Krzysztof Kowalski[1],
Elżbieta Mielicka[2],
Tomasz Marek Kowalski[3]

Modelling and Designing Compression Garments with Unit Pressure Assumed for Body Circumferences of a Variable Curvature Radius

[1]Department of Knitting Technology,
Lodz University of Technology,
ul. Żeromskiego 116, 90-924 Łódź, Poland
E-mail: krzysztof.kowalski@p.lodz.pl

[2]Scientific Department of Knitting and Clothing Technologies,
Textile Research Institute,
ul. Brzezińska 3/15 90-000 Łódź, Poland

[3]Department of Computer Engineering, ,
Lodz University of Technology,
ul. Żeromskiego 116, 90-924 Łódź, Poland

Abstract

The paper presents a basis for modelling compression garments with the intended value of unit pressure for the body circumference of a variable curvature radius. The Laplace law, mechanical characteristic of a knitted fabric and the local curvature radius were taken into consideration in deriving dependencies on the dimensions of circumferences of knitted fabrics in a free state. The possibilities of applying 3D human body scanning techniques to determine the curvature radius of the circumference, for which the intended value of unit pressure is designed were indicated. The consequences of using Laplace law for non-circular circumferences were pointed out. The basis of modelling presented can be applied in designing compression garments supporting external treatment such as after-burn therapy and lymphadema.

Key words: *medtextiles, unit pressure, Laplace law, mechanical parameters, knitted fabrics, 3D scanning technique.*

Symbols

- F - *circumferential force along knitted bend*
- P - *unit pressure*
- G_1 - *circumference of human body and circumference of knitted fabric in stressed state*
- G_0 - *circumference of knitted fabric in free state*
- s - *width of knitted band*
- a, b - *regression coefficient*
- ε - *relative elongation of knitted fabric*
- R - *radius of curvature of human body circumference in the form of a circle*
- R_n - *subsequent radii of curvature for an ellipse*
- P_{int} - *intended value of unit pressure*
- P_n - *value of unit pressure along the circumference in the form of an ellipse*

An important parameter of compression garments supporting the process of external therapy is a unit pressure exerted on the covered body parts. The range of values of this parameter is determined from the medical point of view depending on the type of therapy. The range should be complied in practice [1 - 6]. The most unambiguous values of the range of unit pressure are specified for therapies for varicose veins. Depending on the severity of the disease, the values are classified in four stages of pressure [6]. The human body is a figure, which in many parts has a cross section similar to a circle or an ellipse. Works concerning the modelling of a unit pressure [6 - 9] are based on the model of the human body, in which its circumferences are treated as circles (***Figure 1***). [7] presents the results of modelling the unit pressure with the use of the finite element method for the case of a cylinder and cone. While in [9], next to the analytical model using the Laplace law, the finite element method was also used for compression bands covering a cylindrical model of the body part.

Another field of research related to the application of compression garments is the experimental evaluation of unit pressure. Experimental methods usually use the Laplace law in measurement procedures developed [9 - 12].

In this study the purpose of modelling is to determine the dependencies of the dimensions of knitted fabric in a free state as a function of mechanical parameters thereof , as well as the unit pressure P required and the value of circumference G1 of the body covered and its geometrical parameters. The derived dependencies of the dimensions of knitted compression garments in a free state are the basis for designing knitted compression garments of intended pressure for the following cases:

- For body parts of circumferences in the form of a circle
- For body parts of circumferences of different curvature radius.

Assumptions

1. Modelling the pressure is performed on the basis of the Laplace law.
2. Forces F in the knitted fabric along the circumference of the human body are constant, as they are equalised during use.
3. It is necessary to know the mechanical characteristics of the knitted fabric, that is the relation of the force in the band and relative elongation determined for the values of these parameters in the relaxation phase in the 5th cycle of hysteresis of stretching and decompressing.
4. For circumferences of the human body with different curvature radii, the unit pressure can be determined with the intended value only for a selected part of the circumference, which can be expressed by a part of the circle – the known value of the curvature radius for this part of the human body is required.

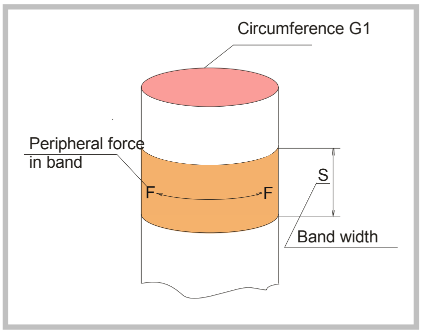


Figure 1. *Cylindrical model of the body part covered with a compression band.*

5. The susceptibility of the body to the action of unit pressure is omitted.

The final effect of modelling is to determine the dimensions of knitted fabric in a free state, which is the basis for designing knitted compression garments of intended unit pressure.

An analytical model for determining the dimensions of circumferences of compression garments in a free state for circle-shaped cross sections of the body is presented in ***Figure 1***. A detailed analysis of this model and its empirical verification are presented in [8].

The basic equation describing the relationship between the unit pressure on a cylindrical model of circumference G_1 and circumferential force F in a band of width s is given by the Laplace law.

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

where:
F in cN – circumferential force in the knitted band of width s,
G_1 in cm - circumference of the body part,
S in cm - width of the knitted band,
P in hPa – unit pressure.

Studies on the mechanical properties of typical knitted fabrics designed for compression garments indicated that a general relation between the force and relative elongation ε in the decompression phase after the 5th stretching cycle is the following:

$$F = a \cdot \varepsilon^b \qquad (2)$$

Where a and b are the regression coefficients relative elongation is:

$$\varepsilon = \frac{G_1 - G_0}{G_0} \qquad (3)$$

where:
G_0 - circumference of a knitted fabric in a free state in cm,

After the substitution of ***Equations 2*** and ***3*** into ***Equation 1***, and after transformation we obtain a dependence for the circumference of knitted fabric G_0 in a free state as a function of pressure P and circumference G_1 required for a certain characteristic of knitted fabric.

$$G_0 = \frac{(2\cdot\pi\cdot a)^{\frac{1}{b}}}{(P\cdot G_1\cdot s)^{\frac{1}{b}} + (2\pi\cdot a)^{\frac{1}{b}}}\cdot G_1 \qquad (4)$$

Designing the dimensions of compression garments in a free state for circumferences of diverse curvature radii

An analysis of unit pressure for a circumference in the form of a mathematical ellipse and an exemplary real circumference of the human body determined using the 3D human body scanning technique is presented below.

Determination of the dimensions of the products' circumferences in a free state and values of unit pressure is performed using an exemplary ellipse of the following geometrical parameters: circumference G_1 = 104 cm, semi-axis a = 20 cm, b = 13 cm (***Figure 2***).

The curvature radius can be determined for an ellipse described by the equation of the Lissajous curve. The value of the curvature radius calculated for the ellipse shown in ***Figure 2*** is within the range 8.6 ÷ 30.7 cm (***Figure 3***). According to the Laplace law (6), the unit pressure is inversely proportional to the curvature radius R. The value of unit pressure P_{int} for the selected area of the circumference of an ellipse with radius R is equal to:

$$P_{int} = \frac{F}{R\cdot s} \qquad (6)$$

After introducing a general form of equation for dependencies between the force and relative elongation of knitted fabric, we obtain:

$$P_{int} = \frac{a\cdot\varepsilon^b}{R\cdot s} \qquad (7)$$

Hence, the value of relative elongation equals:

$$\varepsilon = \sqrt[b]{\frac{P_{int}\cdot R\cdot s}{a}} \qquad (8)$$

To ensure the value of unit pressure required for the area of the circumference of an ellipse selected, the value of relative elongation ε of knitted fabric cover-

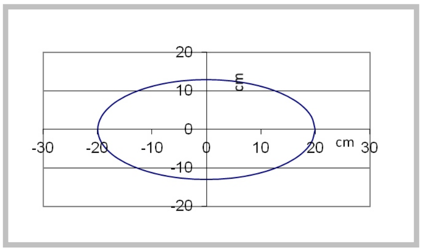


Figure 2. *Geometry of an ellipse: circumference G_1 = 104 cm, semi-axes a = 20 cm and b = 13 cm.*

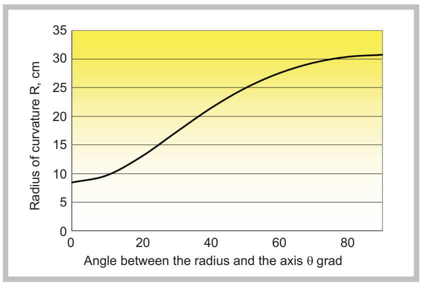


Figure 3. *Radii of curvature of the ellipse, depending on the angle between the vector radius and axis for an ellipse with circumference G_1 = 104 cm, semi-axes a = 20 cm and b = 13 cm.*

ing the circumference of the body with a length of G_1 should be equal to that calculated according to ***Equation 8***. After introducing the dependence of the value of relative elongation and after transforming ***Equation 9*** with regard to G_0 we obtain ***Equation 10*** of the value of dimensions of knitted fabrics in a free state G_0 for the circumference covered G_1.

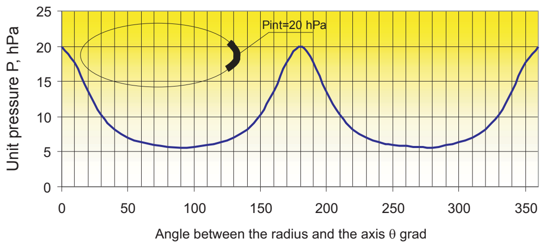
$$\frac{G_1}{G_0} - 1 = \sqrt[b]{\frac{P_{int}\cdot R\cdot s}{a}} \qquad (9)$$

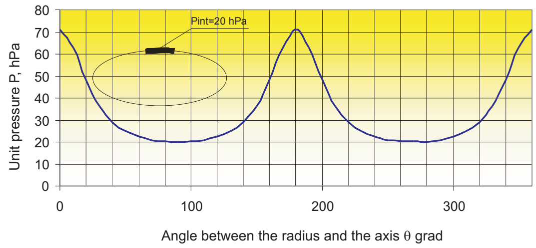
$$G_0 = \frac{G_1}{\sqrt[b]{\frac{P_{int}\cdot R\cdot s}{a}} + 1} \qquad (10)$$

Whereas the value of unit pressure P_n along the circumference of an ellipse at curvatures radii R_n is calculated according to the following equation:

$$P_n = P_{int}\cdot\frac{R}{R_n} \qquad (11)$$

An analysis of ***Figures 4*** and ***5*** shows that the value of unit pressure along the circumference of the ellipse varies in a wide range. Depending on the choice of place for which we design, for example for an intended value of pressure P = 20 hPa, it will be within the range P = 5 - 70 hPa. An excessive pressure of the product on the body occurs when its intended value applies to the part of the circumference of the maximum curvature





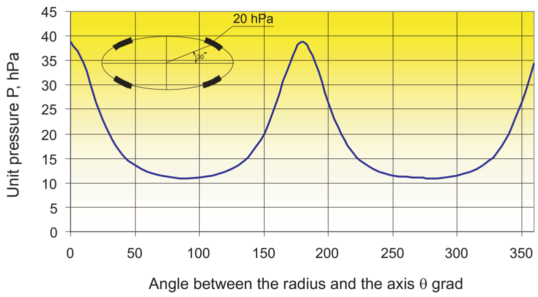


Figure 4. *Unit pressure along the circumference of the ellipse for the intended value P_{int} = 20 hPa in the area of the minimum value of curvature radius R = 8.65 cm. Parameters for calculations: a = 241.77, b = 0.7739, 8.65 < R_n < 30.71 cm.*

Figure 5. *Unit pressure along the circumference of the ellipse for the intended value P_{int} = 20 hPa in the area of the maximum value of curvature radius R=30.71 cm. Parameters for calculations: a = 241.77, b = 0.7739, 8.65 < R_n <30.71 cm*

Figure 6. *Unit pressure along the circumference, assuming that the circumference given in **Figure 2** is a circle. Parameters of calculations: G_1 =104 cm, R= 16.56 cm, P_{int} = 20 hPa.*

radius (***Figure 5***). Then in the part of a circumference with a minimum value of the curvature radius, excessive values of unit pressure, from a medical point of view, may occur (eg 70 hPa, ***Figure 5***).

In current practice, the designing of compression garments for after-burn therapy is conducted assuming that the circumferences of the human body are circular. The consequence of this assumption is the variable value of the pressure of the product along the circumference of the body part covered. The value of this pressure in the after-burn therapy treated area may not fulfil the condition of the minimum value of pressure. This is illustrated in ***Figure 6***, which shows the results of modelling the value of unit pressure assuming that the circumference presented in ***Figure 2*** is a circle. The calculations were performed assuming a value of pressure P = 20 hPa and radius R = 16.56 cm, which corresponds to the length of a circle of circumference G_1 = 104 cm. In this case, the unit pressure is within the range P = 11 - 39 hPa. For a large part of the circumference of the body, the condition of the minimum value of unit pressure (eg 20 hPa) for effective after-burn therapy is not fulfilled.

For circumferences of the human body different from the geometry of a circle or an ellipse, the results of the 3D scanning of the human body can be used. These results can be utilised to calculate the curvature radius in the circumference part, for which the value of intended unit pressure is designed. This case relates mainly to the torso of the human body, where there are circumferences of curvature substantially different from the circle (***Figures** 7* and ***8***).

In order to determine the radius of curvature, the coordinates of at least three

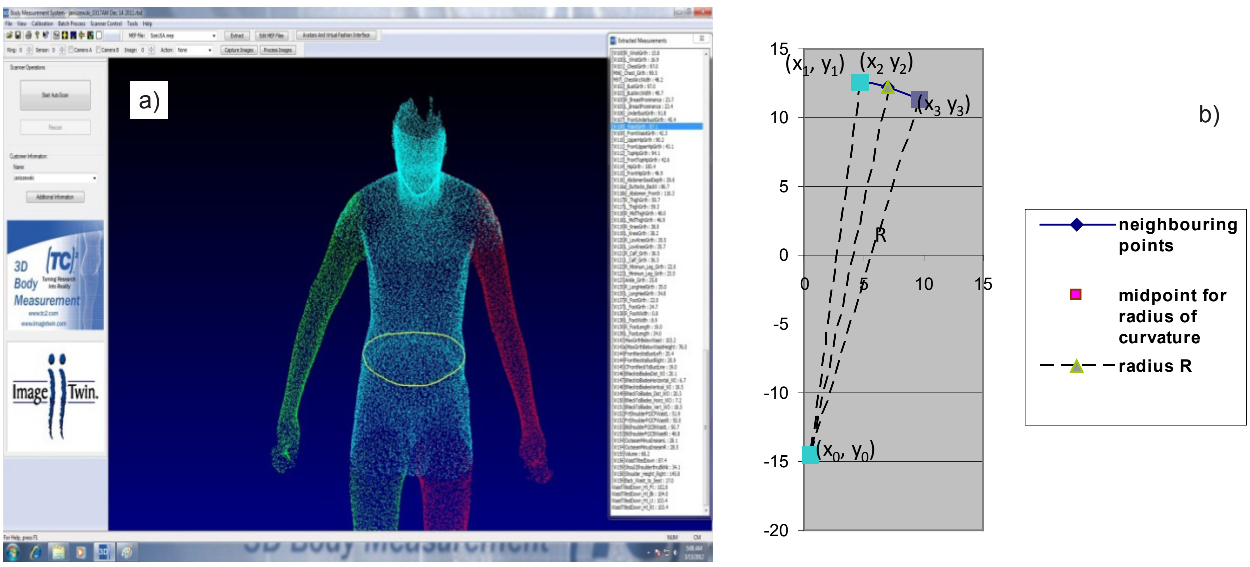


Figure 7. *a) 3D human body scanning technique, scaner TC² b) Coordinates of three points in the part of the curvature of the body circumference.*

points from the body part selected have to be known.

For three neighbouring points of circumference (x_1, y_1), (x_2, y_2), (x_3, y_3) we estimate the radius R of the curvature by determining the centre of a circle (x_0, y_0) containing these points. Using Pythagorean Theorem, we obtain the following set of equations:

where x_1, y_1, x_2, y_2, x_3, y_3 are variables and R, x_0, y_0 are unknown.

$$R^2 = (x_1 - x_0)^2 + (y_1 - y_0)^2 \quad (5.1)$$

$$R^2 = (x_2 - x_0)^2 + (y_2 - y_0)^2 \quad (5.2)$$

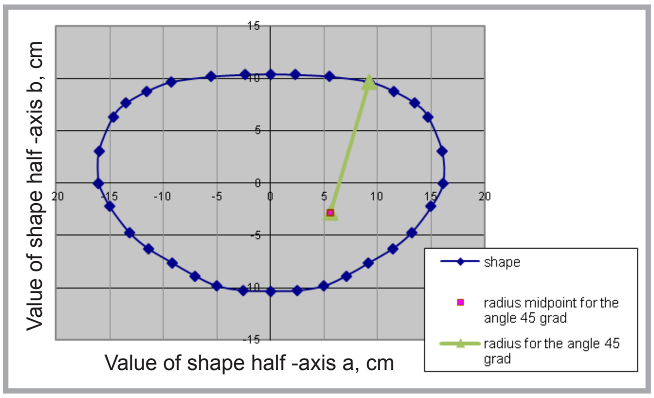
$$R^2 = (x_3 - x_0)^2 + (y_3 - y_0)^2 \quad (5.3)$$

The values of curvature radii determined for the circumference in ***Figure 8*** are presented in ***Figure 9.***

The following ***Figures 10 – 12***, present the distribution of unit pressure for the following three cases:

- for the measured value of unit pressure P_{int} = 20 hPa for the part of the circumference with the minimum value of the curvature radius;
- for the measured value of unit pressure P_{int} = 20 hPa for the part of circumference in the range of maximum values of the curvature radius;
- for the measured value of unit pressure P_{int} = 20 hPa with an assumption that the circumference analysed is a circle of radius R = 13.68 cm.

Figure 8. Geometry of the circumference determined with the use of 3D scanning technique with an exemplary radius midpoint for an angle of 45°.



The analysis of ***Figures 10*** and ***11*** shows that the value of unit pressure along the circuit analysed, presented in ***Figure 8***, changes within a wide range. Depending on the choice of a place for which we design, for example an intended value of pressure P = 20 hPa, it will be within the range P = 0.8 - 238 hPa. An excessive pressure of the product on the body occurs in the case where the intended value is related to the part of the circumference with maximum values of the curvature radius (***Figure 11***). Then in the part of the circumference with a minimum value of the curvature radius, excessive values of unit pressure from a medical point of view may appear (eg, 238 hPa, ***Figure 11***).

Figure 12 shows the results of modelling the value of unit pressure assuming that the circumference presented in ***Figure 8*** is a circle. The calculations were performed assuming a value of pressure

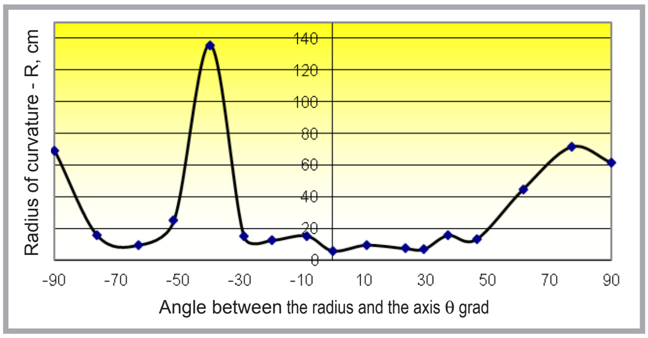


*Figure 9. Curvature radii of the circumference given in **Figure 8**, depending on the angle between the vector radius and axis for circumference G_1 = 86 cm.*

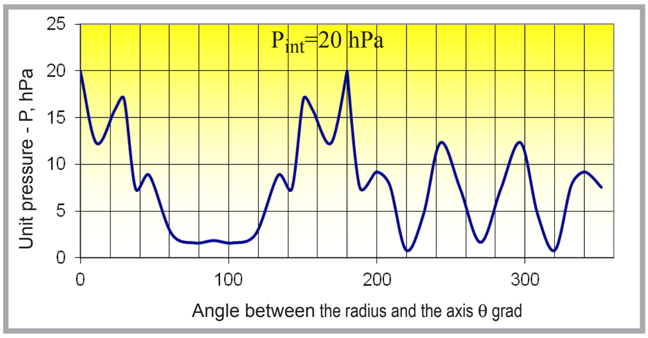


*Figure 10. Unit pressure along the circumference presented in **Figure 8** for the intended value of P_{int} = 20 hPa in the area of the minimum value of curvature radius R = 5.8 cm. Parameters for calculations: a = 241.77, b = 0.7739, 5.8 < R_n <136 cm.*

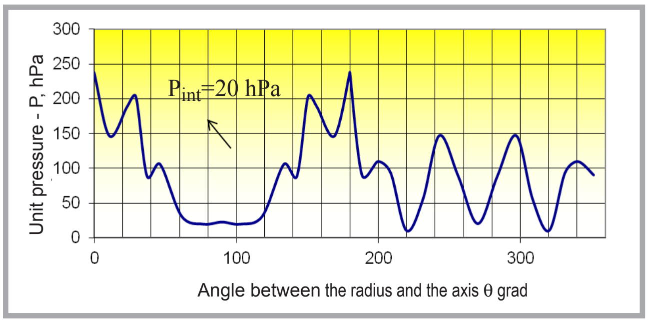


*Figure 11. Unit pressure along the circumference presented in **Figure 8** for the intended value P_{int} = 20 hPa in the area of the value of curvature radius R = 68.9 cm. Parameters for calculations: a = 241.77, b = 0.7739, 5.8 < R_n < 136 cm.*

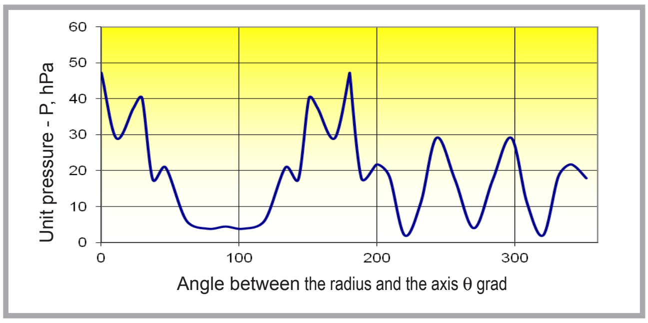


*Figure 12. Unit pressure along the circumference assuming that the circumference presented in **Figure 3** is a circle. Parameters for calculations: G_1 = 85.96 cm, R = 13.68 cm, P = 20 hPa, 5.8 <R_n < 136 cm.*

P = 20 hPa and radius R = 13.68 cm, which corresponds to the length of a circle with a circumference G_1 = 85.96 cm. In this case, the unit pressure is between P = 2 - 47.2 hPa. The condition of the minimum value of unit pressure (eg 20 hPa) necessary for effective after-burn therapy is not fulfilled for a part of the circumference of the body.

The designing of compression garments on the assumption that the body circumferences are circular can lead to failure in medical requirements relating to the values of unit pressure recommended. In particular, it refers to the circumference of the human body. In such cases very useful is the 3D scanning technique, which should be updated with software in order to determine the curvature radius for the circumferences of the body analyzed.

Conclusions

- Compression garments supporting the process of external treatment, for example in after-burn therapy and lymphedema do not provide a constant unit pressure along the circumference of individual body parts with different curvature radii.
- In order to meet the requirements related to providing a certain value of unit pressure in the place of hypertrophic scars (keloids) for parts of the body with different curvature radii of the circumference, it is necessary to consider the curvature radius in a place subjected to pressotherapy in the procedure of designing the product. Then the value of circumference of knitted fabric in a free state G_0 is defined by ***Equation 10***.
- Sample calculations of unit pressure made for the circumference of a body in the form of an ellipse with the following geometrical parameters: G_1 = 104 cm, semi-axes a = 20 cm and b = 13 cm for areas with a minimum and maximum curvature radius and intended value of unit pressure P = 20 hPa for these locations, were within the following ranges: from 5.0 to 20 and from 20 to 70 hPa. In contrast, assuming the mentioned ellipse as a circle of radius R arising from the circumference of an ellipse, and the intended value of unit pressure P = 20 hPa results in the following range of pressure 11 ÷ 39 hPa along its circumference.

Acknowledgment

This work was supported by structural funds obtained within the framework of the project entitled 'Development of the research infrastructure of innovative techniques and technologies of the textile clothing industry' CLO – 2IN – TEX, financed by Operational Programme Innovative Economy, 2007-2013, Action 2.1.

References

1. Nyka W, Tomczak H. Rehabilitacja chorych z oparzeniami termicznymi. *Rehabilitacja Medyczna* 2003; 7; 4.
2. Garrison SJ. *Podstawy rehabilitacji i medycyny fizykalnej*. Warszawa Wyd. Lek. PZWL, 1997.
3. Adamczyk W, Magierski M. Healing hypertrophic scars by the pressing method (in Polish). *Roczniki Oparzeń* 1996-97; 7/8: 219-222.
4. Mikołajczyk A, Sośniak K, Fryc D, Miś K. Strategia postępowania w leczeniu blizn przerostowych u dzieci oparzonych. *Dermatologia Kliniczna i Zabiegowa* 1999; 1, 2: 74-76.
5. Fritz K , Gahlen I, Itschert G. *Gesunde Venen – Gesunde Beine*. Rowohlt Taschenbuch Verlag GmbH 1996, Reinbek bei Hamburg.
6. Standards: ISC 11.120.20 prEN 12718: 1997.
7. Mirjalili Seyed Abbas, Rafeeyan Mansour, Soltanzadeh Zeynab. The Analytical Study of garment Pressure on the Human Body Using Finite Elements. *Fibres & Textiles in Eastern Europe* 2008; 16, 3(68): 69-73.
8. Maklewska E, Nawrocki A, Ledwoń J, Kowalski K. Modelling and Designing of Knitted Products used in Compressive Therapy. *Fibres & Textiles in Eastern Europe* 2006; 14, 5: 111-113.
9. Nawrocki A, Kowalski K, Maklewska E. *Modelowanie i ocena instrumentalna ucisku wywieranego przez wyroby tekstylne stosowane w leczeniu i rehabilitacji blizn pooparzeniowych*. Research Project 4T08 E 05425, Łódź, 2006.
10. Maklewska E, Nawrocki A, Kowalski K, Andrzejewska E, Kuzański W. New measuring device for estimating the pressure under compression garments. *International Journal of Clothing Science and Technology* 2007; 19, 3/4: 215-221.
11. Liu R, Kwok Y-L, Li Y, Lao T-T. Fabric Mechanical-Surface Properties of Compression Hosiery and their Effects on Skin Pressure Magnitudes when Worn. *FIBRES & TEXTILES in Eastern Europe* 2010; 18, 2(79): 91-97.
12. Senthilkumar M, Kumar LA, Anbuman N. Design and Development of a Pressure Sensing Device for Analysing the Pressure Comfort of Elastic Garments. *FIBRES & TEXTILES in Eastern Europe* 2012; 20, 1(90): 64-69.

Received 28.12.2011 Reviewed 12.04.2012