31**	**63.43**	**14.43** ± 2.74	**18.99**
	II	1	38.74 ± 0.69	1.78	18.13 ± 0.44	2.43
		2	13.32 ± 0.60	4.50	12.15 ± 0.27	2.22
		3	15.65 ± 0.39	2.49	15.17 ± 0.45	2.97
		4	14.99 ± 0.52	3.47	13.12 ± 0.56	4.27
		Mp	**20.68 ± 10.66**	**51.56**	**14.66 ± 2.34**	**15.93**

carried out *in vivo* studies in the standing position and at different levels of the leg at four measurement points (front, inner side, back, outer side) with compression stockings belonging to different classes of pressure, using a multichannel measurement system - FlexiForce. They found that the pressure on the leg is not uniform. In areas situated at different heights and in different positions along the leg there are substantial differences in the pressure values. The highest pressure was obtained on the ankle in the front and back position, and the smallest for the inner side position. Similar distribution of the pressure on the ankle was documented by Dai et al. [28]. Variations in the pressure values may occur because the cross-section of a human leg diverges from the circular shape in many places [1,26]. They could also be caused by differences in anatomy, including bone structure, muscle, fatty tissue, the depth of soft tissue, and the like.

As presented above, the knee-length socks tested have the same stitch and different stitch densities and the pressure values obtained for four measurement points are different for both socks. Statistical analysis of the results determined for the four measurement points in the *in vitro* and *in vivo* tests showed the lack of a linear relationship between the measurement points tested for both knee-length socks.

Determination of average pressure values

Table 2 shows the average pressure values for both knee-length socks calculated from 15 measurements for each of the four measurement points (M) and calculated from all measurements (4 × 15) (Mp) for the ankle and calf.

Higher pressure values for the *in vivo* and *in vitro* studies were provided by knee-length socks I and II on the ankle, but they decreased on the calf. In the area of the ankle, the average pressure values obtained in the *in vivo* test are lower by 11-12% than for the artificial leg model (*in vitro*). The average pressure value for the *in vitro* studies on the calf is 37 - 38% higher than the results obtained under the *in vivo* conditions.

The standard [25] recommends that the average value of the pressure on the calf should be contained within the range of 50-80% of the pressure values noted for the ankle. The testing method applied (*in vivo* and *in vitro*) confirmed that the knee-length socks examined meet this requirement.

Due to the fact that the manufacturers state the average pressure value measured on the ankle, we analysed the results of measurements made for this area. The average pressure on the ankle for knee-length socks I and II (*in vitro* and *in vivo*) was consistent with the pressure declared by the manufacturers. In both the *in vitro* and *in vivo* tests, similar average pressure values were obtained for knee-length socks I and II. It was found, however, that in the case of the *in vitro* tests for the ankle there is a much greater spread of the values than for the *in vivo* one. This diversity is not observed for the calf, which may result from differences in the anatomy/topography of both parts of the leg.

The average pressure values for the knee-length socks were also analysed for the presence of a correlation between the *in vivo* and *in vitro* tests (***Table 3***).

It was found that there is linear regression between the *in vitro* and *in vivo* tests (***Table 3***, ***Figure 8***). Values of the correlation coefficient $r_I = 0.9430$ indicate high regression strength for the test conditions compared for knee-length sock I. In the case of knee-length sock II, $r_{II} = 0.8036$, which is substantially lower. The values of F statistics and t corresponding level of probability $p = 0.001$ confirm a significant dependence on the level of $p < 0.05$.

In order to verify if the average pressure values of the knee-length socks differ significantly, the significance of the differences was analyzed using the Kruskal-Wallis test. It was found that at $p = 0.4233$ ($H = 2.8011$) there is no difference between the average values of the pressure (understood as the median) for the knee-length socks (***Figure 9***). Based on the analysis it can be stated that the version of the *in vivo* study on the volunteer and the *in vitro* one on the artificial leg had no statistically significant effect on the average value of pressure.

Table 3. *Results of regression analysis including the average pressure values for knee-length socks observed in the in vivo and in vitro tests. r - correlation coefficient, F - Fisher-Snedecor test.*

Knee-length sock	r	F
I	0.9430	464.89
II	0.8036	105.71

It should be noted, however, that the anatomy of the limbs of the human population is very diverse, and therefore further research using I-SCAN will cover a wider range of users.

Conclusions

In this study knee-length socks belonging to pressure class I (18 - 21 mm Hg) with the same stitch and similar composition were characterised. It was shown that the highest pressure of the knee-length socks for the ankle and calf appeared at the 1-front point of measurement and the lowest at the 2-inner side point. It was found that there is a correlation between the *in vivo* and *in vitro* tests. Higher values of pressure for both knee-length socks were obtained for the *in vitro* tests. The pressure determined for the calf is within the range of 50-80% of the values obtained for the ankle. The method applied using the I-SCAN system allows to determine the pressure in both *in vivo* and *in vitro* conditions and to assess differences in the pressure for each measurement point. No linear correlation was found between the four measurement points, both in the *in vitro* and *in vivo*

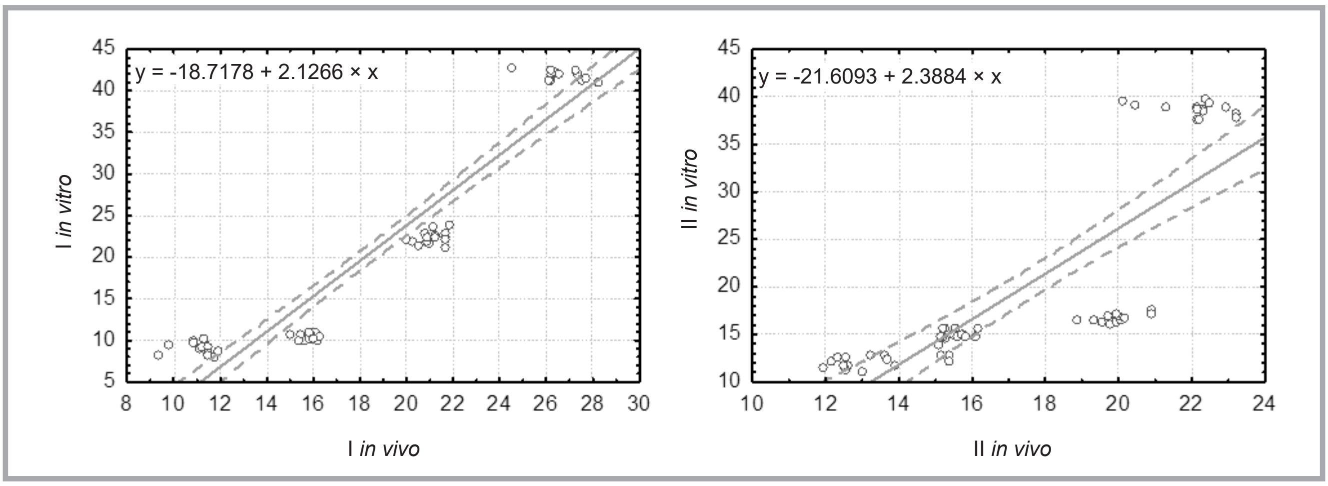

Figure 8. *Correlation between the in vivo and in vitro tests for the knee-length socks.*

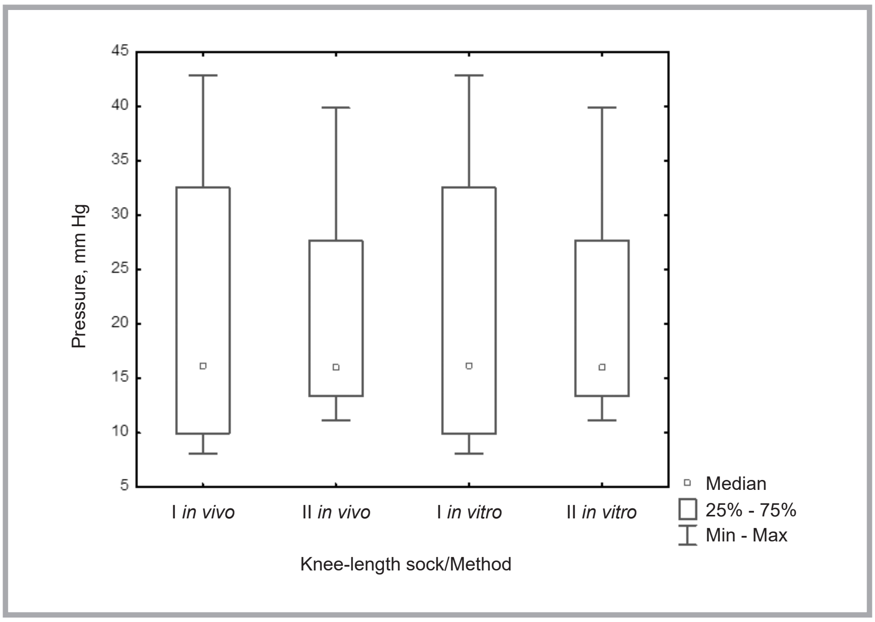

Figure 9. *Position of the median for the in vivo and in vitro tests.*

tests. Results of this preliminary study indicate that the method may be particularly beneficial for customizing product designs (not only in the area of compression products) and also assessing the values and distribution of the pressure of underwear, bodyshaping textiles and products with various pressure zones. Its usefulness in this scope will be experimentally verified in a further study.

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