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Modelling and Designing of Knitted Products Used in Compressive Therapy

Abstract
The paper presents a procedure for designing compressive garments (CG) with a pre-set value of unit pressure exerted on the human body, such as are used in the compressive therapy of hypertropic scars (HS). The garment dimensions were determined in a free state, in dependence on the values of the body parts' circumferences and the assumed value of unit pressure. The procedure is based on a developed dependency which considers the Laplace law, and on the garment's mechanical characteristics in the form of a non-linear function of force vs. elongation. The procedure for designing compressive garments as elaborated was verified with the use of a special measuring stand designed to estimate the compression exerted by stocking products.

Key words: *compressive garment, pressure measurement, Laplace law, stretching rigidity.*

Introduction

The use of garment products applied in compressive therapy consists in their exerting a pressure on the patient's body by the garment. In the case of compressive biotextiles, such as anti-varicose vein stockings and compressive products which heal hypertropic scars (HS), the value range of pressure exerted is precisely determined from the medical viewpoint, and should be maintained exactly. The compressive therapy using compressive garments (CG), applied after the wound healing process, is known to be the most effective treatment, especially in preventing and healing hypertropic scars (HS) [1]. CGs manufactured from elastic knitted or woven fabrics should be designed so that the pressure on the protected part of the body (with the scar) is within the range of 20 to 25 mm Hg (26.7 to 33.3 hPa), and should be worn by the patient for about 23 hours per day over a six-month period [2 - 6].

Designing and manufacturing underwear which supports the healing of HSs should be preceded by modelling based on the analysis of the compression phenomenon, and the mechanical properties of the textile material used should be considered. Currently, the technique of designing and manufacturing compressive garments is generally based on an identical percentage decrease of the basic constructional circumferences' dimensions in relation to the appropriate real value of the patient's body dimensions [7 - 10].

The aim of this work is to elaborate a procedure for designing compressive garment products which would guarantee the assumed recommended pressure on the patient's body.

Pressure modelling

The following assumption were accepted for our further considerations:

- the relationship between unit pressure, circumference force F in the textile band with given width W and the body circumference W is described by the Laplace formula;
- the relationship between the force F and the elongation ε of the knitted fabric will be assessed on the basis of experimental characteristics determined for the knitted fabric's cyclic stretching and relaxation under different ranges of stretching elongation (for the fifth hysteresis cycle);
- the circumferences of the body G_0 are accepted as circles;
- the longitudinal stretching of the knitted fabric band is not acknowledged in our considerations;
- the influence of the body's susceptibility to change its circumference dimension under the action of the knitted fabric's band pressure is excluded.

The basic equation which describes the relation between the pressure P exerted on a cylindrical model with the circumference G_1 of a part of the human body, and the circumference force F in a knitted fabric's strip with the width W, is determined by the Laplace formula [1] presented below:

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

where:
F – the force in the knitted fabric's strip with width W, in cN,
G_1 – the circumference of the body part (or cylinder), in cm,
W – the width of the knitted fabric strip, in cm, and
P – the pressure exerted by the knitted fabric.

In order to maintain the pressure P at the expected level, the circumference force in the knitting should be of an exactly specified value in dependence on the body's circumference value G_0. The value of force F in the knitted strip with width W depends on the stretching rigidity and the relative elongation ε. This is why the information regarding the knitted fabric's characteristic, i.e. the dependency of force vs. elongation, is essential for a wide range of relative elongations ε, as it is visible from Equation (1) that the proportionally higher values of the force F, and at the same time the greater values of relative elongation are related to the greater values of circumferences G_1.

Determining the mechanical characteristics of the knitting

A three-needle guide warp-knitted fabric was selected for the tests. The fabric was knitted from a 78 dtex textured polyamide filament yarn (consisting of a 76% share of the knitting), which formed a bonding stitch with the vertical polyurethane threads with a linear density of 480 dtex (share of 24%). The basic stitch of the fabric is presented in Figure 1.

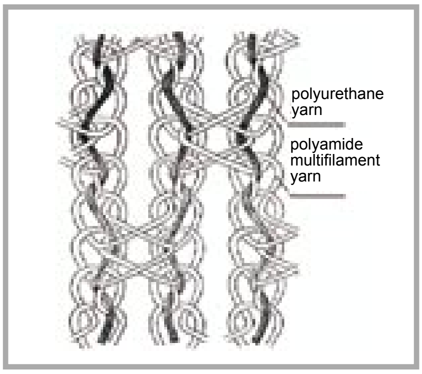

***Figure 1.** View of the stitches of the high elastic knitted fabric with a content of elastomer threads.*

The knitted fabric is characterised by the following parameters: course stitch density P_c = 120, wale stitch density P_w = 140, and area mass M = 233 g/m^2.

The textile materials are visco-elastic materials. In this case, the value of force as a function of elongation is dependent on time. This was why our investigation of the knitted fabric mechanical properties was carried out after mechanical conditioning (in the form of five cycles of stretching and relaxation in some courses), at a low deformation velocity of 5 mm/min. The samples, with a width of 10 cm and a circumference length of 31 cm, were tested with use of an Instron tensile tester. A wide range of relative elongations from 5% to 120% was used in individual stretching cycles up to 5, 10, 20, 30, 50, 80, 100, and 120% of relative elongation. Then, in order to determine the knitted fabric characteristic, the values of force and the values of relative elongation related to them were measured during the relaxation period of the fifth cycle hysteresis loop. Accepting the force values for the relaxation period brings the measurement conditions closer to those under which the compressive garments are used, considering the force relaxation in long-term use. It should also be stated that for the data used to determine the generalised characteristics of the knitted fabric, we accepted such force values of the relaxation period which were placed between the maximum force values resulting from stretching during the subsequent test cycles.

The force in the knitted strip, re-calculated on the width of 1 cm as a function of the relative elongation, is presented in Figure 2.

Equation (2) presents the experimental dependency determined between the force in the knitting strip with 1 cm width and the relative elongation ε, during the relaxation phase after the fifth stretching cycle, for the warp knitted fabric with a content of elastane threads, which is used in hypertropic scar therapy, and was accepted by us for the tests.

$$F = 241.77 \cdot \varepsilon^{0.7739} \qquad (2)$$

This exponential dependency is characterised by a correlation coefficient R = 0.98, which is slightly higher than the correlation coefficient of the linear course, and so was accepted for further considerations.

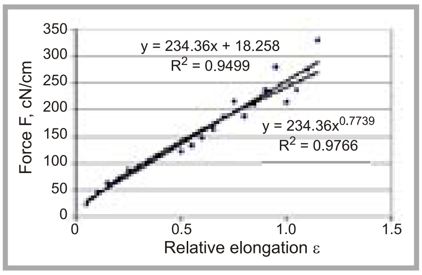

Figure 2. *Generalised mechanical characteristics of a knitted fabric determined for the relaxation period during the fifth cycle of the hysteresis loop; in the figure the experimental points and two courses of the dependency, a) approximated to a linear equation, and b) approximated to a exponential relation, are marked.*

Model for determining the dimensions of the pressure garment for a pre-set pressure value

The general form of Equation (2) is shown below:

$$F = a \cdot \varepsilon^{b} \qquad (3)$$

The relative elongation ε is described by:

$$\varepsilon = (G1 - G_0)/G_0 \qquad (4)$$

where:
G_0 is the circumference of the knitting fabric band in free state, in cm.

After substituting Equations (3) and (4) for Equation (1), at W = 1 cm, and after its transformation, we obtain a dependency characterising the knitted fabric which describes the knitted fabric band circumference in free state G_0 as a function of the required pressure P and the circumference G_1 of the appropriate part of the body:

$$G_0 = \frac{(2 \cdot \pi \cdot a)^{\frac{1}{b}}}{(P \cdot G_1)^{\frac{1}{b}} + (2\pi \cdot a)^{\frac{1}{b}}} \cdot G_1 \qquad (5)$$

where a and b are coefficients of Equation (3).

As mentioned earlier, compressive garments used in hypertropic scars therapy should be so designed so that the interface pressure on the covered part of the body are within the range of 20 to 25 mm Hg (26.7 – 33.3 hPa) [6, 7]. For the above-mentioned range of unit pressure, the relations between the circumferences G_0 and G_1, as well as the relative elongations ε as functions of the circumference G_1 are presented in Figure 3.

It should be emphasised that the knitted fabric for the pressure of 34.7 hPa, and for body circumstances of G_1 = 52 cm, required a relative elongation close to 120%, whereas for the pressure of 28.6 hPa a similar relative elongation is obtained for a circumference of G_1 = 66 cm, The modelling carried out indicates the differentiated relative elongations in dependence on the circumferences of the body part.

Examples of designing compressive garment products

The design of a compressive garment product is presented by an example of a stocking section in the form of a compressive band with circumferences G_1 altered according with the standardised dimensions of a model leg in accordance with Standard EN 12718-1997 'Healing compressive stockings'. The dimensions of the model leg are presented in Figure 4.

Calculations of the knitted fabric circumferences in free state G_0, were made for the circumferences R, E, D, C, and B1 of the model leg, marked in Figure 4, all for the pressure of P = 26.6 hPa according to dependency (5); these circumferences were additionally enlarged on a reserve for seams.

According to information from literature, as well as from contacts with producers of compressive garments, the preparation of ready-made compressive products is based on a constant 10-percentage decrease in the dimensions of knitted fabric elements in relation to the circumferences

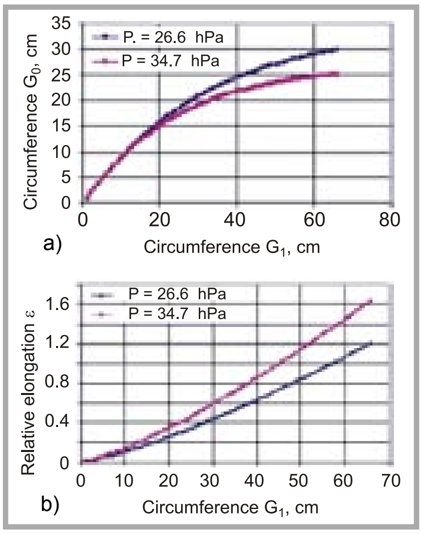

Figure 3. *a) Relation between the circumference G_1 and the knitted fabric bands circumference in free state G_0 for pressure P = 26.6 hPa and P = 34.7 hPa; b) relation between the circumference G_1 and the required relative elongation ε of the knitted fabric, for pressure P = 26.6 hPa and P = 34.7 hPa.*

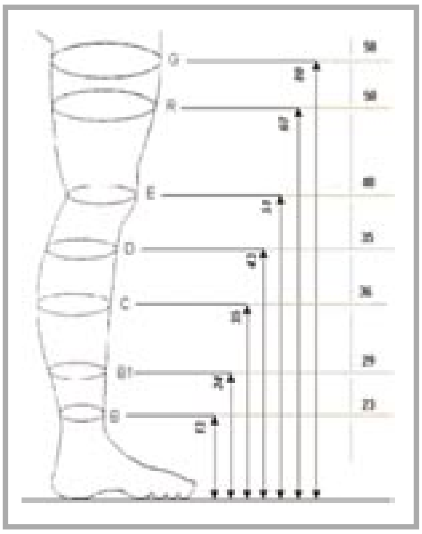

Figure 4. Dimensions of a model leg in accordance with Standard EN 12718-1997 for a long stocking of [nominal dimension 23]; in the figure the lengths and circumferences of the model leg are marked.

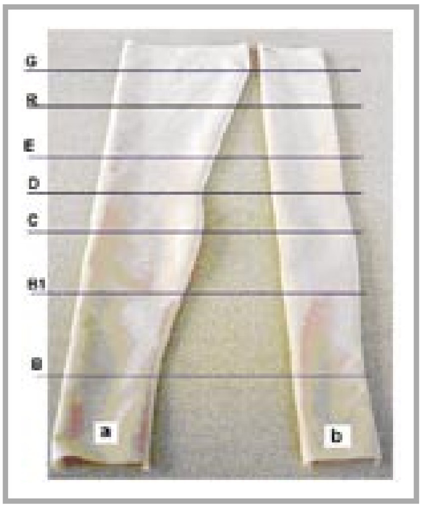

Figure 5. Stockings manufactured for our tests: a) stocking with dimensions decreased by 10% in relation to the dimensions standardised, b) stocking with dimensions calculated according to relation (5) for the pressure of P =26.6 hPa.

Figure 6. Tests of a compressive garment band carried out with the use of the Presstest device.

of the body. Therefore for the purpose of our pressure test, the products were prepared with circumferences decreased by 10% in relation to the dimensions of G_1, with the aim of comparing both manufacturing technologies. The products prepared for tests are presented in Figure 5. The pressure tests were carried out with the use of a measuring stand in the form of a flat model of the leg (Figure 6); the stand was linked to a computer [10]. The measurements were performed by stretching the product from the inner side, without any clamps or grips, i.e. in a non-destructive way. During the five stretching and relaxation runs of the product, the circumference forces at the standardised points were measured by 10 tensometric gauges placed on the upper measuring board. Next, the values of pressure from the relaxation curves for the fifth hysteresis loop were automatically determined as a function of the circumferences G_1.

The pressure values P in hPa assessed for the above-mentioned stocking products are presented in Figure 7. As expected, the values of pressure along the product, whose dimensions at lengths related to the standardised circumferences have been decreased by 10% (variant a), fell continuously, and were included within the range of 10.0 hPa to 6.2 hPa.

In contrast, for the product prepared according to variant b, whose dimensions were calculated according to the dependency (5), we obtained values of the unit pressure which were close to the pre-set values. Some differences between the calculated values and the values determined according to the measuring procedure for both product variants, which were practically irrelevant, resulted from the influence of circumference forces acting at different values of the knit's circumference G_0 along the 5-cm segments of the tensometric gauges placed on the measuring board. The calculation model assumes the constant values of the circumferences at the standardised lengths of the product.

Conclusions

On the basis of the research results, the following conclusions can be drawn:

- Designing compressive products with pre-set unit pressure exerted on the user's body, should be preceded by investigations into the mechanical characteristic of the knitted fabric, i.e. the dependency of force vs. relative elongation for a wide range of elongations, as the Laplace formula shows that the value of unit pressure depends in direct proportion on the quotient of circumference force and the circumference of the knitted fabric which encircles the body.

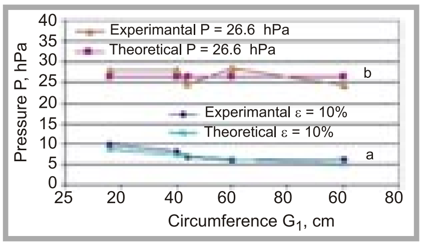

Figure 7. The calculated and analytical/experimental values of the unit pressure for different product variants.

- The knitted fabrics designed for making up underwear supporting the external healing of hypertropic scars should be characterised by sufficient ranges of relative elongations and forces which will guarantee obtaining the pre-set recommended values of unit pressures within the range of P = 26.6 – 34.7 hPa for the largest circumferences of human body parts.
- Making up compressive garments devoted to the therapy of hypertropic scars on the basis of a constant percentage value of decreasing the dimensions of knitted fabric elements, independently of the circumferences' values of the patients body, would not guarantee that the assumed, constant unit pressure value would be obtained.

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