

Krzysztof Kowalski^{1,*},
Krzysztof Karbowski²,
Magdalena Klonowska¹,
Anita Ilska¹,
Witold Sujka³,
Magdalena Tyczyńska³,
Błażej Włodarczyk³,
Tomasz Marek Kowalski⁴

¹Lodz University of Technology,
Department of Knitting Technology,
Łódź, Poland
* E-mail: krzysztof.kowalski@p.lodz.pl

²Cracow University of Technology,
Mechanical Department,
Kraków, Poland

³Tricomed S.A.,
Łódź, Poland

⁴Lodz University of Technology,
Computer Engineering Department,
Łódź, Poland

Influence of a Compression Garment on Average and Local Changes in Unit Pressure

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Abstract

On the basis of models developed and experimental studies, the impact of a compression garment on average and local changes in unit pressure was analysed. The study was based on the analysis of the results of 3D scans of selected parts of female and male bodies. It was found out that surface pressure exerted by the compression garment leads to some changes in the geometry of body circumferences and in their lengths and, consequently, to a change in the average pressure value, as well as local changes along the circumference. The main purpose of this work was to estimate the size of these changes in the example of selected parts of female and male bodies.

Key words: *compression products, Laplace's law, unit pressure, 3D scanner, body's susceptibility.*

ucts designed for an individual patient's body dimensions are more useful in terms of their effectiveness, as they provide intended and programmable unit pressure values, consistent with medical requirements, providing they are designed according to Laplace's law [1-4]. However, it should be noted that according to this law, cylindrical models of human body parts are used for design purposes. The consequence of this assumption is variable pressure exerted by the product along the circumference of the protected body part, whose geometry deviates from that of a circle [4, 5]. Currently, in many cases, the technique of constructing compression products is based on identical percentage reduction of the basic structural dimensions, regardless of the patient's real body circumference [6-10]. In the case of compression garments supporting the process of external treatment, relatively high accuracy is required in determining G1 circumference values. Therefore more and more often 3D scanners are used to measure the human body, which eliminates some of the causes of scatter of the results, which are due to the manual methods of taking the measurements [11-17]. In order to increase the accuracy and repeatability of results of determining body circumferences with 3D scanning, it is necessary to stabilise and position the human body and its moving parts by introducing appropriate support points.

At present, in the design of compression products, calculating the product dimensions in a relaxed state is based on the circumference value, without taking into account the body's susceptibility to unit

pressure. Surface pressure exerted by the compression garment leads to some changes in the geometry of body circumferences and in their lengths, and consequently changes the average pressure and its local values along the circumference. The main purpose of this work was to estimate the size of these changes in the example of selected parts of female and male bodies.

Methodology and research program

The assessment of unit pressure changes was performed on the basis of model and experimental studies using an algorithm developed for calculating unit pressure and experimentally determined circumferences with and without a compression garment, with an intended unit pressure of $P_{int} = 24$ hPa.

The products were made of a warp-knitted three-guide-bar fabric consisting of a combining stitch made of textured polyamide silk with a linear mass density of 78 dtex (76%) and vertical wefts made of polyurethane yarns with a linear mass density of 480 dtex (24%). Parameters characterising the knitted fabric are as follows: course density $P_r = 720$ courses/100 mm, wale density $P_k = 154$ wales/100 mm and surface mass $G = 244$ g/m² [18]. The relationship between the force and relative elongation for the tension phase in the 5th hysteresis loop with respect to a fabric strip of width $s = 1$ cm is described by the following function: $F = 678.84 \cdot \epsilon^3 - 964.96 \cdot \epsilon^2 + 830.89 \cdot \epsilon$, $R^2 = 0.994$. Designating the function is discussed in publication [18].

Introduction

In therapies supporting external treatment, two types of products can be distinguished – ready-made products available in different sizes, unified on the basis of standardised anthropometric data concerning the human body, and custom-made personalised products. Prod-

Measurements of hand and leg circumferences were performed using 3D scanning for a female figure with a BMI (Body Mass Index) of 17.72 and a male one with a BMI of 29.37.

Two spatial scanners using structured light were used for the measurements. The first one was used to measure upper limbs. The scanner's measuring head rotates around the scanned object. Scanner configuration:

- Two monochrome 1.3 MPix cameras,
- DLP projector 1280 x 1024,
- FlexScan3D software ver. 3.1

The second scanner is designed for measuring lower limbs and trunk. The patient stands on a rotating platform stabilising the body. Scanner configuration:

- Two monochrome 2.8 MPix cameras,
- DLP projector 1280 x 1024,
- FlexScan3D software ver. 3.3

Scanning accuracy was assessed using VDI/VDE 2634, Part 2 'Optical 3D measuring systems – Optical systems based on area scanning'. For evaluating the scanning accuracy, a model was constructed made of two balls attached to a base. The diameter of the test ball was 44.629 ± 0.005 mm and the distance between the balls was 120.093 ± 0.005 mm. Scanning measurements were performed for 7 positions of the model in the test section, in accordance with the instructions given in the standard. The average display error equaled 0.062 mm, which in relative terms means that errors fall within the range $\pm 0.1\%$.

Digitisation of the patient's body was completed by combining 5 scans performed during the scanner's rotation (scanner in **Figure 1**) or patient's rotation (scanner in **Figure 2**). In order to measure the circumferences of the patient's body in selected cross-sections, the scanning results were processed in a specially developed computer program, implementing a 3D convex hull algorithm. For surrounding a selected cross-section with a width of 20 mm (10 mm above and below the cross section), a convex hull was generated which simulates measuring the patient using flexible 20 mm linear measuring tape. For the geometry thus formed, a cross section was made in the computer modeling system, and its length was measured to obtain the circumference of the body for the cross-section selected.



Figure 1. 3D scanner with instrumentation for measuring upper limbs.



Figure 2. 3D scanner with instrumentation for measuring lower limbs and trunk.

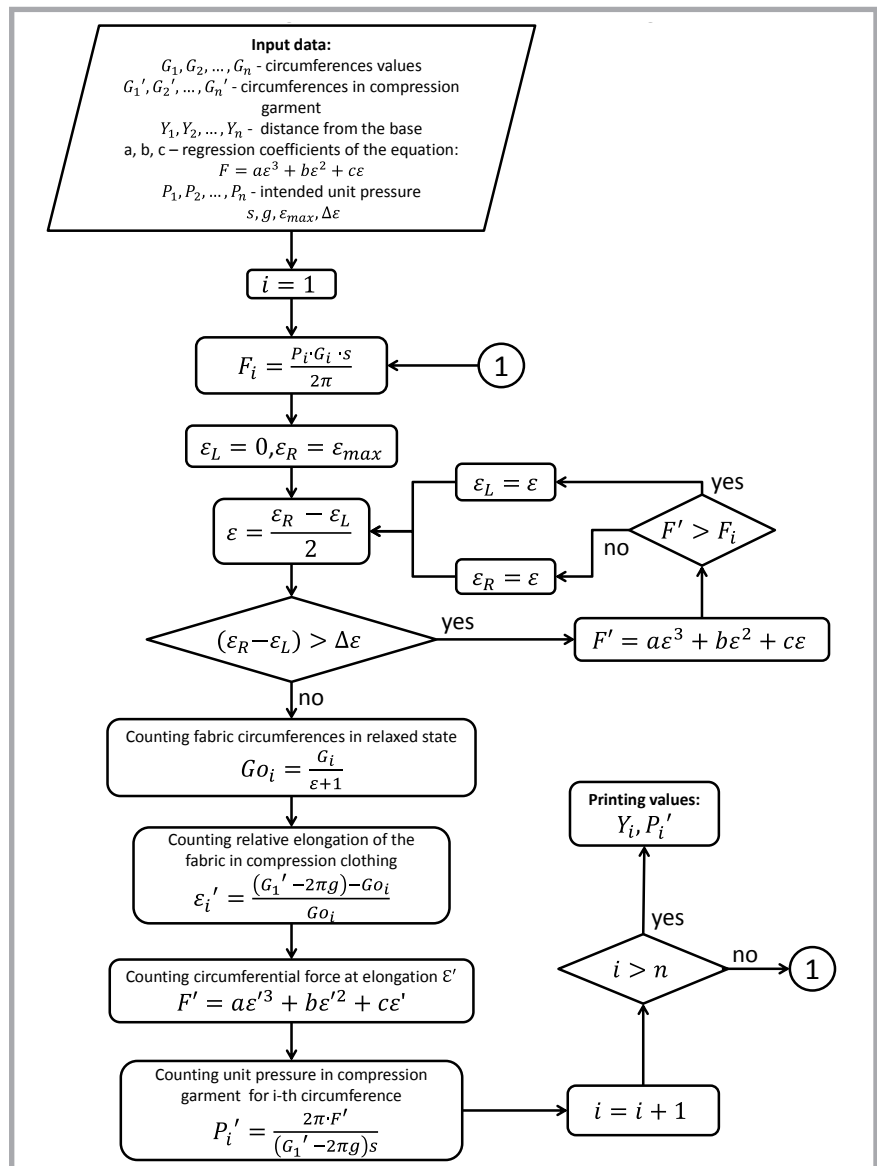


Figure 3. Calculation algorithm of the corrected value of unit pressure for the subsequent body circumferences.

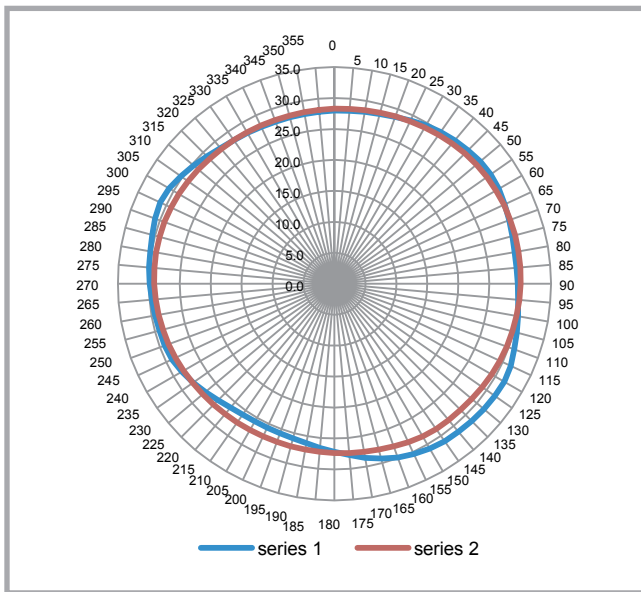


Figure 4. Example of the geometry of a female hand cross-section at a distance $Y = -130$ mm from the base (center of the elbow joint) in a polar coordinate system. Series 1 – circumference without compression clothing, series 2 – circumference with compression clothing.

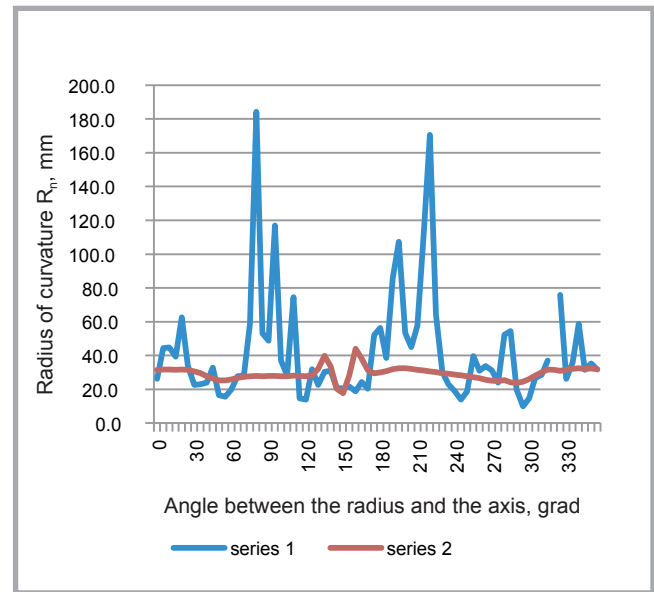


Figure 5. Example values of the radii of curvature of a female hand circumference at a distance $Y = -130$ mm from the base. Series 1 – radius of curvature of the circumference without compression clothing, series 2 – radius of curvature of the circumference with compression clothing.

For the purpose of experimental research, compression garments were made for a leg and hand of a man and woman.

Theoretical part

The purpose of the studies presented in the theoretical part is to develop a model for calculating the corrected value of unit pressure under the influence of changes in the body circumference in a compression product.

Assumptions:

The following assumptions were made for the purpose of these considerations:

- the relationship between unit pressure, circumferential force in a knitted fabric of width s and the body circumference is described by Laplace's relation,
- the relationship between the force and elongation of the knitted fabric is determined on the basis of experimental characteristics for the tension phase

of the fabric in the 5th hysteresis cycle and different stretching ranges,

- the body's susceptibility to unit pressure was determined by measuring the circumferences of body parts with and without a compression garment.

The value of relative elongation of the product along the circumferences of the body in the compression garment ϵ' can be determined on the basis of the body circumferences ($G'_1 - 2\pi g$) under the pressure exerted by the garment of coating thickness g and circumference of the product in a relaxed state G_0 .

$$\epsilon' = \frac{G'_1 - 2\pi g - G_0}{G_0} \quad (1)$$

Analysis of the mechanical characteristics of knitted fabrics used in compression products shows that the relationship between the force and relative elongation can be described with sufficient accuracy by the third degree polynomial:

$$F = a \cdot \epsilon'^3 + b \cdot \epsilon'^2 \quad (2)$$

After inserting the relative elongation ϵ' into the function describing the relationship of the force and relative elongation of the knitted fabric, the value of force F' can be determined in a fabric strip of width s along the body circumference analysed

$$F' = a \cdot \epsilon'^3 + b \cdot \epsilon'^2 + c \cdot \epsilon' \quad (3)$$

If the body circumference is reduced under the influence of the compression gar-

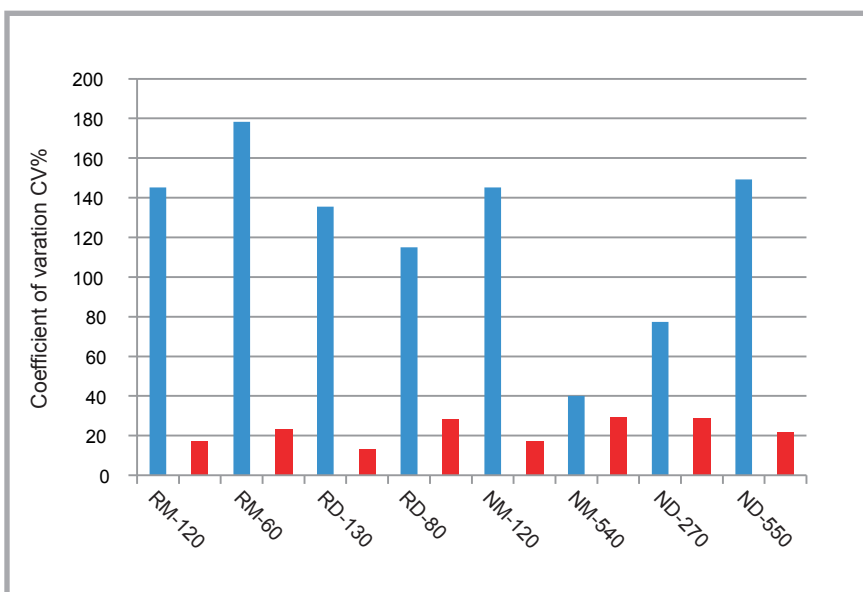


Figure 6. Values of coefficients of variation for radii of the curvature of female and male hands and leg circumferences with and without compression clothing. Symbols: RM & RD – male and female hand, respectively, NM & ND – male and female leg, respectively ■ – variant with clothing.

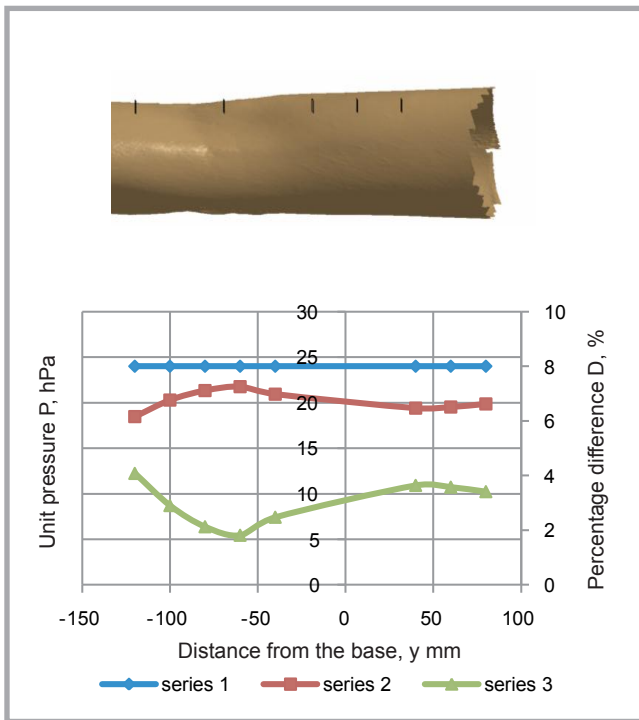


Figure 7. Examples of changes in the average values of unit pressure P (series 2) and percentage difference D (series 3) between the circumferences with and without compression clothing under the influence of the susceptibility of soft tissue of a male hand for subsequent circumferences and the intended value $P_{int} = 24$ hPa (series 1). Parameters calculated: circumferences without clothing: $G_1 = 28,7 \div 30,8$ cm, circumferences with clothing $G'_1 = 27,8 \div 30,0$ cm.

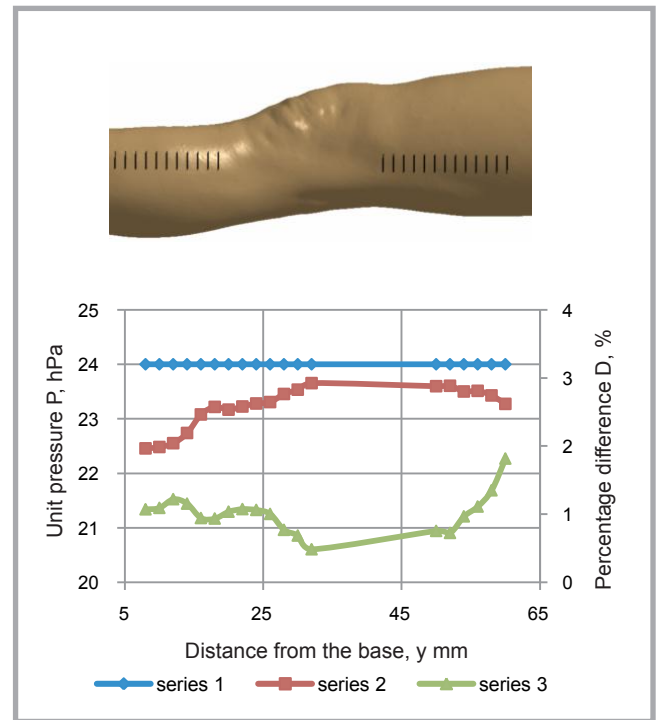


Figure 8. Examples of changes in the average values of unit pressure P (series 2) and percentage difference D (series 3) between the circumferences with and without compression clothing under the influence of the susceptibility of soft tissue of a male leg for subsequent circumferences and the intended value $P_{int} = 24$ hPa (series 1). Parameters calculated: circumferences without clothing: $G_1 = 26,3 \div 54,2$ cm, circumferences with clothing $G'_1 = 26,1 \div 53,5$ cm.

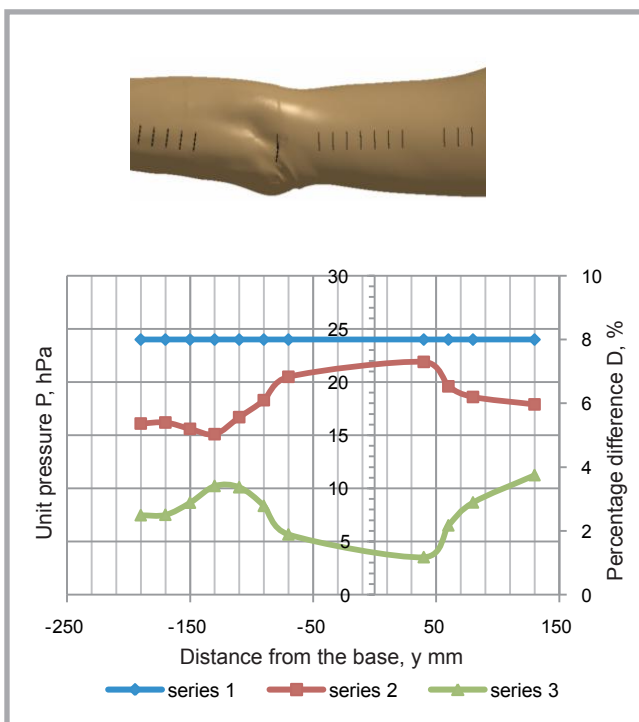


Figure 9. Examples of changes in the average values of unit pressure P (series 2) and percentage difference D (series 3) between the circumferences with and without compression clothing under the influence of the susceptibility of soft tissue of a female hand for subsequent circumferences and the intended value $P_{int} = 24$ hPa (series 1). Parameters calculated: circumferences without clothing: $G_1 = 15,3 \div 24,5$ cm, circumferences with clothing $G'_1 = 15,2 \div 23,8$ cm.

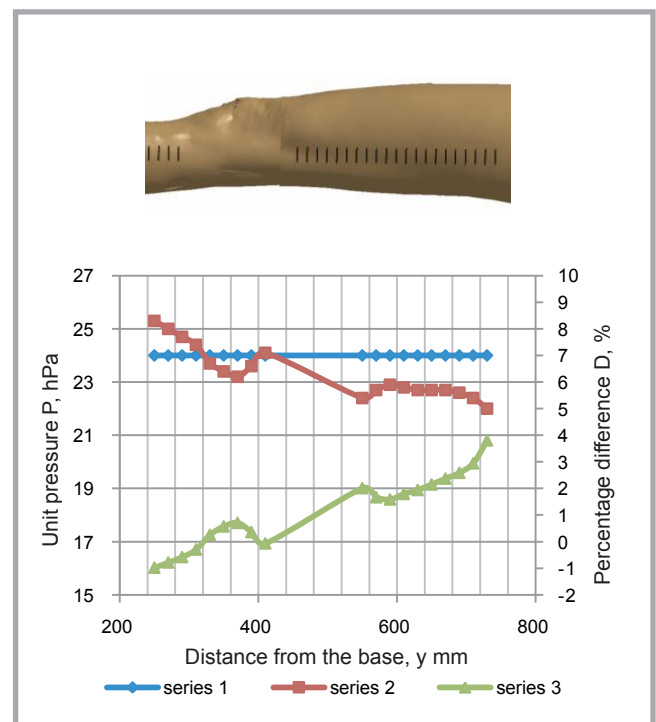


Figure 10. Examples of changes in the average values of unit pressure P (series 2) and percentage difference D (series 3) between the circumferences with and without compression clothing under the influence of the susceptibility of soft tissue of a female leg for subsequent circumferences and the intended value $P_{int} = 24$ hPa (series 1). Parameters calculated: circumferences without clothing: $G_1 = 26,7 \div 49,4$ cm, circumferences with clothing $G'_1 = 27,2 \div 47,8$ cm.

ment, the value of force F' will be smaller for the body circumference without the compression clothing than the value resulting from the calculations. This results in a decrease in unit pressure, compared with the intended value. The corrected value of unit pressure P' under the influence of changes in the value of the body circumference caused by the body's susceptibility to pressure can be calculated according to the relation:

$$P' = \frac{2 \cdot \pi \cdot F'}{(G_1' - 2\pi g) \cdot s} \quad (4)$$

The value of unit pressure P' obtained determines the average pressure value along the circumference. After determining local values of the radii of curvature of the circumference, it is possible to determine local pressure changes along the circumference.

A detailed scheme for calculating the corrected unit pressure value for the subsequent circumferences is shown in **Figure 3**. The input parameters for the calculation model are as follows: body circumference with and without the compression garment G_{1i} i G_{1i}' , distance between the circumferences and base Y_i , intended pressure values P_i , regression coefficients of the relationship between the force and relative elongation of the knitted fabric: a, b and c, thickness of the compression material g , accuracy factor of the elongation calculation $\Delta \varepsilon$ and maximum fabric elongation ε_{max} . Coefficients ε_L and ε_R stand for the range within which we search for the relative elongation value ε . At the beginning this range is $\langle 0, \varepsilon_{max} \rangle$ (ε_{max} can equal 1 or more) and should correspond to the relative elongation of the knitted fabric. In the subsequent steps of calculations by the bisection method, we narrow the range by changing ε_L or ε_R . As we search for ε with an accuracy to a specified delta, we divide this range until its size is smaller than the delta. Finally we choose the value of relative elongation ε in the middle of the range.

■ Analysis of research results

The radii of curvature for the selected cross-section were calculated after transforming the geometry of the circumference into a polar coordinate system with a resolution of 5° (**Figure 4**). The radius of curvature at the selected point was calculated from the equation of a circle passing through 3 points (a selected point and two adjacent ones).

Examples of changes in the radii of curvature for the selected circumference of a female hand are shown in **Figure 5**. They show that the radii of curvature in the compression garment are always less changeable than without it. The compression product "smooths" the unevenness of the body surface. This is illustrated in **Figure 6** by the coefficients of variation of the radii of curvature for the circumferences of the hand and leg of female and male silhouettes.

In addition to the changes in the radii of curvature along the circumference under the influence of the compression garment, the length of the circumference also changes, which results in a change in the average unit pressure compared with its intended value. These changes are caused by the soft tissue's susceptibility to pressure. The results of the tests shown in the following **Figures 7-10** may be used to illustrate the influence of the body's susceptibility to the length of the circumferences and the pressure value.

In the case of arms and legs, most circumferences have been reduced to a value close to 4%. In the case of female leg circumferences situated 270 to 310 mm from the base, a slight increase was observed in the circumference value in the compression garment compared with circumferences without the garment (**Figure 10**).

Changes in the length of the circumferences under the influence of the compression garment result in a change of the unit pressure. The boundary minimum average pressure values were lower than the intended value by 37%, while the average value for 57 circumferences analysed equalled 9.2%.

For relatively small circumferences, for example female and male hands, the reduction in the pressure value was quite significant compared with the intended value ($P = 24$ hPa), as the average pressure value dropped below the lower limit of the first compression class (**Figure 9**). Such a significant decrease in the average pressure value is related to the relationship between the body circumference and longitudinal rigidity of the compression knitted fabric. The smaller the circumference of the protected body part and the greater the longitudinal rigidity of the knitwear, the greater the decrease in the average pressure value.

Local pressure changes along the circumferences of the body were calculated in order to better visualise the changes in unit pressure. These calculations were performed assuming that the value of the circumferential force F in the knitted fabric along the body circumference analysed is a constant value, and that the differences in unit pressure values result from the different radii of the curvature R_n . The intended unit pressure value P_{int} equals:

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

Where, R stands for the radius of curvature, assuming that the circumference analysed is a circle. For the real geometry of the circumference, values of radii of the curvature are not constant. Hence the pressure value P_n on the circumference section, which can be approximated by a circle with radius R_n , is:

$$P_n = \frac{F}{R_n \cdot s} \quad (7)$$

After determining force F and comparing both sides of the equations:

$$P_{int} \cdot R \cdot s = P_n \cdot R_n \cdot s \quad (8)$$

The value of local pressure determined will be:

$$P_n = P_{int} \cdot \frac{R}{R_n} \quad (9)$$

For comparative purposes, **Figures 11 to 14** additionally present local pressure values along the circumferences with and without the compression garment. In the case of circumferences in compression clothing, these values approximate the real pressure, as they refer to the measured circumferences affected by pressure. However, referring to the lengths and geometry of the circumferences without compression clothing, the pressure values presented do not take into account the susceptibility to pressure demonstrated by soft tissue.

As expected, pressure values calculated for the geometry and lengths of the circumferences with the compression garment are less variable than those for the non-compressed circumferences, which corresponds to the coefficients of variation for the radii of curvature shown in **Figure 6**.

Visualization of local changes in unit pressure for selected female hand and leg circumferences caused by the body's

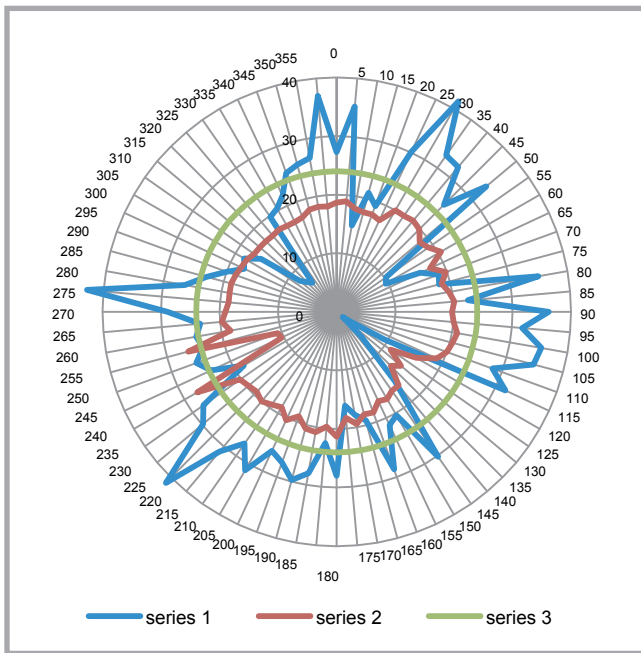


Figure 11. Examples of pressure changes along the circumference of a male hand at a distance $Y = -120$ mm from the base (center of the elbow joint). Series 1 – pressure values calculated without compression clothing, series 2 – pressure values with compression clothing, series 3 – intended value $P_{int} = 24$ hPa.

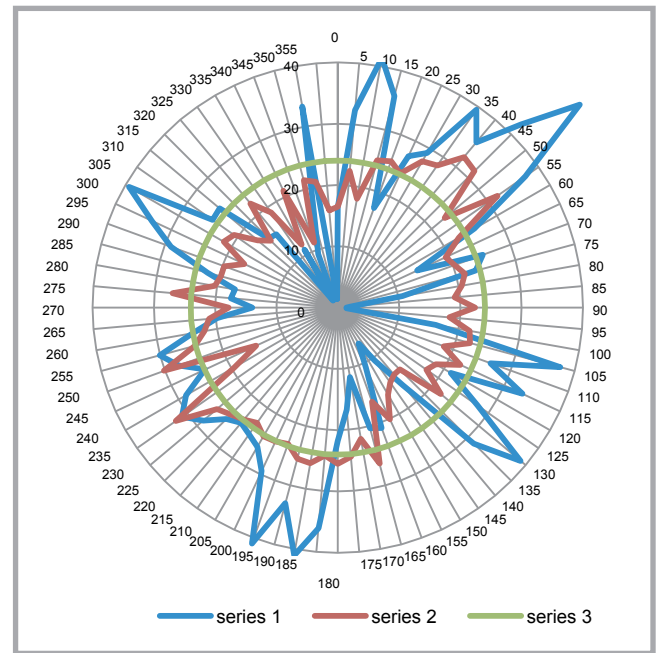


Figure 12. Examples of pressure changes along the circumference of a male hand at a distance $Y = -60$ mm from the base (center of the elbow joint). Series 1 – pressure values calculated without compression clothing, series 2 – pressure values with compression clothing, series 3 – intended value $P_{int} = 24$ hPa.

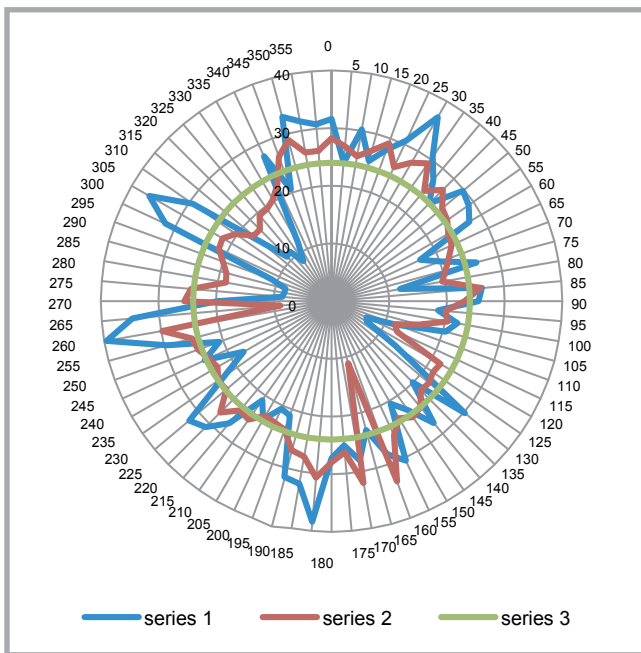


Figure 13. Examples of pressure changes along the circumference of a male leg at a distance $Y = 540$ mm from the base (ankle). Series 1 – pressure values calculated without compression clothing, series 2 – pressure values with compression clothing, series 3 – intended value $P_{int} = 24$ hPa.

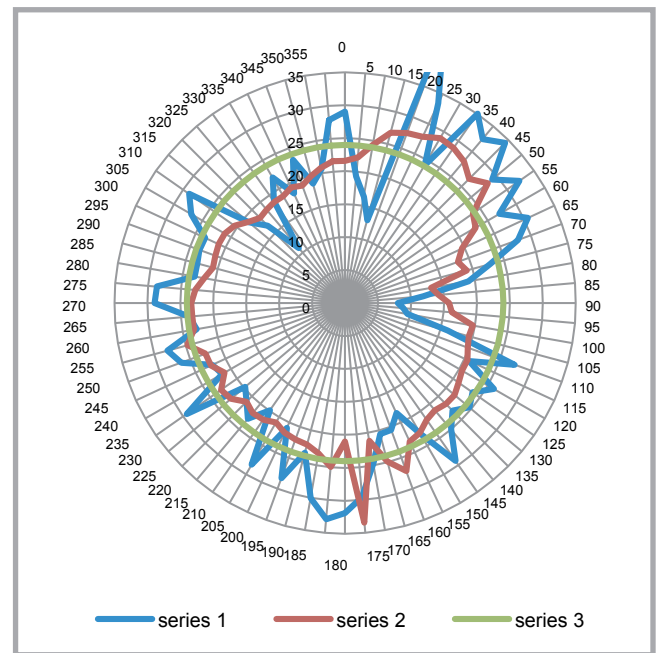


Figure 14. Examples of pressure changes along the circumference of a male leg at a distance $Y = 120$ mm from the base (ankle). Series 1 – pressure values calculated without compression clothing, series 2 – pressure values with compression clothing, series 3 – intended value $P_{int} = 24$ hPa.

susceptibility to pressure is shown in **Figure 15**. In this case, it was found that local values of unit pressure decreased under the influence of the compression garment. These pressure values for the four circumferences analysed are in most

places smaller than the intended value $P = 24$ hPa. The results of the model and experimental studies presented above prove that soft tissue's susceptibility significantly affects the values of unit pressure.

Conclusions

1. To increase the accuracy of dimensioning the human body for the design of compression products which support the process of external treatment,

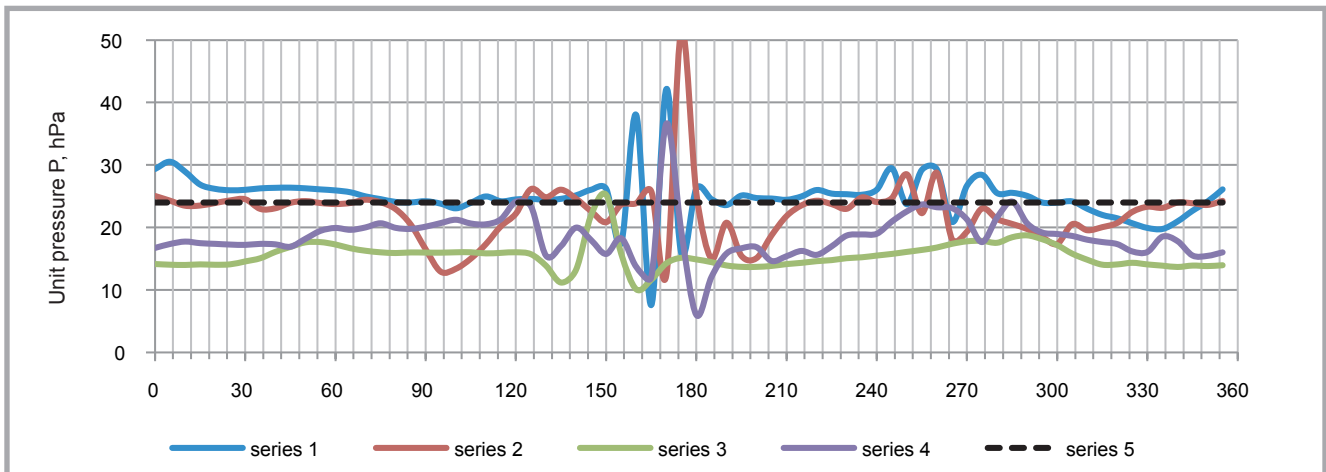


Figure 15. Local changes in unit pressure along selected circumferences of a female hand and leg with a compression garment. Series 1 – 270 mm from the base, series 2 – 550 mm from the base, series 3 – 130 mm from the base, series 4 – 80 mm from the base, series 5 – 550 mm intended pressure value.

- it is required to use 3D scanners. These devices must be characterised by high measurement accuracy and provide stability of the scanned body parts by introducing appropriate support points.
- Designing compression products on the basis of the body circumference measured without compression clothing leads, in most cases, to underestimating the value of unit pressure compared with the intended value. The analyses showed that the boundary minimum average pressure values were smaller than the intended value by 37%, while for the 57 circumferences analysed, the average value equalled 9.2%.
 - Values of local unit pressure along the circumferences in the compression garment determined on the basis of the Laplace law and knowledge of the radii of curvature are lower and less changeable than those determined for non-compressed circumferences.



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