Reasons for changes in the value of unit pressure of compression products supporting external treatment

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Abstract. The paper presents the basics of modelling compression products with intended values of unit pressure for body circumferences with fixed and variable radius of curvature. The derived relationships referring to the dimensions of the fabric's circumferences in a relaxed state of the product were based on Laplace law, local values of the radius of curvature, and the characteristics of stretching and relaxing (deformation) of the knitted fabric, described by experimental relation for the stress and relaxation phase for the 6th hysteresis loop, taking into account confidence intervals. The article indicates the possibilities of using 3D scanning techniques of the human body to identify the radius of curvature of various circumference of the human silhouette, for which the intended value of the unit pressure is designed, and quantitative changes in the body deformation due to compression. Classic method of modelling and design of compression products, based on a cylindrical model of the human body does not provide in each case the intended value of unit pressure, according to specific normative requirements, because it neglects the effect of different values of the radius of curvature of the body circumference and the properties of the viscoelastic knitted fabrics. The model and experimental research allowed for a quantitative and qualitative assessment of the reasons for the changes in the value of unit pressure of compression products supporting the process of external treatment.

1. Introduction

Compression therapy is a method of supporting external treatment used among others in case of varicose veins, lymphedema, post-burn and post-surgical scars. An important parameter determining the effectiveness of this method is the value of unit pressure which the product exerts on the user's body. The range of values of this parameter, depending on the type of therapy and the severity of the patient's condition is determined from the medical point of view [1-3]. The unit pressure can be constant along the whole length of the body (e.g. in treating post-burn scars) or graded - as in the prevention of varicose veins and lymphatic edema. Compression products used in adjuvant therapy are designed based on the cylindrical model of the body. Deviations from this model apply in particular to the human trunk, where there are circumferences whose curvature substantially differs from the circle. In most studies [4-7] modelling of unit pressure is based on assuming circular geometry of body circumferences. Ref. [4] presents the results of modelling unit pressure by finite elements method for a cylinder and a cone. However, in [8] the pressure exerted on the legs by the cuffs of socks was evaluated by theoretical and experimental method for the actual geometry of the leg circumference. Research on the influence of radii of curvature body circumference of on the value of the pressure unit is shown in [7].

The aim of this study is to document, on the basis of qualitative and quantitative analyzes, the reasons for changes in the value of unit pressure of compression products resulting from the following factors:
- differences between the cylindrical body model and the actual geometry of the circumference,
- deformability of the body and the resulting changes in body shape under the influence of the compression product,
- characteristics of stress and relaxation in knitted fabrics related to their rheological properties.

2. Basis for modelling compression knitted fabrics

Modelling and designing of compression products is based on Laplace law (1). It describes the relationship between the unit pressure exerted on a cylindrical body model of the circumference G_1 and circumferential force F for a stripe of a knitted fabric of the width s. In order to design the dimensions of a compression product in free state, with the intended value of unit pressure, it is necessary to know the mechanical characteristics of the knitted fabric, in the form of a relation between force and relative elongation F = f (ε). Relative elongation of the knitted fabric ε on the covered part of the body circumference is described by a well-known dependence (3).

$$P = \frac{2\pi F}{G_1 s} = \frac{F}{R \cdot s} \qquad (1)$$

$$F = f(\varepsilon) \qquad (2)$$

$$\varepsilon = \frac{G_1 - Go}{Go} \qquad (3) \text{, where:}$$

P [hPa]   - unit pressure,

F [cN]   - circumferential force in the stripe of a knitted fabric of width s,

G_1 [cm]   - circumferences of the body parts,

s [cm]   - width of the fabric stripe,

G_0 [cm]   - fabric circumference in free state,

ε - relative elongation of the fabric.

After substituting equations (2) and (3) to equation (1), and after necessary transformation we obtain dependence for the value of the fabric circumference G_o in free state as a function of the required value of pressure P and body circumference G_1 along the length of the covered body part for the given characteristics of the knitted fabric (2).

2.1   Subject of study

Compression products used in the treatment of burns are most often made of plain stitch warp-knitted fabrics with elastomeric threads, whose stitch is shown in Figure 1. The presented fabric is a three-guide knitted fabric composed of a binding stitch made of a textured polyamide silk with a linear density of 78 dtex (76 %), and vertical wefts made of polyurethane yarn with a linear density of 480 dtex (24 %). The parameters describing the fabric are course density $P_r = 720$, wale density $P_k = 154$ and surface mass $G = 244$ g/m^2.
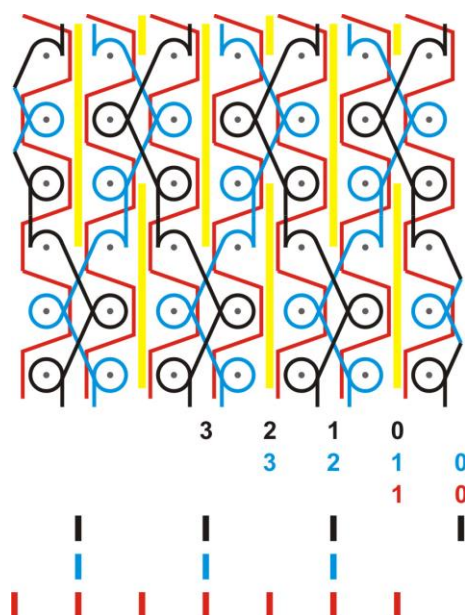
Threading report :

I full set   - polyurethane yarn

II 1 in, 1out   – polyamide multifilament

III 1 in, 1 out   – polyamide multifilament

Recording of model links:

I   11/ 00//
II   34/ 32/34/ 43/ 45/43//
III   32/ 34/ 32/ 23/ 21/ 23

Fig. 1a Record of   schematic stitches of highly elastic warp-knitted fabric with elastomeric threads

Fig. 1b Threading report with a record of cell shape

2.2   Mechanical characteristics of the knitted fabric

Research on knitted compression products performed by the procedure shown in [8], was carried out for a range of relative elongation $\varepsilon \in$ <0; 1> in separate stretching areas enlarged by 0.1 of the relative elongation. For each value of the strain, the test was carried out for 5 rectangular samples with a length of 200 mm and width of 75 mm, stitched with a flat seam along the shorter side, cut from different locations of the compression fabric and submitted (by loop method), to stretching and relaxation at a speed of 200 mm/min on the Hounsfield tensile testing machine using needles stabilizing the width of the fabric. For each stretching range 6 hysteresis loops were performed. Figure 2 shows the changes in the average values of the force as a function of the individual ranges of the strain for the 6th hysteresis loop for the stress and relaxation phase, taking into account for, the subsequent relative elongations, maximum forces in the stress phase and minimum forces in the relaxation phase from the confidence intervals. Confidence interval for the mean value is defined by the formula $\bar{x} \pm \dfrac{U_\alpha S}{\sqrt{n}}$ (5),
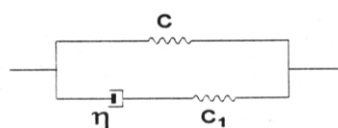
wherein: $\bar{x}$ - the arithmetic average counted on the basis of n - elemental sample population, S - experimental estimation of the standard deviation U_α - value of the random variable U of standardized normal distribution (N (0,1)) defined in such a way so as to satisfy the relation (6):

$$P\left\{\bar{x} - \frac{u_\alpha \cdot s}{\sqrt{n}} < m < \bar{x} + \frac{u_\alpha \cdot s}{\sqrt{n}}\right\} = 1 - \alpha$$ (6), wherein for 1-α = 0.95; U_α = 1.96   [10].

Significant differences between the values of forces in stress and relaxation phase, for the same elongation values result from the rheological properties of the compression fabric. Qualitative interpretations of these differences can be explained on the basis of standard Zener rheological model, according to which the process of forces relaxation is described by the relationship (7).

$$F_1 = C \cdot \varepsilon + C_1 \cdot e^{\frac{-t \cdot C_1}{\eta}}$$ (7),   where:

C, C_1 - relative longitudinal rigidity,
η- relative absolute viscosity

Transferring model interpretations onto the behavior of a compression product during use it should be noted that the circumferential forces in the fabric will tend to be equal to $C \cdot \varepsilon$, because the expression $\exp(-t \cdot C_1/\eta)$ for $t \to \infty$ takes the value 0. This explains the significant differences between the values of forces for the stress and relaxation phases.
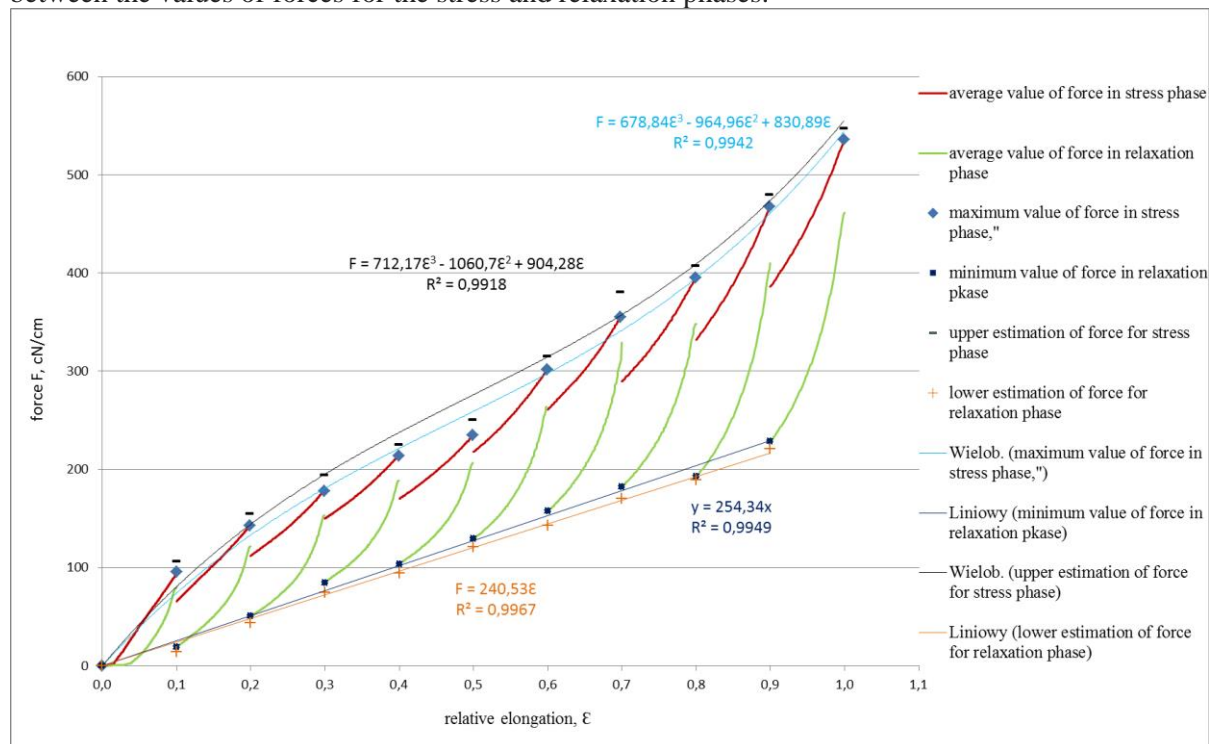

Fig. 2 Characteristics of a knitted fabric – average values of the force as a function of relative elongation for the 6th loop in the stress and relaxation phase with the confidence intervals for the maximum values in the stress phase and minimum values in the relaxation phase

The equations (8.1 ÷ 8.4) referred to the fabric stripe of the width s = 1 cm, describe the mechanical characteristics of the fabric in the form of relations between the force F and relative elongation ε for the stress and relaxation phase and from confidence intervals. Experimental functions for stress phase:

$$F = 678{,}84 \cdot \varepsilon^3 - 964{,}96 \cdot \varepsilon^2 + 830{,}89 \cdot \varepsilon \qquad R^2 = 0.9942 \text{ for the maximum values (8.1)}$$

$$F = 712{,}17 \cdot \varepsilon^3 - 1060{,}7 \cdot \varepsilon^2 + 904{,}28 \cdot \varepsilon \qquad R^2 = 0.9918 \text{ for the maximum values from the confidence interval (8.2)}$$

Experimental functions for relaxation phase:

$F = 254.34 \cdot \varepsilon$ $R^2 = 0.9949$ for the minimum values (8.3)

$F = 240.53 \cdot \varepsilon$ $R^2 = 0.9967$ for the minimum values from the confidence interval (8.4)

3.   Influence of the geometry of the circumference on the value of unit pressure

As mentioned above, compression products are designed according to Laplace law. Human body contains numerous circumferences of variable curvatures, and therefore the obtained pressure values are different in places where the radius differs from the one taken into account while designing the product for a cylindrical model of the body part.

Figure 3 depicts the geometry of scanned circumferences selected from the trunk of a female body with and without a compression product. The observed difference in the geometry of the circumferences results from the body's susceptibility to pressure. The measurements were carried out

at the Textile Research Institute in Lodz, in Scientific Division Knitting Technologies and Clothing, by the silhouette scanning technique using 3D Body Scanner.

In order to determine the effect of various values of the radius of curvature on the value of unit pressure, the values of R_n radii we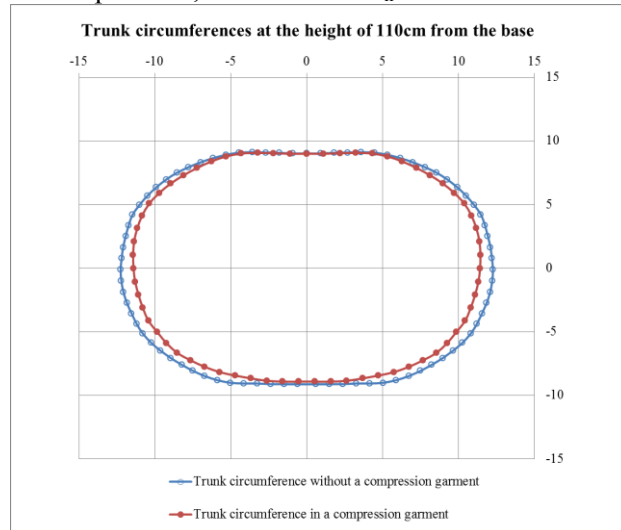re determined using the Pythagorean theorem. The radius of curvature was determined for the successive i-points of the circumference as the radius of a circle, approximated on the basis of 5 neighboring points: (x_{i-2}, y_{i-2}), (x_{i-1}, y_{i-1}), (x_i, y_i), (x_{i+1}, y_{i+1}), (x_{i+2}, y_{i+2}). Approximation is based on minimizing the mean square error (distance between the points and the circle), while the weight of error at the extreme points is reduced by half. The determined values of the radii of curvature of the given circumference in the range of angles $0 \div 360°$ before and after putting on the compression product, i.e. including the body's susceptibility to pressure are presented in (Figure 4).

Fig. 3 The geometry of scanned circumferences selected from the trunk of a female body with and without a compression product
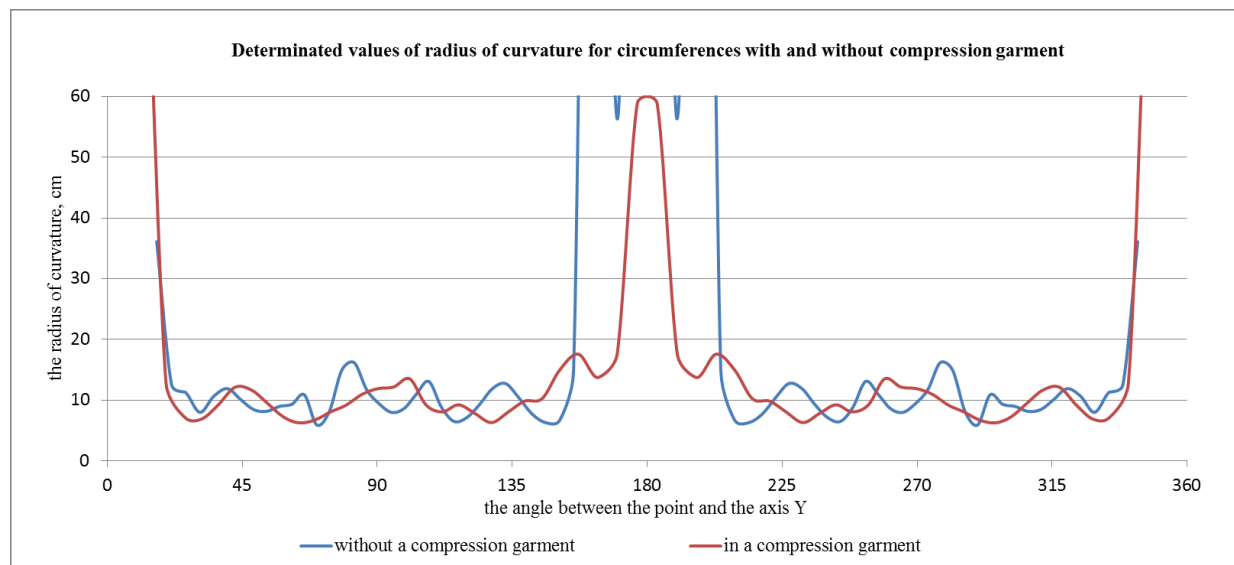

Fig. 4 Determined values of radius of curvature for circumferences with and without compression garment

Figure 5 shows the changes in the unit pressure P for the geometry of the circumference with and without the compression garment. Assuming that the value of the longitudinal force at the circumference is constant, we obtain equation (9) describing the value of unit pressure along the circumference. $P = P_{int} \cdot \dfrac{R}{R_n}$ (9), where P_{int} is the intended value of pressure equal to 20hPa, R_n values of the successive radii of curvature of the circumference, R values of radius of curvature of the circumference treated as a circle. As a result of the body's susceptibility to pressure, the circumference

with the compression clothing was reduced, resulting in reduction of relative elongation of the fabric and circumferential force. Local changing the radius of curvature of the circumference in compression clothing and the circumferential force causes a change of unit pressure (Figure 5).
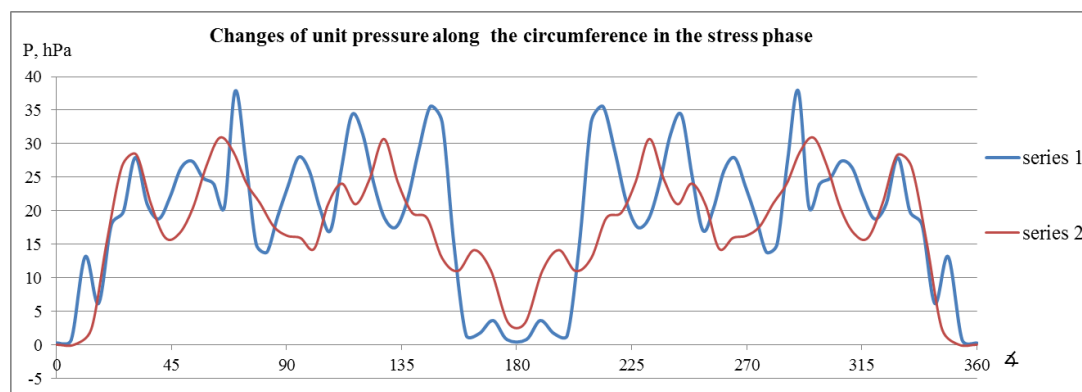

Fig. 5 Examples of changes of unit pressure along the circumference in the stress phase for the following cases:

Series 1 counting parameters: G_1=70.3 cm, R=11.19 cm, P=20 hPa, $F = 678.84\ \varepsilon^3 - 964.96\ \varepsilon^2 + 830.89\ \varepsilon$

Series 2 counting parameters: G_1=66.8 cm, R=10.63 cm, $F = 678,84\ \varepsilon^3 - 964,96\ \varepsilon^2 + 830,89\ \varepsilon$

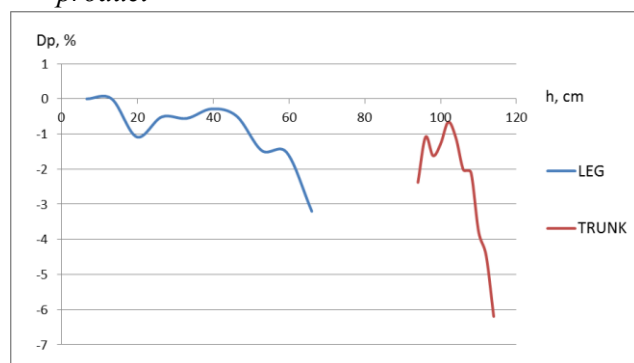*3.1 Percentage changes in the length of the circumferences under the influence of compression product*

Fig. 6 Percentage changes of legs and trunk circumferences under the influence of a compression product, where:
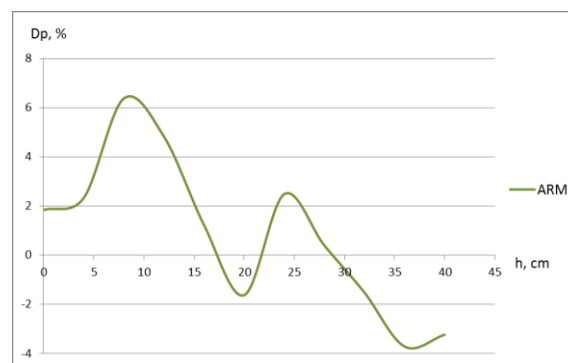Dp, % - percentage differences
h, cm - the height from the base

Fig. 7 Percentage changes of hand circumferences under the influence of a compression product, where:
Dp, % - percentage differences
h, cm - the height of the wrist

Figures 6 and 7 show, determined on the basis of the relationship $Dp = \frac{G_2 - G_1}{G_2} \cdot 100, \%$, where:

G_2- circumference in the compression product, cm
G_1- circumference without the compression product, cm
percentage changes in the circumferences of the trunk, legs and arm under the influence of the compression device designed to 20 hPa on the basis of a cylindrical body model.

The biggest changes in the length of circumferences can be observed at the trunk (waist), upper part of the leg (thigh), and the hand. These changes result from the deformability of the body and its deformation under the influence of compression. Depending on the body area and the fat content the percentage changes Dp will differ. Due to the phenomenon of deformation of the geometry

of the circumference and the changes in the radius of curvature under unit pressure, parameter Dp should in some cases be taken into account in designing compression products.

4.   Changes in the value of unit pressure, taking into account the impact of the force function and relative elongation of the knitted fabric for the stress and relaxation phase
In the next stage of the study the unit pressure changes occurring by the same relative elongation ε for the stress and relaxation phase were determined. In that stage, firstly the values of relative elongation for the body circumference without compression clothing were calculated according to the procedure currently used in the design of compression products of an intended unit pressure P = 20 hPa. Then, for the same value of relative elongation unit pressure values were determined using the functions describing the forces in the relaxation phase $P = \dfrac{2\pi \cdot (254{,}34 \cdot \varepsilon)}{G_1 s}$ (10).

The results presented in Figure 8 show a significant decline in the value of unit pressure under the influence of stress relaxation. The presented graph shows that only in the stress phase, in those places of the circumference in which the radius of curvature is equal to the radius for which the product was designed, the intended value of the unit pressure was achieved, while in the relaxation phase this value has not been reached.
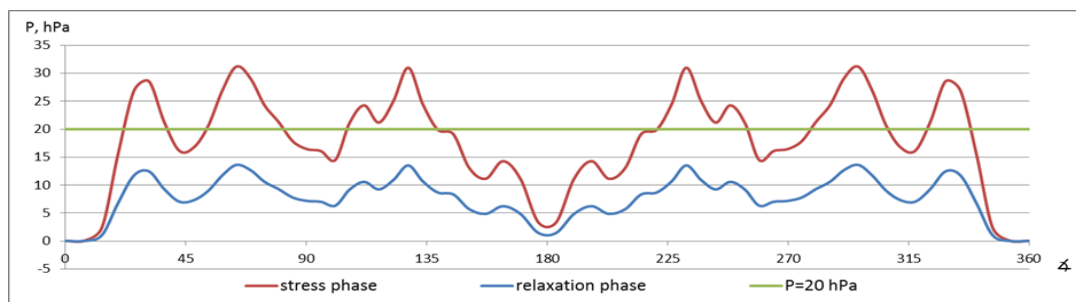

Fig. 8 Unit pressure values taking into account force function and relative elongation of the fabric for stress and relaxation phase. Counting parameters: G_1=66.8cm, R=10.63 cm, ε= 0.33
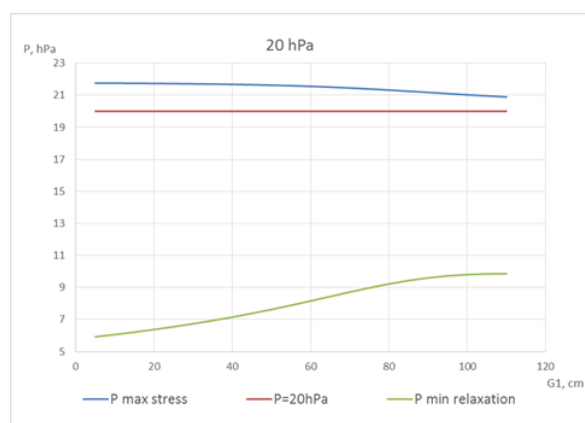

Fig. 9 Changes in the value of unit pressure taking into account the impact of force function and relative elongation of the fabric, using the determined confidence intervals for the stress and relaxation phase as a function of circumference G_1 and the intended value 20 hPa.

In the last stage of the research some generalization was made of unit pressure for a wide range of circumferences G_1. In the first stage of calculations, values of relative elongations were determined for the stress phase and the intended pressure P = 20 hPa for each circumference $G_1 \in$ <5;110> cm. Then, the calculated values of relative elongation were introduced accordingly to the equations (11), (12) to calculate the value of unit pressure:
- for the stress phase
$$P = \dfrac{2\pi(712{,}17 \cdot \varepsilon^3 - 1060{,}7 \cdot \varepsilon^2 + 904{,}28 \cdot \varepsilon)}{G_1 s} \quad (11)$$
- for the relaxation phase
$$P = \dfrac{2\pi \cdot 240{,}53 \cdot \varepsilon}{G_1 s} \quad (12)\;.$$
The calculated pressure values for the stress and relaxation phase, taking into account the impact of the force function F and relative

elongation ε of the knitted fabric, using the determined confidence intervals for both phases as a function of circumference G_1 and the intended value 20hPa are presented in Figure 9.

The values of unit pressure in the relaxation phase are significantly lower than the intended ones, which confirms the significant impact of the relaxation phenomenon on the value of unit pressure.

5.   Conclusions

On the basis of qualitative and quantitative analyzes the paper presents the changes in the value of unit pressure exerted by compression products on the user's body resulting from the following factors:
a) the characteristics of stress and relaxation of the knitted fabric resulting from its rheological properties. The study shows that the procedure currently valid for determining mechanical characteristics in the form of the relation between the force and relative elongation of a knitted fabric limited to the stress phase leads to a significant lowering of values of the unit pressure, because it does not take into account the relaxation processes occurring during the usage of products, which in case of many therapies are worn practically all day and over a period of several months.
b) the actual geometry of body circumferences having different radii of curvature. Design of compression products for circumferences of circular geometry makes it possible to obtain the intended values of unit pressure only in the body areas in which the real radius of curvature is the radius of a circle, which in some cases may reduce the effectiveness of the therapy. Thus, the local value of the radius of curvature should be in certain cases taken into account while designing compression products.
c) the susceptibility of the body to pressure. This factor is the reason for subsequent changes in the values of unit pressure, due to changes in the circumferences and the radii of curvature.

Acknowledgements

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