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Issues Regarding the Design of Textile Compression Products for Small Body Circumferences

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Abstract
On the basis of models developed, an analysis was made of the impact of the seam and adopted manufacturing tolerances of a compression product on the value of unit pressure depending on the longitudinal rigidity of a compression fabric for relatively small body circumferences. Algorithms were developed using Laplace's law and can be applied for designing textile compression products connected by seams, with an intended value of unit pressure. The research results allowed to formulate some general guidelines for designing compression products for relatively small body circumferences.

Key words: *compression products, unit pressure, body circumference, dimensional tolerance, Laplace law.*

Introduction

In the design of textile compression products supporting the process of external treatment, one of the most important issues is the value of unit pressure which the product exerts on the user's body. The range of this parameter is determined from a medical point of view depending on the type of therapy and should be strictly respected [1 - 6]. Unit pressure can be a constant along the whole length of the body (e.g. in the treatment of post-burn scars) or graded - as in the prevention of varicose veins and lymphatic edema. Most of the works concerning modelling unit pressure [7 - 10] are based on a model of the human body in which the circumferences are regarded as circles. In [8], apart from an analytical model using Laplace's law, the finite element method was also applied for the case of a cylinder and cone. The authors obtained comparable results of the compression degree while using both the analytical model and finite element method. By theoretical and experimental methods in [11], the pressure of socks cuffs was analysed from the point of view of the actual geometry of the leg circumference. The authors documented a decline in unit pressure as a function of the duration of use of the product. Modelling textile compression products with an intended value of unit pressure for body circumferences with a variable radius of curvature was the subject of work [12]. Work [13] analysed the influence of the inhomogeneity of mechanical properties of a knitted fabric and methods of determining the characteristics of its strain and relaxation- deformation on the value of unit pressure of textile compression products. Evaluation of the impact of body deformability and associated changes in body shape under the influence of the compression product on the pressure value is presented in [14].

The aim of this study is to document, on the basis of qualitative analyses, the reasons for changes in the value of unit pressure of textile compression products designed for body parts with relatively small circumferences, such as fingers or upper limbs. These reasons stem from the presence of the seam and manufacturing tolerances of the compression product. The results of the research allowed the ormulation of some general guidelines for the design of textile compression products with an intended value of unit pressure for relatively small body circumferences.

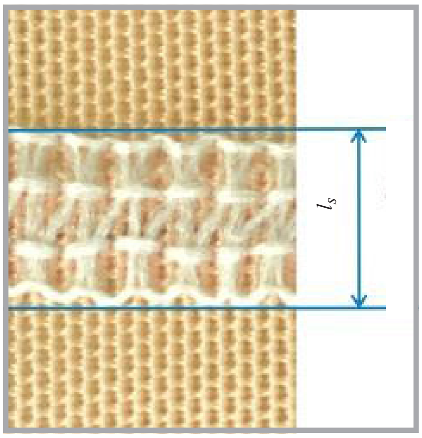

Figure 1. Flat seam formed on autolap, stitch type covering chain – Class 607 (ISO 4915:1991).

Impact of the seam on changes in unit pressure

A traditional technique based on combining elements of a textile product with seams reveals the influence of the seam on the changes in unit pressure. It is par-

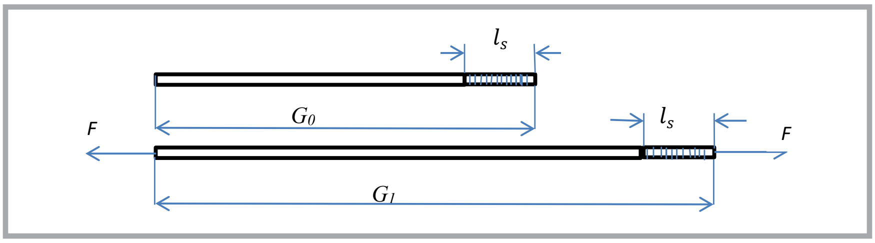

Figure 2. Part of a band connected by a seam of circumference G_0 in a relaxed state and under the action of circumferential force F.

ticularly important in the case of products designed for body parts with small circumferences, where elements of the product are connected by flat seams formed on an autolap (***Figure 1***).

For the purpose of modelling the impact of the seam on changes in unit pressure, it was assumed that compared with fabric elasticity, the elasticity of the seam is practically negligible. This assumption is based on the construction of a seam which is made of two overlapping layers of fabric additionally reinforced by a bilateral arrangement of sewing threads of low elasticity.

The theoretical analyses conducted were based on the following assumptions:
1. For body parts of circular cross-sections, pressure modelling is based on Laplace's law.
2. The relation between the force and relative elongation of the compression knitted fabric is described by a linear relationship.
3. Forces F in the fabric along the circumference of the human body are a constant value, because usage leads to their equalisation
4. Body susceptibility to unit pressure can be neglected.

Relative elongation of fabric circumference reduced a by seam of width l_s is equal to (***Figure 2***):

$$\varepsilon_1 = \frac{(G_1 - l_s) - (G_0 - l_s)}{G_0 - l_s} = \frac{G_1 - G_0}{G_0 - l_s} \qquad (1)$$

The value of unit pressure P_1 resulting from Laplace's law (2) and the linear characteristic of the relationship between force F_1 and relative elongation ε_1, $F_1/s = c_1 \cdot \varepsilon_1$ is obtained from ***Equation 3.***

$$P_1 = \frac{2 \cdot \pi \cdot F_1}{G_1 \cdot s} \qquad (2)$$

$$P_1 = \frac{2 \cdot \pi \cdot c_1 (G_1 - G_0)}{G_1 \cdot (G_0 - l_s)} \qquad (3)$$

Assuming that the longitudinal rigidity of the seam is equal to the fabric elasticity, the value of the relaxed length of circumference G_0 of the knitted fabric can be determined as follows.

The intended value of unit pressure for the body circumference G_1 in a strip of knitted fabric of width s = 1 cm equals:

$$P = \frac{2 \cdot \pi \cdot F}{G_1 \cdot s} \qquad (4)$$

For the linear characteristic of the relationship between the force in the fabric strip of width s and relative elongation ε, $F_1/s = c_1 \cdot \varepsilon$, we obtain:

$$P = \frac{2 \cdot \pi \cdot c_1 \cdot \varepsilon}{G_1} \qquad (5)$$

After introducing the well-known dependence for the value of relative elongation ε (6) into ***Equation 5***, and after conversion with respect to G_0, we obtain ***Equation** 7*.

$$\varepsilon = \frac{G_1 - G_0}{G_0} \qquad (6)$$

$$G_0 = \frac{2 \cdot \pi \cdot c_1 \cdot G_1}{2 \cdot \pi \cdot c_1 + P \cdot G_1} \qquad (7)$$

After introducing expression (7) into ***Equation 3***, we obtain relationship (8), with which it is possible to calculate the inflated unit pressure P_1, resulting from the presence of the seam.

$$P_1 = \frac{2 \cdot \pi \cdot c_1 \cdot P \cdot G_1}{2 \cdot \pi \cdot c_1 \cdot G_1 - 2 \cdot \pi \cdot c_1 \cdot l_s - P \cdot G_1 \cdot l_s} \qquad (8)$$

Calculation results shown in ***Figure 3*** indicate that the presence of the seam affects the value of unit pressure. The smaller the body circumference, the greater the effect. Percentage differences decrease from a value close to 28% for a circumference of 2 cm to about 2% for circumference G_1 = 30 cm (***Figure 4***). It was observed that percentage differences are practically independent of the intended value of unit pressure.

Elimination of the increase in unit pressure occurring due to the presence of the seam can be achieved by taking into account in the calculation algorithm some parameters of the seam, such as its width l_s and longitudinal rigidity c_2. The algorithm proposed can also be used for calculating the circumferences of a fabric in a relaxed state for textile compression products composed of two sets of fabrics with different longitudinal rigidity.

The generalised calculation algorithm (***Figure 5***, see page 118) enables determination of the circumferences of a fabric in a relaxed state G_0 depending on the value of the circumference G_1, the intended value of unit pressure P as well as on the longitudinal rigidity of the knitted fabric c_1 and seam c_2. In the first stage of calculations for a given value of unit

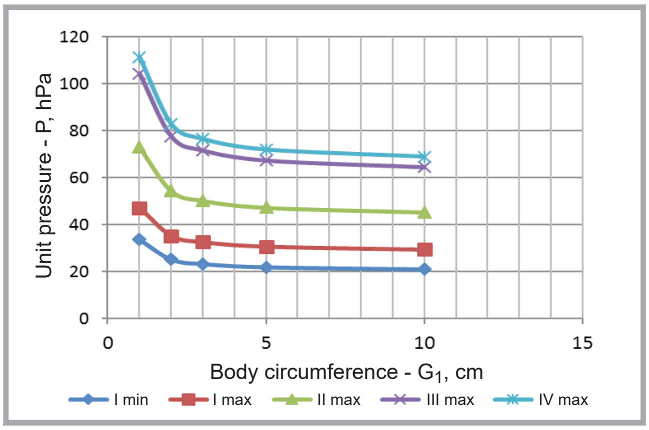

Figure 3. *Influence of seam on the change in unit pressure P as a function of the body circumference G_1 for different classes of pressure. Counting parameters: I min, I max, II max, III max, IV min - unit pressure values for each pressure class, respectively, P = 20, 28, 43, 61, 65 hPa, G_1= 1 - 10 cm, relative longitudinal rigidity c_1 = 670 cN/cm, l_s = 0.4 cm.*

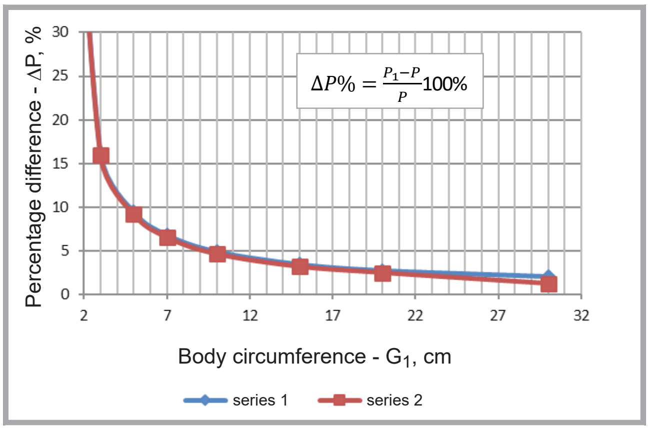

Figure 4. *Influence of the seam on the percentage change in the value of unit pressure as a function of the circumference value for the I and IV pressure classes. Series 1 - percentage difference for a lower value from pressure class I P = 20 hPa, Series 2 - percentage difference for a lower value from pressure class IV P = 65 hPa.*

pressure P and body circumference G_1, the value of the circumferential force in a strip of width s is determined from the transformed Laplace's formula.

$$\frac{F}{s} = \frac{P \cdot G_1}{2 \cdot \pi} \quad (9)$$

The value of circumferential force F is the same in both the compression fabric and seam. In the next stage of calculations the values of relative elongations ε_1 and ε_2 are determined based on a specific value of circumferential force F and experimental functions $F = f(\varepsilon_1)$ and $F = f(\varepsilon_2)$, describing the relationship between the force and relative elongation of the fabric and seam. After calculating relative elongations ε_1 and ε_2 from the experimental functions and the F/s value from Laplace's law, the relaxed length of the fabric L_{01} and width of the seam in a relaxed state l_s can be determined by ***Equations 10*** and ***11***, wherein l'_s denotes the seam length in a stretched state.

$$L_{01} = \frac{G_1 - l'_s}{1 + \varepsilon_1} \quad (10)$$

$$l_s = \frac{l'_s}{1 + \varepsilon_2} \quad (11)$$

Assuming that seam extensibility is negligible compared to that of the fabric ($c_2 >> c_1$), which means $l'_s \approx l_s$, s, it can be assumed that $G_0 = L_{01} + l_s$.

In that case, for the linear characteristic of the tensile force F as a function of the relative elongation of the fabric ε_1, the value of relative elongation ε_1 of the fabric under the influence of the circumferential force F/s can be calculated from ***Equation 12.***

$$\frac{F}{s} = \frac{P \cdot G_1}{2 \cdot \pi} = c_1 \cdot \varepsilon_1 \quad (12)$$

After substituting the designated relative elongation ε_1 into equation $G_0 = L_{01} + l_s$ and for $l'_s = l_s$ we get:

$$G_0 = \frac{(G_1 - l_s) \cdot 2 \cdot \pi \cdot c_1}{2 \cdot \pi \cdot c_1 + P \cdot G_1} + l_s \quad (13)$$

Circumferences values in a relaxed state G_0 calculated according to the algorithm for small circumferences of body parts $G_1 = 3 - 10$ cm (***Figure 6***) indicate that knitted fabrics of low longitudinal rigidity c_1 are more useful in that case, since the lower the value of longitudinal rigidity, the greater the difference between the value of body circumference G_1 and relaxed length G_0. This statement will be further documented by analysis of the impact of the manufacturing tolerance of the compression product on the value of unit pressure.

Influence of the manufacturing tolerance of textile compression products on the pressure value

In the traditional technique of constructing textile compression products based on sewing separate elements of garments made of piece good fabrics, manual execution of templates and patterns of elements of the product may be the cause for their dimensional inaccuracy. Therefore using this traditional method of producing textile compression products with a seam (especially for small values of body circumferences like a finger or a child's hand), it is difficult to maintain the intended value of unit pressure exerted on the user's body.

On the basis of ***Equation 14***, which is obtained after the conversion of ***Equation 13***, changes in the unit pressure under the adopted manufacturing tolerances of the compression device were determined $G_0 = \pm 0.1$ and ± 0.2 cm.

$$P = \frac{2 \cdot \pi \cdot c_1 (G_1 - G_0 + G_0)}{G_1 \cdot (G_0 + G_0 - l_s)} \quad (14)$$

Figures *7* and ***8*** show the changes in unit pressure under the influence of the

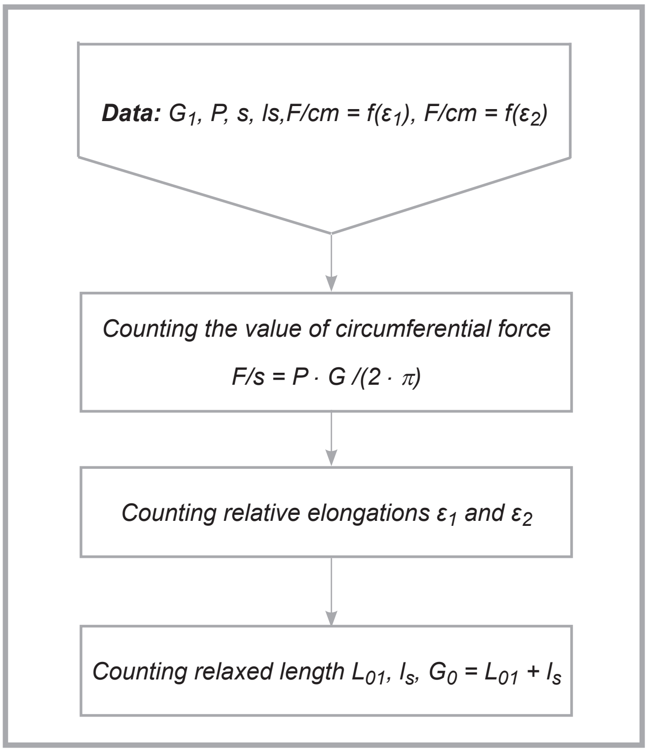

Figure 5. *General scheme for calculating the relaxed length of the fabric circumference.*

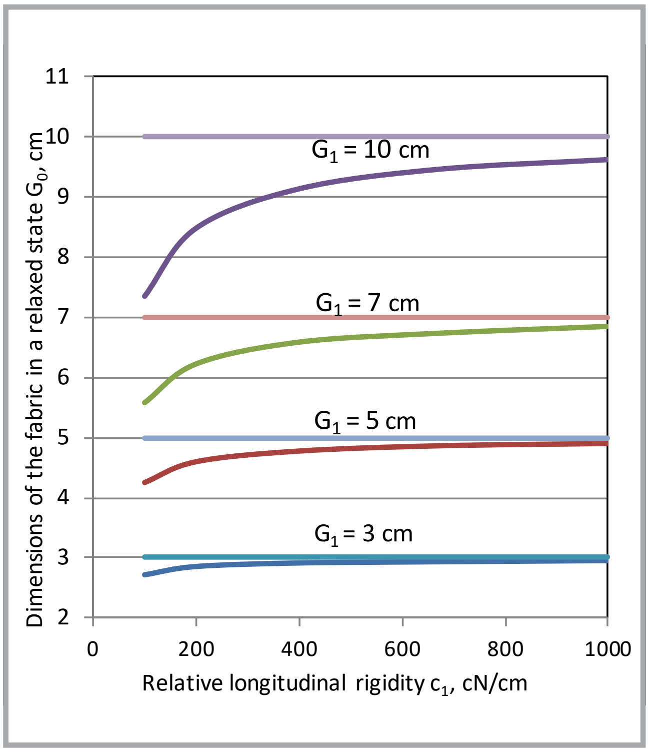

Figure 6. *Influence of the relative longitudinal rigidity of fabric dimensions in a relaxed state, where $G_0 = L_{01} + l_s$. Counting parameters: G_1= 3 - 10 cm, l_s = 0.4 cm, c_1 = 100 - 1000 cN/cm, P = 24 hPa.*

adopted values of manufacturing tolerance of circumferences of the products for the cases when $G_0 \mp 0.1$ cm and $G_0 \mp 0.2$ cm. Analysis of the figure shows that in the case of compression fabrics with higher relative longitudinal rigidity c_1 = 1000 cN/cm, a relatively small deviation of ∓ 0.1 causes significant variations in the unit pressure *P*. The smaller the value of circumference G_1 , the larger the variations. This is of particular importance in the case of products protecting the fingers in the treatment of post-burn scars. Some examples of changes in pressure for body circumference G_1= 7 cm (e.g. finger circumference) are illustrated in ***Figure 9*** (see page ...). For relative longitudinal rigidity c_1 = 670 cN/cm - (typical value for knitted fabrics used in the treatment of post-burn scars [14]) – manufacturing tolerance $G_0 \mp 0.1$ cm, causes a change in the value of unit pressure *P* in the range of 14.8 - 33.5 hPa ie. below and above the first pressure class. However, for a fabric with relative longitudinal rigidity c_1 = 200 cN/cm, a change in the value $G_0 \mp 0.1$ cm alters the unit pressure *P* in the range of 20.8 - 27.8 hPa, which is located in the first pressure class. Therefore fabrics used for producing compression garments for small values of body circumferences should be characterised by low longitudinal rigidity.

Referring the modelling results received to textile compression products manufactured by seamless techniques e.g. on numerically controlled flat knitting machines, the manufacturing tolerance of the product is indirectly connected with the needle pitch of the machine, and directly with the width of wale. In the process of narrowing and expanding the product, the change in the circumference of the fabric in a relaxed state depends on the number of needles forming the wales, and the minimum difference in the circumference of the fabric corresponds to the width of one wale.

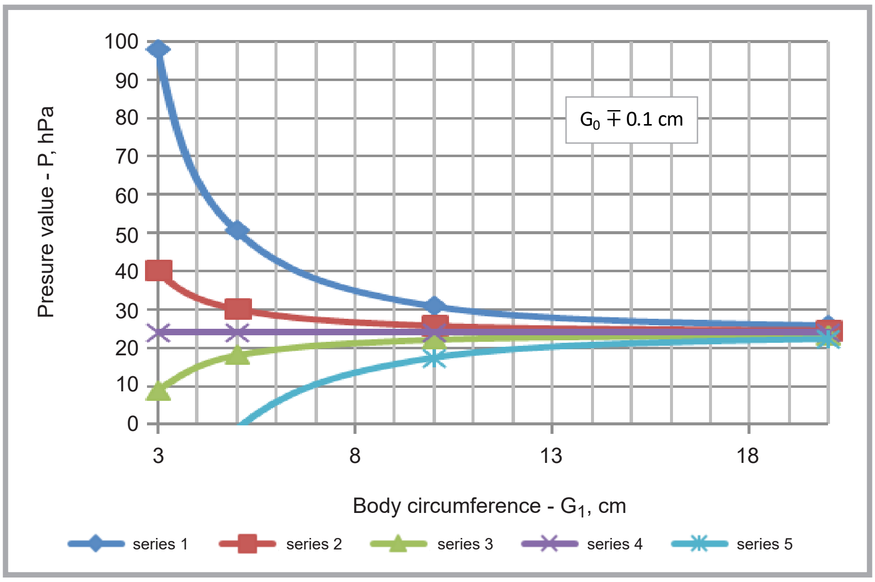

Figure 7. *Influence of the manufacturing tolerance of the product on the values of unit pressure as a function of circumference G_1 depending on the longitudinal rigidity. Series 1 - changes in unit pressure as a function of circumferences G_1 for (G_0 – 0.1 cm) c_1 = 1000 cN/cm, Series 2 - changes in unit pressure as a function of circumferences G_1 for (G_0 - 0.1 cm) c_1 =200 cN/cm, Series 3 - changes in unit pressure as a function of circumferences G_1 for (G_0 + 0.1 cm) c_1=200 cN/cm, Series 4 - intended value of unit pressure for nominal values of the circumference of knitted fabric in a relaxed state G_0 as a function of circumferences G_1, Series 5 - changes in unit pressure as a function of circumferences G_1 for (Go + 0.1 cm) c_1 = 1000 cN/cm.*

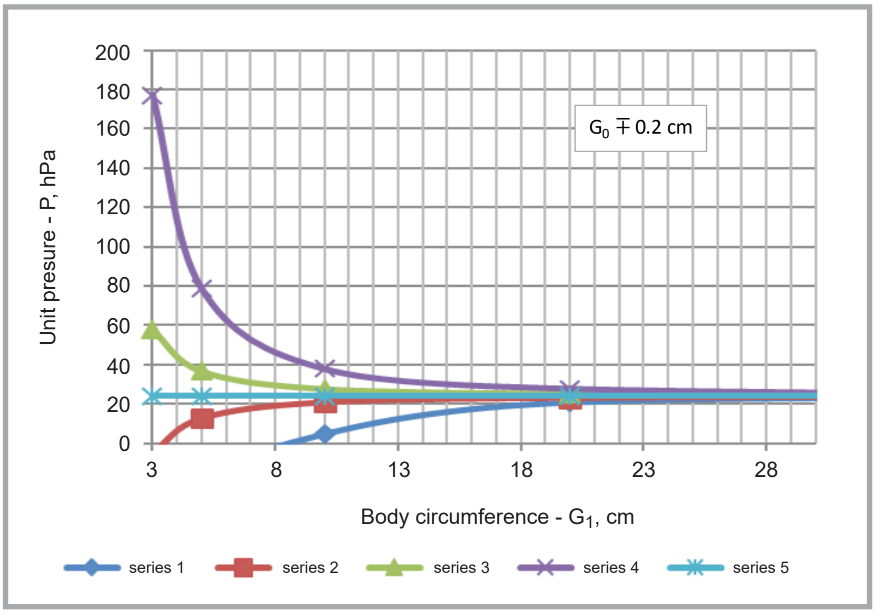

Figure 8. *Influence of the manufacturing tolerance of the product on the values of unit pressure as a function of circumferences G1 depending on relative longitudinal rigidity Series 1 - changes in unit pressure as a function of circumferences G_1 for (Go + 0.2 cm), c_1 = 1000 cN/cm, Series 2 - changes in unit pressure as a function of circumferences G_1 for (G_0 + 0.2 cm), c_1 =200 cN/cm, Series 3 - changes in unit pressure as a function of circumferences G_1 for (G_0 - 0.2 cm), c_1 = 200 cN/cm, Series 4 - changes in unit pressure as a function of circumferences G_1 for (G_0 - 0.2 cm), c_1 = 1000 cN/cm, Series 5 - intended value of unit pressure for the nominal value of the circumference of the knitted fabric in a relaxed state Go as a function of circumferences G_1.*

Summary and conclusions

In the paper, based on models developed for relatively small circumferences of body parts, analyses were carried out on the impact of the seam and intended manufacturing tolerances of the compression product on the value of unit pressure depending on the longitudinal rigidity of the compression fabric.

1. The study shows that for small circumferences of body parts, such as on fingers or upper limbs, the influence of the seam on the value of unit pressure is especially important. The smaller the body circumference, the greater the effect. Percentage differences in the expected values decrease from a value close to 30% for a circumference of 2 cm to about 2% for circumference G_1 = 30 cm (***Figure 4***). The percentage differences are practically independent of the intended value of unit pressure.

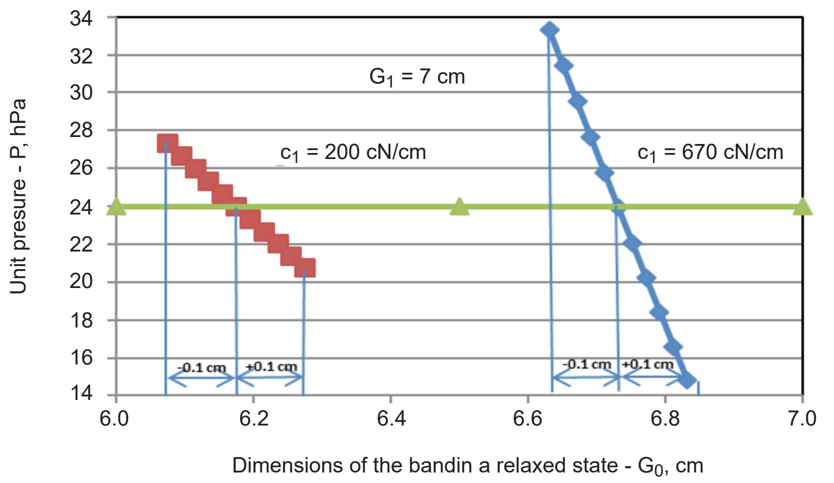

Figure 9. *Influence of the manufacturing tolerance of a knitted band on the value of unit pressure depending on the relative longitudinal rigidity of the fabric. Counting parameters: G_1 = 7 cm, P = 24 hPa, c_1 = 200 and 670 cN/cm , $G_0 \mp 0.1$ cm.*

2. The mathematical model allows the design of a compression product in which the presence of the seam does not cause additional changes in unit pressure in relation to its intended value.

3. To minimise the impact of the inevitable dimensional inaccuracies of the compression product occurring during the manual execution of templates and patterns of the product elements, knitted fabrics for producing compression clothing for small values of body part circumferences should be characterised by low longitudinal rigidity.

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References

1. Nyka W and Tomczak H. Rehabilitacja chorych z oparzeniami termicznymi, *Rehabilitacja Medyczna* 2003; 7, 4, wydawca: Elipsa-Jaim s.c.
2. Garrison S J. *Podstawy rehabilitacji i medycyny fizykalnej*. Warszawa Wydawnictwo Lekarskie PZWL 1997.
3. Adamczyk W and Magierski M. Leczenie blizn przerostowych metodą presyjną, *Roczniki Oparzeń* 1996-97.7/8.219-222.
4. Mikołajczyk A, Sośniak K, Fryc D and Miś K. Strategia postępowania w leczeniu blizn przerostowych u dzieci oparzonych. *Dermatologia Kliniczna i Zabiegowa* 1999, 1, supl. 2, 74-76.
5. Fritz K, Gahlen I and Itschert G. *Gesunde Venen – Gesunde Beine*. Rowohlt Taschenbuch Verlag GmbH 1996, Reinbek bei Hamburg
6. Normy: ISC 11.120.20 prEN 12718: 1997
7. CEN/TR 15831:2009 „Method for Testing Compression in Medical Hosiery”:
8. Mirjalili Seyed Abbas, Rafeeyan Mansour, Soltanzadeh Zeynab: The Analytical Study of garment Pressure on the Human Body Using Finite Elements. *Fibres and Textiles in Eastern Europe* 2008, No 3(68): 69-73.
9. Maklewska E, Nawrocki A, Ledwoń J, Kowalski K. Modelling and Designing of Knitted Products used in Compressive Therapy. *Fibres and Textiles in Eastern Europe* 2006: 14, 5: 111-113.
10. Nawrocki A, Kowalski K and Maklewska E. *Modelling and instrument evaluation of compression exerted by textile garments used in a treatment and rehabilitaion of post-burn scars.* Research Project 4T08 E 05425, Łódź, 2000.
11. Dan R, Dan M-H, Fan X-R, Chen D-S, Shi Z, Zhang M. Numerical Simulation of Dynamic Pressure and Displacement for the Top Part of Men's Socks Using the Finite Element Method. *Fibres and Textiles in Eastern Europe* 2013; 21, 4(100): 112-117.
12. Kowalski K, Mielicka E, Kowalski T M. Modeling and Design of Compression Products of the Intended Unit Pressure for the Circuits of the Body with a Variable Radius of Curvature. *Fibres and Textiles in Eastern Europe* 2012; 20, 6A(95): 98- 102.
13. Ilska A, Kowalski K, Kłonowska M, Kowalski TM. Influence of Stress and Relaxation Characteristics of Knitted Fabrics on the Unit Pressure of Compression Garments Supporting External Treatment. *Fibres and Textiles in Eastern Europe*, 2014, 22, 4(106).
14. Kowalski K, Ilska A, Kłonowska M. *Reasons for changes in the value of unit pressure of compression products supporting external treatment*. 48th IFKT Congress 8-10 /06/2016 - 48th International Federation of Knitting, Materials IOP Conference Series: Materials Science and Engineering.

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