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Influence of Stress and Relaxation Characteristics of Knitted Fabrics on the Unit Pressure of Compression Garments Supporting External Treatment

Abstract

The paper presents an analysis of the influence of the mechanical properties' heterogeneity of knitted fabrics and the method of determining their characteristics of stress and relaxation (deformation) on the value of unit pressure of compression garments. Changes in the value of force as a function of relative elongation were described by experimental dependencies for stress and relaxation phases for the 6th hysteresis loop, taking into account the confidence intervals. Model calculations were performed for a wide range of body circumferences $G_1 = 5 - 110$ cm and for two values of unit pressure: 20 and 30 hPa using Laplace's law and experimental functions determined which describe the relationship between force and relative elongation of a knitted fabric. The research indicates one of the reasons for changes in the unit pressure in the compression garments designed.

Key words: medtextiles, unit pressure, Laplace law, mechanical parameters, knitted fabrics, body circumferences.

Introduction

An effective method supporting the process of external treatment is the compression therapy used, among others, in the treatment of post-burn scars, lymphoedema, varicose veins, and after plastic surgery operations. An important parameter of compression garments supporting the process of external treatment is the unit pressure exerted on the protected (covered) body parts. The range of values of this parameter, depending on the type of therapy, is determined from a medical point of view and should be obeyed [1 - 6]. Works on the modelling of unit pressure [6 - 9] are based on a model of the human body in which the circumferences are treated as circles (**Figure 1**). Changes in the value of unit pressure depending on the circumferences, with a variable radius of curvature of the human body circumferences, is shown in [10]. [7] presents the results of modelling the unit pressure with the finite element method for the case of a cylinder and

cone. In these works, the linear mechanical characteristic of knitted fabric of a constant value of stretching rigidity was assumed for modelling.

An important step in the procedure of designing compression garments is the method of determining the mechanical characteristics of a knitted fabric in the form of the relationship between the force and relative elongation. The aim of the study was to determine the influence of the characteristics of stress and relaxation (deformation) of a compression knitted fabric on the changes in values of the unit pressure exerted on the cylindrical model of a body for a wide range of body circumferences taking into consideration the confidence intervals determined for the dependencies mentioned above. The aim of the study also includes the development of a new procedure for determining the stress-relaxation (deformation) characteristics of a knitted fabric, which takes into account the results of tests on the basis of a partition into sub-ranges of deformations, instead of a single range thereof.

Basis for modelling compression knitted fabrics

The basis for modelling and designing compression garments is Laplace's law (1), which describes the relationship between the unit pressure exerted on a cylindrical body model of circumference G_1 and the peripheral force F in a knitted band of width s (**Figure 1**).

$$P = \frac{2\pi F}{G_1 s} \quad (1)$$

where: P - unit pressure in, hPa, F - peripheral force of a knitted band of width s , in cN, G_1 - circumference of a body part, in cm, s - width of a knitted band, in cm.

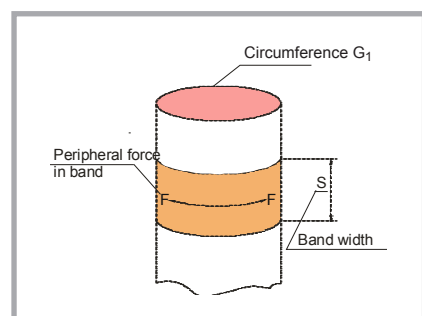


Figure 1. Cylindrical model of a body part covered with a compression band (tourniquet) [7].

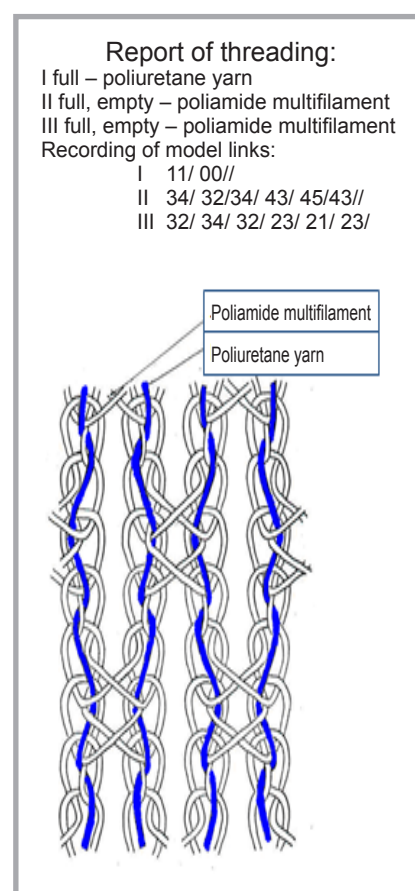


Figure 2. Report of threading with a recording of model links and a stitch of highly elastic knitted fabric with elastomeric threads.

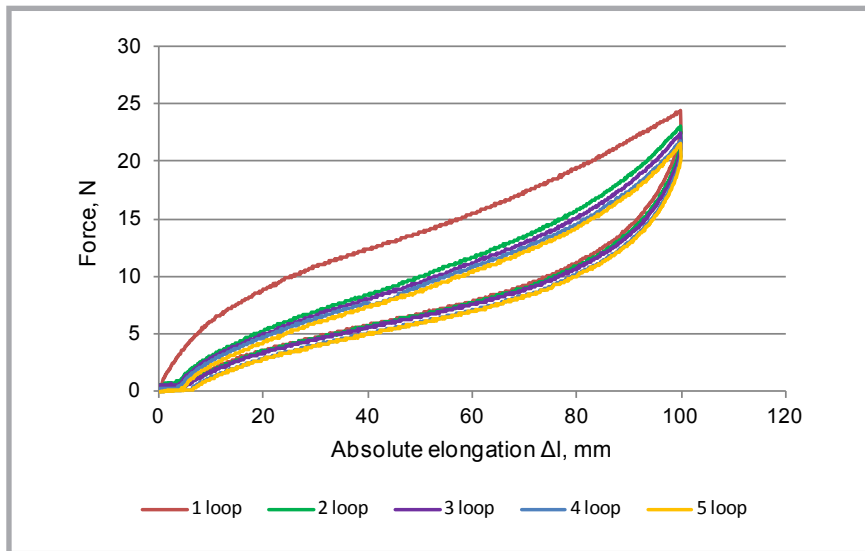


Figure 3. Exemplary graph of force as a function of absolute elongation in hysteresis loops in the stress and relaxation cycle. Research conditions: width of sample s 5 cm, length of sample 10 cm, and rate of deformation 5 mm/min.

In order to determine the dimensions of a compression garment in a free state with the value of unit pressure assumed, it is necessary to know the mechanical characteristics of the knitted fabric in the form of an experimental relationship between the force and relative elongation.

Research subject and methodology

Compression garments used in post-burn therapies are often made from plain stitch warp-knitted fabric with elastomeric threads, whose stitch is presented in **Figure 2**. It is a three-guide knitted fabric composed of a binding stitch made of textured polyamide mul-

tilament with a linear density of 78 dtex (76%) and vertical weft threads made of polyurethane yarn with a linear density of 480 dtex (24%). The parameters describing the yarn are the following: course density $P_r = 120$, wale density $P_k = 140$ and surface mass $G = 234$ g/m².

Compression garments used in e.g. post-burn therapies are practically worn 23 hours a day over a period of several months. In order to maintain the unit pressure desired at a specific range of values determined from a medical point of view, the product should have characteristics of the body seeking to be perfectly elastic, which involves obtaining a minimum hysteresis loop during stretching and relaxation.

The research on a knitted fabric was conducted by increasing the range of elongation of 0.25 of the relative elongation ε in five separate cycles of stretching and relaxation. In total, 25 rectangular samples were used in the tests, 5 for each range of stretching. The knitted samples were stretched and relaxed at a rate of 5 mm/min using a tensile testing machine by Hounsfield.

The relationship between the force F and relative elongation was determined on the basis of experimental results obtained from the 6th hysteresis loop for the stretching and relaxation phases. The assumption of six hysteresis loops is associated with the mechanical conditioning of a knitted fabric. Differences between the values of forces for the stress and

relaxation phases decrease with the number of hysteresis loops performed. The largest differences occur between the 1st and 2nd loop, while those between the 4th and 5th loop are insignificantly small, as shown in **Figure 3**, which presents five examples of hysteresis loops.

Differences in the values of forces between the phases of stress and relaxation of a knitted fabric can be interpreted qualitatively from the behaviour of the three-element standard Zener model [11] (**Figure 4**), because knitted fabrics with elastomeric threads are subject to the laws for viscoelastic materials. The relationship between the relative elongation ε , the value of tensile force F , the working time t of this force and rheological parameters c , c_1 & η in the Zener model is described by the following differential **Equation 2**:

$$F + \frac{\eta}{C_1} \frac{dF}{dt} = C\varepsilon + (C + C_1) \frac{\eta}{c_1} \frac{d\varepsilon}{dt} \quad (2)$$

Assuming that the rate of increase of relative deformations is constant $d\varepsilon/dt = \text{const}$ and the initial force during stretching is $F_0 = 0$, **Equation 2** takes the **Equation 3** for this case:

$$F_1 = C \cdot \varepsilon + \eta \cdot \frac{d\varepsilon}{dt} \left(1 - e^{-\frac{t}{\tau}} \right) \quad (3)$$

In both the stress and relaxation phases, the Maxwell term in the standard model is responsible for the relaxation process.

Table 1. Results of statistical analysis.

| Stress phase | | | |
|--|--------|--------------|----------------------|
| F _{ng} ; R = 0.9992; F = 686.81; p < 0.00009 | | | |
| Regression coefficient | value | t statistics | Significance level p |
| bo | 0 | | |
| b1 | 905.9 | 8.248 | 0.003732 |
| b2 | -943.9 | -3.696 | 0.034373 |
| b3 | 473.0 | 3.360 | 0.043721 |
| F _{ns} ; R = 0.9959; F = 616.914; p < 0.00001 | | | |
| bo | 0 | | |
| b1 | 433.6 | 24.838 | 1.97E-06 |
| b2 | 0 | | |
| b3 | 0 | | |
| Relaxation phase | | | |
| F _{od} ; R = 0.9993; F = 1131.8; p < 0.00005 | | | |
| bo | 0 | | |
| b1 | 336.4 | 18.518 | 0.000344 |
| b2 | -141.6 | -7.377 | 0.005151 |
| b3 | 0 | | |
| F _{os} ; R = 0.9996; F = 2181.3; p < 0.00002 | | | |
| bo | 0 | | |
| b1 | 366.7 | 18.51758 | 0.000344 |
| b2 | -161.6 | -7.37678 | 0.005151 |
| b3 | 0 | | |

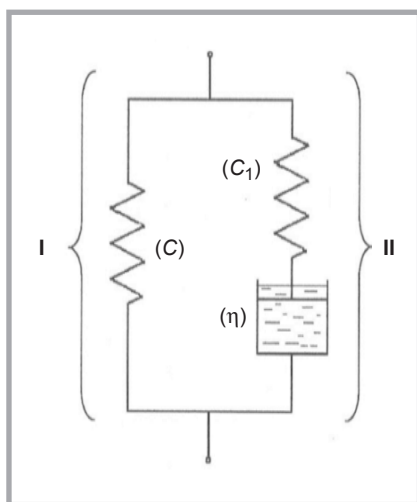


Figure 4. Three-element Zener model: I Hooke's segment, II Maxwell's segment, C , C_1 – elasticity constants, η – dynamic viscosity

From the interpretation of the expression $\exp(-t C_1/\eta)$, which describes the process of relaxation of forces, it results that these forces depend inversely exponentially on their time of action. Transferring these model interpretations to the behaviour of compression garments during use, it should be noted that during several months of usage it refers to the classical process of relaxation. Assuming the conditions of relaxation, i.e. $\varepsilon = \text{const}$, $d\varepsilon/dt = 0$, we obtain **Equation 4**, describing the relaxation process of forces according to the three-element Zener model.

$$F_1 = C \cdot \varepsilon + C_1 \cdot e^{\frac{-t \cdot C_1}{\eta}} \quad (4)$$

From the analysis of the equation it results that the peripheral forces in the knitted fabric will aim to be equal to $C \cdot \varepsilon$ as the expression $\exp(-t C_1/\eta)$ for $t \rightarrow \infty$ takes the value of 0. The relaxation of forces occurs as a result of adopting the deformations of a spring with rigidity C_1 by a viscous term (attenuator).

From the considerations presented above, a thesis can be advanced that introducing mechanical characteristics of a knitted fabric in the form of the relationship between the force and relative elongation for the stress phase into the procedure of designing compression garments causes the lowering of values of the unit pressure in relation to the value intended. For this reason a comparative analysis of changes in the value of the unit pressure will be carried out on the basis of relations between the force and elongation of knitted fabrics for stress and relaxation phases used in the procedure of designing compression garments.

In order to determine a general characteristic of knitted fabrics an analysis of regression was used. As an independent variable the relative elongation of the knitted fabrics was assumed within the range of 0 - 1.25 for the stress phase, and from 1 to 0 for the relaxation phase, in separate cycles of stretching with measuring points every 0.25. For each of the values of elongation five measurements of the force were carried out.

From the point of view of assessing the usefulness of the products, important are not only the average characteristics of forces, but also boundary conditions. For this reason, two characteristics of forces were taken into account as a dependent variable - the mean value and its upper estimation for the stress phase, and a

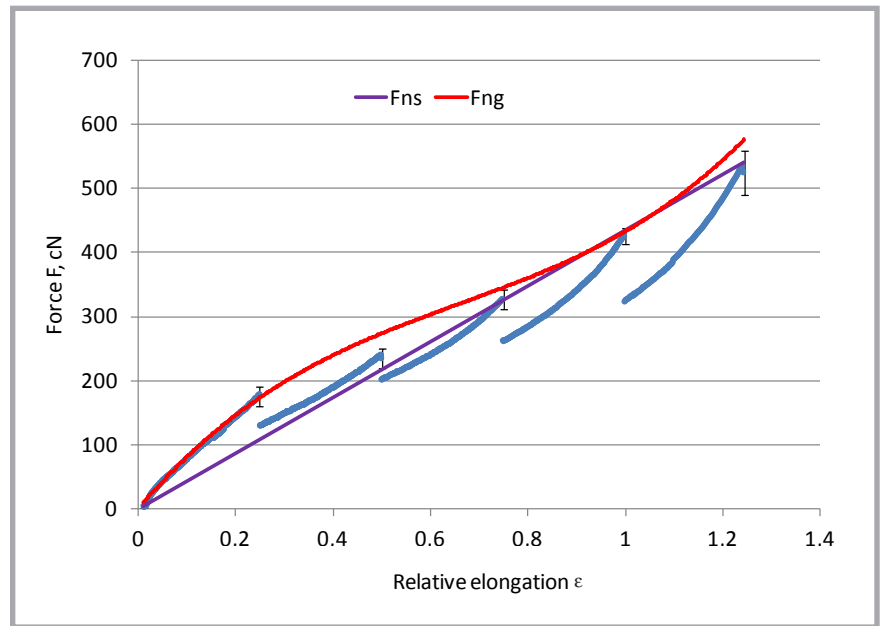


Figure 5. Values of average F_{ns} and upper estimation F_{ng} of confidence intervals for the relaxation phase as a function of the relative elongation ε for the 6th hysteresis loop; width of knitted band $s = 1$ cm.

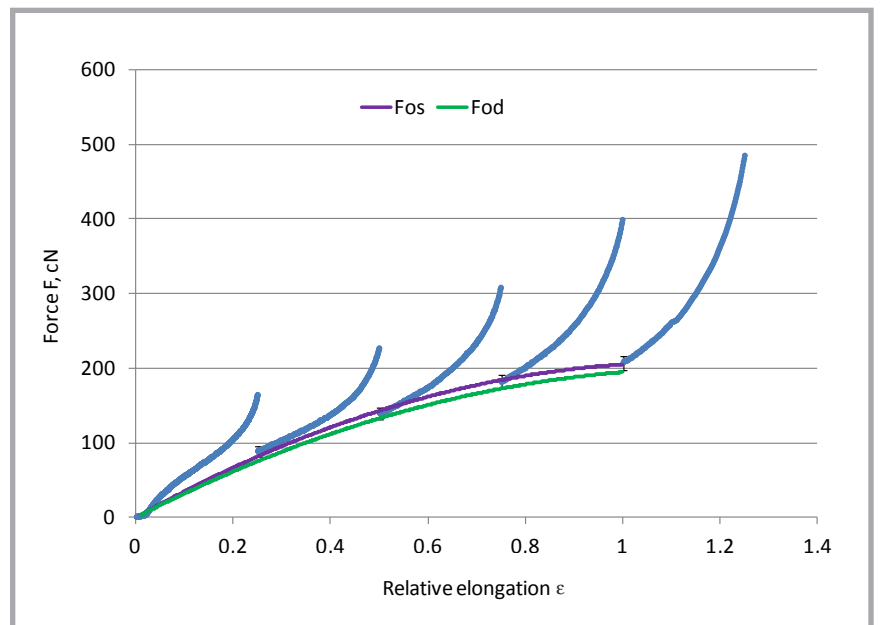


Figure 6. Values of average F_{os} and lower estimation F_{od} of confidence intervals for relaxation phases as a function of the relative elongation ε for the 6th hysteresis loop; width of knitted band $s = 1$ cm.

lower estimation for the relaxation phase, taken as the boundary of the 95% confidence interval for the value of the force expected.

$$F_{ng} = \overline{F_{ns}} + \frac{t_{1-\alpha/2} S}{\sqrt{n-1}} \quad (5)$$

$$F_{od} = \overline{F_{os}} - \frac{t_{1-\alpha/2} S}{\sqrt{n-1}} \quad (6)$$

where: F_{ns} - average value of force in stress phase, F_{os} - average value of force in relaxation phase, F_{ng} - upper estimation of force for stress phase, F_{od} - lower

estimation of force for relaxation phase, S - standard deviation from the sample, n - number of measurements ($n = 5$), $t_{1+\alpha/2}$ - quantile of Student's t-distribution of $n - 1$ degrees of freedom. In order to determine the curves of stress and relaxation the method of backward stepwise regression was used assuming that the regression model for values F_{ns} , F_{os} , F_{ng} , and F_{od} with respect to ε is the polynomial of the degree 3 maximum.

$$F = b_0 + b_1 \cdot \varepsilon + b_2 \cdot \varepsilon^2 + b_3 \cdot \varepsilon^3 \quad (7)$$

Table 1 presents the values of regression coefficients. The values of coefficients equal to 0 were taken for cases where, on the basis of the test of significance for a given regression coefficient, there was no reason to reject the hypothesis that it is equal to zero. For the models obtained the values of multiple regression coefficient R , the results of the regression significance test (F statistics and level of significance p), and the results of tests of the regression coefficient's significance (t statistics and significance level of p) were presented. Only the significant regression coefficients are taken into account in the models adopted. In all cases, due to the insignificance of the absolute term (n_o evidence to reject the hypothesis that $b_0 = 0$), it was necessary to determine a regression model without the absolute term.

On the basis of the results presented in **Table 1**, the following models of the pressing force as a function of the relative elongation were obtained:

■ For the stress phase:

$$F_{ng} = 905.9 \cdot \varepsilon - 943.9 \cdot \varepsilon^2 + 473.0 \cdot \varepsilon^3 \quad (8)$$

$$F_{ns} = 433.6 \cdot \varepsilon \quad (9)$$

■ For the relaxation phase:

$$F_{od} = 336.4 \cdot \varepsilon - 141.6 \cdot \varepsilon^2 \quad (10)$$

$$F_{os} = 366.7 \cdot \varepsilon - 161.6 \cdot \varepsilon^2 \quad (11)$$

The equations determined (8–11) refer to the band width of knitted fabric $s = 1$ cm. Despite the lack of significance of regression coefficients b_0 , b_2 and b_3 of the regression model for value F_{ns} , a polynomial of degree three was used in further calculations (12) because within the range of values of relative elongation $\varepsilon = 0.2 - 0.5$ in the stress zone there is a considerable difference between the experimental values and those calculated according to the linear function (**Figure 5**).

$$F_{ns} = 768.9 \cdot \varepsilon - 682.9 \cdot \varepsilon^2 + 327.4 \cdot \varepsilon^3 \quad (12)$$

$R^2=0.9939$

Influence of characteristics of stress and relaxation (deformations) of knitted fabrics on changes in the unit pressure

Changes in the unit pressure in relation to the intended values of 20 and 30 hPa

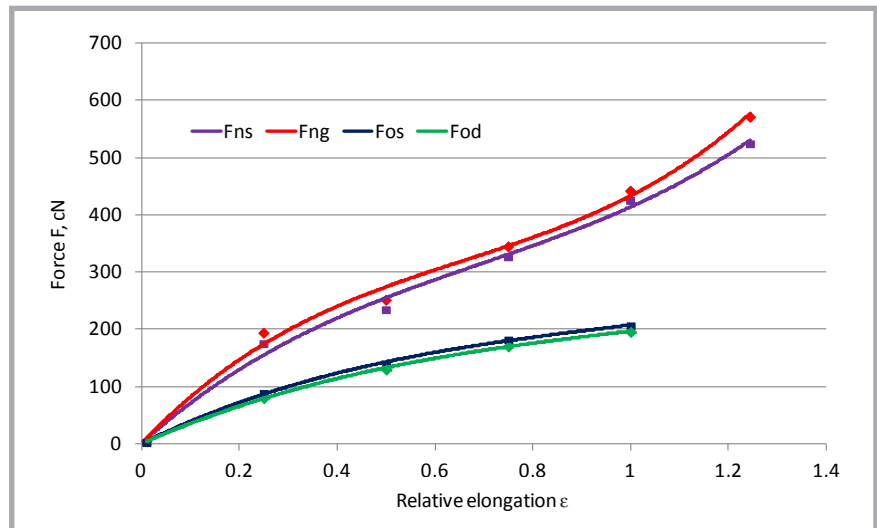


Figure 7. Values and models of force observed in the knitted fabric as a function of the relative elongation in the stress and relaxation phase for average values and the upper & lower estimation of forces, respectively; width of knitted band $s = 1$ cm.

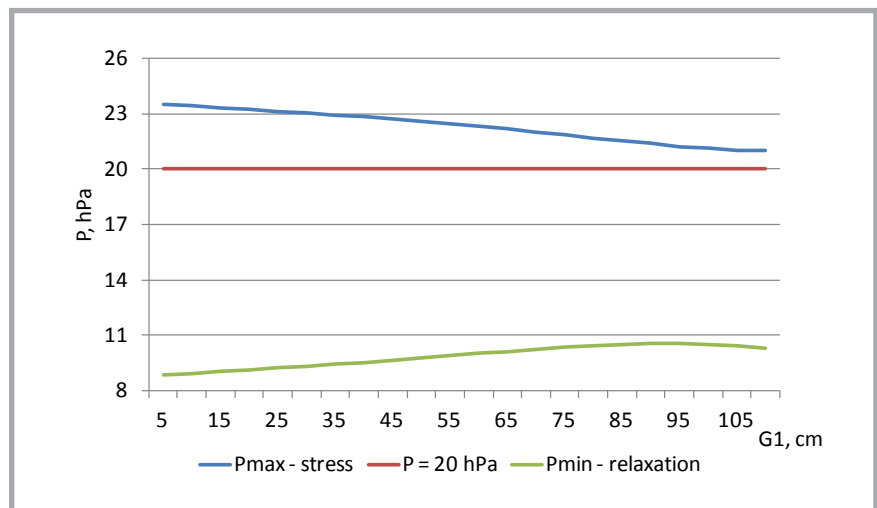


Figure 8. Changes in the values of unit pressure as a function of circumference G_1 as a result of changes in forces from the upper and lower estimation of confidence intervals for the stress and relaxation phases, respectively, in relation to the intended value of pressure $P_{int} = 20$ hPa.

were determined according to the following procedure:

Calculation procedure

Step I: for successive values of circumference G_1 within the range of 5 - 110 cm and those of unit pressure $P = 20$ and 30 hPa, values of the relative elongation ε were defined from **Equation 13**, which was obtained by introducing an experimental function (12) into **Equation 1**. The calculations were performed using Excel tools.

$$P = \frac{2\pi(768.9 \cdot \varepsilon - 682.9 \cdot \varepsilon^2 + 327.4 \cdot \varepsilon^3)}{G_1 s} \quad (13)$$

Step II: Next for successive values of circumference G_1 within the range of

5 - 110 cm, the values of unit pressure were determined by introducing values of the relative elongation ε obtained from the first step into dependence (14), which was obtained by introducing experimental dependence (8) into **Equation 1**. The course of these functions is illustrated by the curves situated above the straight lines of intended values of unit pressure $P = 20$ and 30 hPa (**Figure 7** and **8**), illustrating the maximum values of unit pressure for the upper estimation of ranges for the stress phase.

$$P = \frac{2\pi(905.9 \cdot \varepsilon - 943.9 \cdot \varepsilon^2 + 473.0 \cdot \varepsilon^3)}{G_1 s} \quad (14)$$

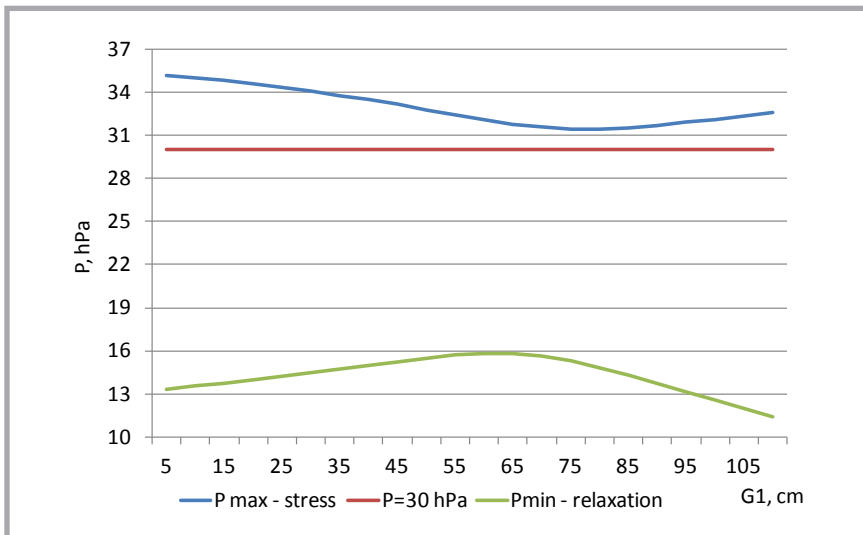


Figure 9. Changes in the values of unit pressure as a function of circumference G_1 as a result of changes in forces from the upper and lower estimation of confidence intervals for the stress and relaxation phases, respectively, in relation to the intended value of unit pressure $P_{int} = 30$ hPa.

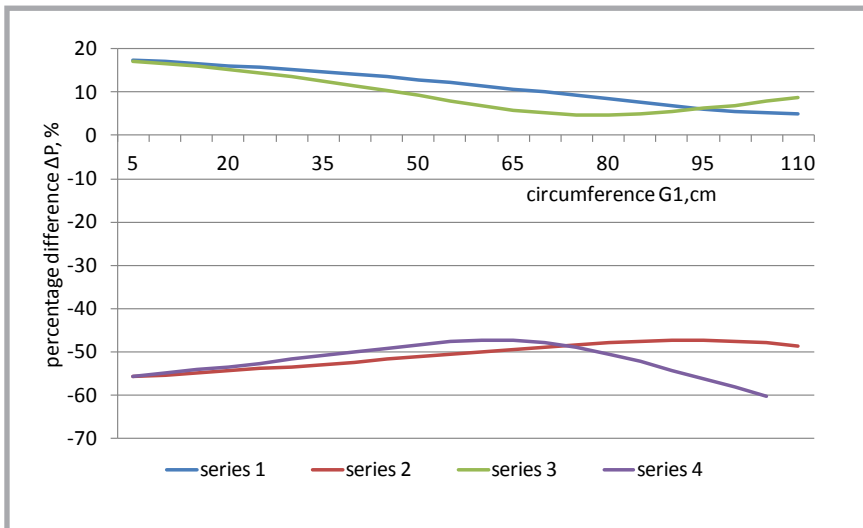


Figure 10. Percentage differences ΔP between the intended values of unit pressure $P_{int} = 20$ and 30 hPa, and the boundary values of P_{cal} calculated for the stress (series 1 and 3) and relaxation phases (series 2 and 4) resulting from the upper and lower estimation of the confidence intervals.

Then, introducing dependence (10) into **Equation 1**, we obtain the minimum values of unit pressure resulting from the lower estimation of the confidence interval for the relaxation phase, which was calculated from **Equation 15**.

$$P = \frac{2\pi(336.4 \cdot \varepsilon - 141.6 \cdot \varepsilon^2)}{G_1 s} \quad (15)$$

The course of these functions is illustrated by the curves in **Figures 7 and 8**, situated below the straight lines of the intended value of unit pressure $P = 20$ and 30 hPa. These curves show the minimum values of unit pressure for the lower esti-

mations of the force from the confidence interval for the relaxation phase.

The results presented in **Figures 8 and 9** show significant changes in the values of unit pressure under the influence of possible, statistically documented, changes in the values of peripheral forces in the knitted fabric for equal values of relative elongation. The percentage differences between the intended value of unit pressure $P_{int} = 20$ and 30 hPa presented in Figure 10, and the values calculated using **Equations 1, 14 and 15** are the generalisation of the results presented in **Figures 8 and 9**. The percentage differences were calculated according to the following Equation:

$$\Delta P = \frac{P_{cal} - P_{int}}{P_{int}} 100\% \quad (16)$$

where: P_{cal} – value calculated, P_{int} – assumed values of 20 and 30 hPa.

A qualitative explanation of the significant decrease in the value of unit pressure (approximately -50%) in relation to the average maximum values obtained for the stress phase can be documented on the basis of the relaxation process analysed above and, at the same time, by not considering in the procedure of designing compression garments the relationship between the force and relative elongation for the relaxation phase of a knitted fabric. Values of unit pressure increased in relation to the assumed values of 20 and 30 hPa from about 6% to 17%, resulting from the upper estimation of the values of forces from the confidence intervals for the stress phase. **Figure 9** shows that the percentage difference ΔP arising from the changes in peripheral forces for this phase decreases with an increase in the value of circumference G_1 . From the considerations given above it results that the procedure currently valid for determining the mechanical characteristics of a knitted fabric for the stress phase - according to Standard [6] - leads to lowering the value of the unit pressure, as it only partially takes into account the relaxation process occurring during the use of garments, which in many therapies are worn practically 23 hours a day over a period of several months. The results obtained correspond to experimental results of the unit pressure of sock tops, for which after 12 hours of usage a decrease in pressure exceeding 50% of the initial pressure was noted [13].

The results presented enable us to clearly state that one of the main causes of lowering the value of the unit pressure in relation to the intended value is the procedure limited to determining the characteristics of stress - deformation.

Conclusions

1. The research conducted 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 garments which in many therapies are worn practically 23 hours a day over a period of several months.

2. Percentage differences in unit pressure in relation to the intended value of pressure determined on the basis of the relaxation phase are about 50% lower due to the visco-elastic properties, mechanical heterogeneity of the knitted fabric tested and the method used for determining its mechanical characteristics.
3. The research performed indicates one of the reasons for changes in the unit pressure of compression garments, which is primarily related to adopting in the design process the characteristic of a knitted fabric in the form of a force and relative deformation in the stress phase.



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