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Using a 3D Body Scanner in Designing Compression Products Supporting External Treatment

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Abstract

The work comprises a statistical tolerance analysis of human body dimensions using a 3D body scanner and its impact on the value of unit pressure exerted by a compression product on the subject's body. Model calculations of changes in unit pressure due to the susceptibility of the human body were carried out on the basis of the Laplace law using experimentally determined values of circumferences of particular parts of a female subject, with and without a compression product. Experimentally documented changes in the body circumferences under the influence of a compression garment are one of the reasons for the differences between the intended and actual pressure value exerted by the product.

Key words: *compression products, laplace law, unit pressure, 3D scanner, dimensional tolerance.*

List of symbols:

P – unit pressure, hPa

P_{int} – intended value of unit pressure, hPa

F/s – circumferential force in the fabric, cN/cm

and – longitudinal rigidity of the knitted fabric, cN/cm

g – fabric thickness, cm

G_0 – fabric circumference in a relaxed state, cm

G_1 – body part circumferences without the compression product, cm

G'_1 – body part circumferences with the compression product, cm

L_0 – fabric length reduced by seam width, cm

$ε$ – relative elongation of the knitted fabric

$ε'$ – relative elongation of the knitted fabric in the compression product

◼ Introduction

Compression therapy is one of the methods supporting the process of external treatment. It is used, among others, for the treatment of post-burn scars, lymphedema, venous diseases, vascular malformations and after plastic surgery. It involves the use of appropriate, controlled pressure, depending on the type and severity of the disease.

Compression therapy uses various types of compression products, which occur in a very wide range. They include, among others, vests, overalls, tights, knee-high socks, headbands and gloves. The best results and effectiveness of compression therapy can be obtained when the patient uses products designed and tailor-made according to individual anthropometric measurements.

The basis for the modeling and design of compression products is the Laplace law (1).

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

According to this law, the value of unit pressure P is directly proportional to the circumferential force F in a fabric strip of width s, and it is inversely proportional to the body circumference G_1. A fundamental stage in the procedure of designing compression products is taking measurements in order to determine the correct values of patients' body circumferences. Nowadays these measurements are often performed with special non-contact tools using 3D scanning technology. Replacing manual dimensioning methods with a non-contact measurement of the circumferences of certain body parts helps to eliminate problems associated with the accuracy, reliability and reproducibility of the results, which are due to the person's skills or methods in taking the measurement. When using a 3D scanner for taking measurements of the human body, the issue of uncertainty, ascribed to unit pressure as a complex value connected with the random variable of circumference G_1 and circumferential force F, is of great importance. In anthropometric studies for the design of classic clothing, body measurement is carried out practically with a single body scan. In the design of compression garments supporting the process of external treatment, much greater accuracy is required in determining circumference G_1, which

is due to the fact that it affects the value of unit pressure exerted on the body and must be consistent with the requirements for medical devices used for a particular kind of therapy [1-6]. For this reason, it is necessary to determine the measurement uncertainty of body part circumferences G_1, which in this work will be characterized by standard uncertainty (standard deviation) and maximum uncertainty (maximum error).

Works [7, 8, 10] discussed the issue of the impact of tension characteristics and relaxation – deformation of the fabric on the value of unit pressure, taking into account medium and extreme force values as a function of relative elongation, and confidence intervals calculated for the phases of tension and relaxation. This made it possible to estimate the uncertainty of unit pressure associated with a random variable, which is the circumferential force F. Papers [9, 11] presented the basics of modeling compression products with an intended value of unit pressure for body circumferences with a variable radius of curvature. They pointed out some possibilities of using 3D techniques of scanning the human body to determine the radius of curvature for the section of the circumference for which the intended value of unit pressure is designed. Applications of 3D scanning techniques in designing compression products were discussed in [12, 13]. It is necessary to extend research on the use of 3D scanners to issues of measurement accuracy in determining geometrical parameters of human body parts.

One of the objectives of this study was to determine, on the basis of statistical analysis, the dimensional tolerance of the human figure measured with a 3D scanner and assessment of unit pressure uncertainty under the influence of the random variable of body circumferences G_1.
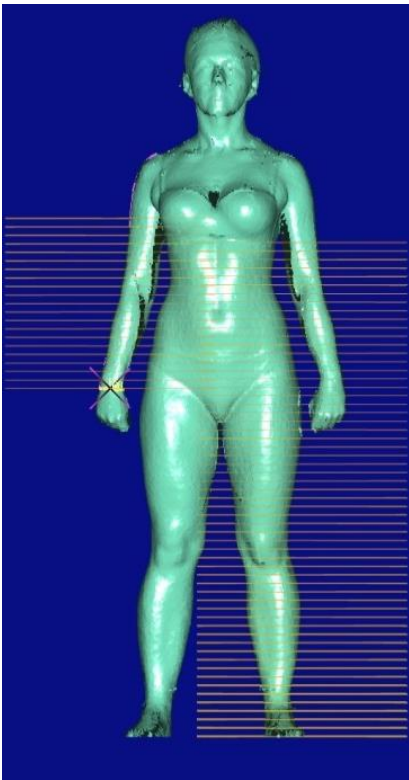
Theoretical part
Due to the susceptibility of soft body tissue, estimating changes in unit pressure under the influence of compression clothing requires knowledge of body circumferences with and without the compression product. Surface pressure exerted by the compression garment leads to some changes in the geometry of the body circumferences and in their lengths. Currently, designing compression products is based on t knowledge of the patient's body part circumferences without compression clothing. The rationale for undertaking this study was the analysis of experimental results, which confirmed there are some differences in the values of individual body circumferences with and without compression clothing. The relations derived in the theoretical part of the work make it possible to determine changes in the unit pressure under the influence of surface susceptibility. The results of these tests will be presented in the experimental part of the work, and have already been presumed in previous studies [9-11].

Assumptions:
1. Modeling the pressure is based on the Laplace relation.
2. Forces F in the fabric along the circumference of the human body are constant values, since they are equalised during use.

Table 1. *The measurements of body circumferences of a female subject.*

| hand								Scan of a female body	leg					
h,cm	G_1,cm					G_1,cm average			h,cm	G_1,cm				G_1,cm average
0	15.5	15.4	14.8	15.8	15.7	15.4			8	23.1	23.7	23.2	23.3	23.4
2	15.5	15.4	15.2	16	15.9	15.6			10	22.2	22.2	22.3	22.4	22.4
4	16.3	16.5	16.3	17.1	17.2	16.7			12	22.9	23	22.9	23.2	23.2
6	17.9	17.8	17.5	19.1	18.7	18.2			14	24.3	24.5	24.5	24.7	24.6
8	19.4	19.6	19.4	20.3	20.4	19.8			16	26.6	26.8	26.5	27	26.8
10	21.3	21.1	20.9	22	21.8	21.4			18	28.6	28.9	28.9	29	29.2
12	23	23	22.8	23.7	23.6	23.2			20	31	31.3	31	31.5	31.2
14	24.4	24.3	24.3	25.3	25.1	24.7			22	32.8	33.1	33.3	33.3	33.4
16	25.2	25.3	25.1	26	25.9	25.5			24	35	35.2	35	35.2	35.1
18	25.2	25.3	25.2	26	25.9	25.5			26	36.5	36.7	36.8	36.8	36.9
20	25	25.2	25	25.3	25.2	25.1			28	37.6	37.9	37.9	38.1	38.1
22	24.3	24.5	24.3	24.5	24.6	24.4			30	38.3	38.5	38.7	38.8	38.9
24	24.3	24.4	24.2	24.3	24.3	24.3			32	38.6	38.9	38.9	39.1	39.2
26	24.4	24.7	24.5	24.8	25.1	24.7			34	38.2	38.4	38.4	38.7	38.8
28	25.1	25	24.9	25.9	26.1	25.4			36	37.4	37.4	37.4	37.7	37.7
30	25.7	25.9	25.7	26.7	27	26.2			38	35.8	35.9	36	36.1	36.1
32	26.6	26.5	26.3	27.6	27.6	26.9			40	34.9	34.6	34.5	34.9	34.7
34	27.3	27.4	27.2	28	28.1	27.6			42	35.6	35	34.8	35.5	34.9
36	28.3	28.2	28.2	29	29.1	28.6			44	36.9	36	35.9	37	36.1
38	29.1	29.7	29	29.6	29.3	29.3			46	38.4	37.7	37.5	38.5	37.2
40	29.9	30.3	30.8	29.7	29.5	30.0			48	39.3	38.8	38.9	39.2	39.2
									50	40.2	39.8	39.8	40.3	40
									52	41.6	40.8	41	41.7	41.3
									54	43.9	43.3	43.1	44.1	43.3
									56	46.2	45.5	45.7	46.1	45.9
									58	48	47.7	47.6	48.3	47.8
									60	50	49.6	49.7	50.1	49.9
									62	51.5	51.3	51.5	51.7	51.7
									64	53.2	53.1	53.1	53.1	53.2
									66	54.4	54.6	54.8	54.5	54.7
									68	56	56.3	56.1	56	56.1
									70	56.9	57.3	57.5	57	57.3
Hand circumferences without clothing								Scan of a female body	Leg circumferences without clothing					
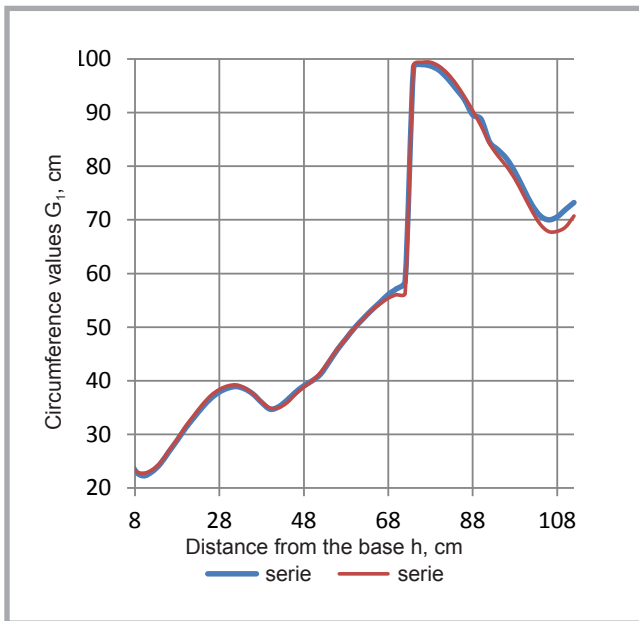
Figuere 1. *Average values of leg and trunk circumferences with and without compression clothing. Series 1 (blue line) – without clothing, series 2 (red line) – with clothing.*
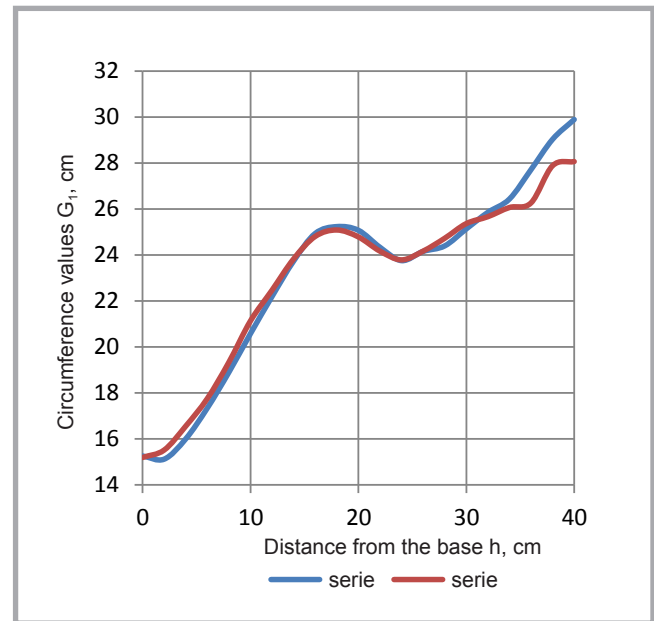

Fiure 2. *Average values of hand circumferences with and without compression clothing. Series 1 (blue line) – without clothing, series 2 (red line) – with clothing*

3. A linear relationship between the force and relative elongation of the fabric was assumed for the considerations.
4. Body susceptibility to unit pressure was determined on the basis of the measurements of body part circumferences with and without compression clothing.

The intended value of unit pressure according to Laplace law equals;

$$P_{int} = \frac{2 \cdot \pi \cdot a \cdot \varepsilon}{G_1 \cdot s} \quad (2)$$

After introducing a well-known relation for relative elongation ε, we receive:

$$P_{int} = \frac{2 \cdot \pi \cdot a \cdot (G_1 - G_0)}{G_0 \cdot G_1 \cdot s} \quad (3)$$

Having transformed the equation relative to the free dimension ,we obtain:

$$G_0 = \frac{2 \cdot \pi \cdot a \cdot G_1}{P_{int} \cdot G_1 \cdot s + 2 \cdot \pi \cdot a} \quad (4)$$

Thus the unit pressure *P'* under the influence of changes in the body circumferencein compression clothing equals;

$$P' = \frac{2 \cdot \pi \cdot a\varepsilon'}{(G_1' - 2\pi g) \cdot s} \quad (5)$$

Where the relative elongation is

$$\varepsilon' = \frac{G_1' - 2\pi g - G_0}{G_0} \quad (6)$$

After substituting *Equation (6)* into *Equation (5)* and after necessary transformations, we obtain dependence *Equation (7)* for 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.

$$P' = P_{int} + \frac{2 \cdot \pi \cdot a}{s} \left[\frac{G_1' - 2\pi g - G_1}{G_1 \cdot (G_1' - 2\pi g)} \right] \quad (7)$$

Experimental part

For measurements of body circumferences of a female subject we utilized a VITUS XXL 3D Body Scanner from Human Solutions GmbH with AN-THROSCAN software. The scanner uses optical light triangulation – laser technology. The BMI (Body Mass Index) of the subject was 22.59. Body circumferences were determined with and without compression clothing with an intended value of unit pressure P_{int} = 20 hPa. Five independent measurements were made of each leg, trunk and hand circumference at intervals of 2 cm (*Table 1*). A total of 760 circumferences were determined for different parts of the body with and without a compression product. The aim of the analysis of measurement results was to determine the following data:
- percentage differences for average values of individual body circumferences with and without compression clothing,
- changes in the value of unit pressure under the influence of body susceptibility resulting from differences between the circumference values with and without compression clothing,
- standard deviation for subsequent circumference measurements,
- maximum error in circumference values for successive scans.

■ Analysis of research results

Percentage differences for average body circumferences with and without compression clothing

The following two figures present average values of leg and trunk circumferences (*Figure 1*) and hand circumferences (*Figure 2*) with and without compression clothing. When scanning the leg and trunk, the distance from the base was calculated from the ground, and the lower edge of the compression product was placed at the height of the medial malleolus of the ankle. For the hand, the distance from the base was calculated from the wrist.

To visualize the changes in circumferences values, percentage differences in the average circumferences with and without a compression garment were calculated according to *Equation (8)*. The calculation results are shown in *Figures 3* and *4*.

$$D\% = \frac{G_1 - G_1' - 2\pi g}{G_1} \times 100\% \quad (8)$$

The biggest differences between the values of average circumferences with and without compression clothing are observed in the area of soft tissue near the edge of the compression product, which
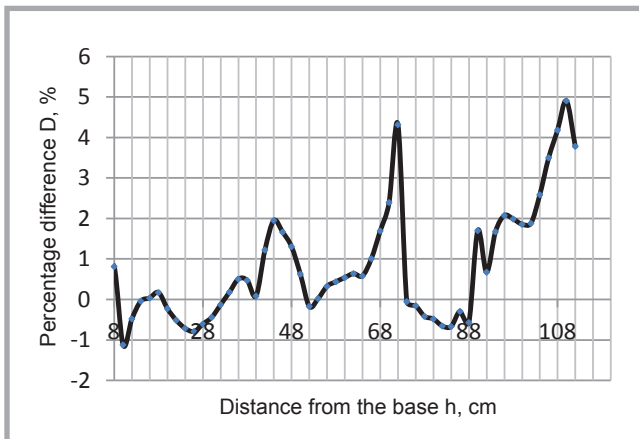
Figure 3. *Percentage differences of average circumferences with and without compression clothing for leg and trunk.*
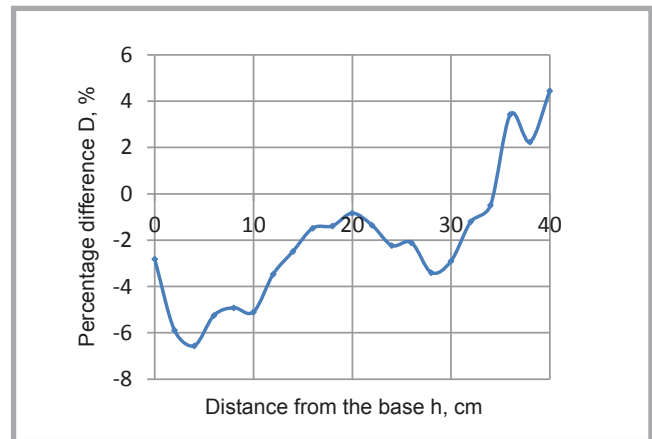

Figure 4. *Percentage differences of average circumferences with and without compression clothing for hand.*
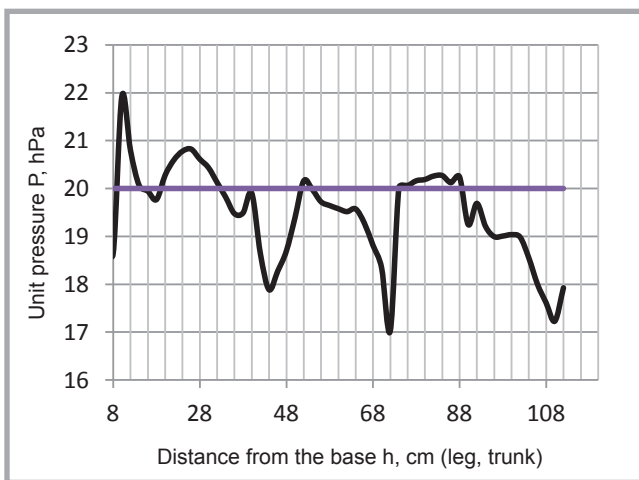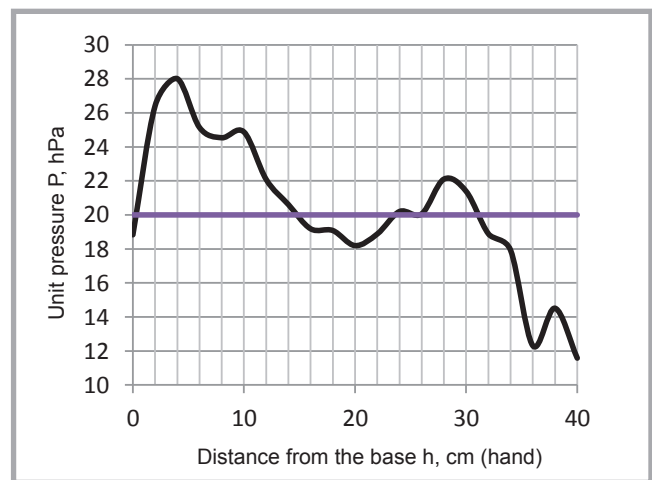

Figure 5. *Changes in unit pressure caused by body susceptibility for leg, trunk and subsequent circumferences for/intended value P_{int} = 20 hPa. Calculation parameters: G_1 = 22,3÷98,9 cm, G_1'' = 22,8÷99,4 cm, g = 0,04 cm, a = 615 cN/cm, s = 1 cm.*

Figure 6. *Changes in unit pressure caused by body susceptibility for hand and subsequent circumferences for intended value P_{int} = 20 hPa.Calculation parameters: G_1 = 15,1÷29,9 cm, G_1'' =15,45÷28,35 cm, g = 0,04 cm, a = 615 cN/cm, s = 1 cm.*

is the reason for the decrease in unit pressure (***Figures 5*** and ***6***). Therefore the recommendation that the compression product should extend at least 5 cm from the edge of the area undergoing therapy seems reasonable [14].

Analysis of ***Figures 3*** and ***4*** shows that depending on the circumference location, the pressure exerted by the garment causes a decrease or increase in the body circumference. The variable effect of the surface pressure on the circumference value is caused by the changes in its geometry. It may become closer to a circle, thereby reducing the circumference, or more similar to an ellipse, which increases the circumference. Negative values of percentage differences D% confirm an increase in the circumference under the influence of surface pressure, and positive values – its decrease.

Changes in the value of unit pressure under the influence of body susceptibility resulting from differences between circumferences values with and without compression clothing

Changes in the value of unit pressure resulting from variations in body circumferences with compression clothing were calculated according to ***Equation (7)***. In the procedure of designing compression products, the determined value of the circumference of a knitted fabric in a relaxed state refers to the body circumference without a compression product. Changing the body circumference to the value (under the pressure exerted by the product at constant circumferences of the knitted fabric in a relaxed state causes changes in the unit pressure. The values of unit pressure shown in ***Figures 5*** and ***6***, refer to a cylindrical model of body parts.

They show a reduction or an increase in the average value of unit pressure in relation to its intended value P_{int}= 20 hPa. The increase in the value of unit pressure is caused by an increase in the body circumference in compression clothing, with the reduction in unit pressure corresponding to a decreased circumference.

Changes in standard deviation and maximum error for subsequent body circumferences

The dispersion of values of body circumferences measured by a 3D body scanner, expressed as standard deviation, is presented in ***Figures 7*** and ***8***. In order to present in numerical form the changes in unit pressure under the influence of dimensional tolerance in measuring human body parts with a 3D scanner, the difference between the average value for each
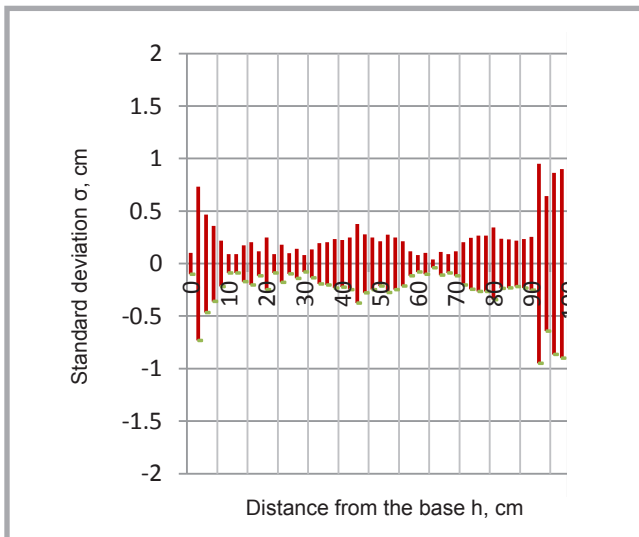
Figure 7. Standard deviation of subsequent leg and trunk circumferences without compression clothing.
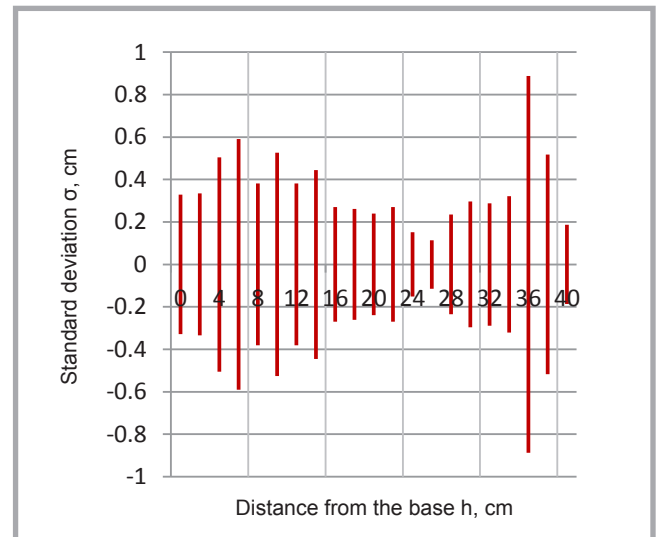

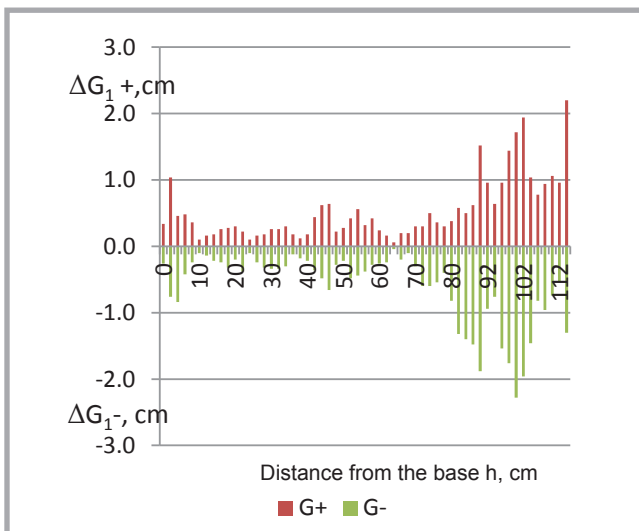*Figure 8. Standard deviation of subsequent hand circumferences without compression clothing.*

Figure 9. Dimensional tolerances of a female figure for subsequent circumferences measured with a 3D scanner without a compression product (leg, trunk).
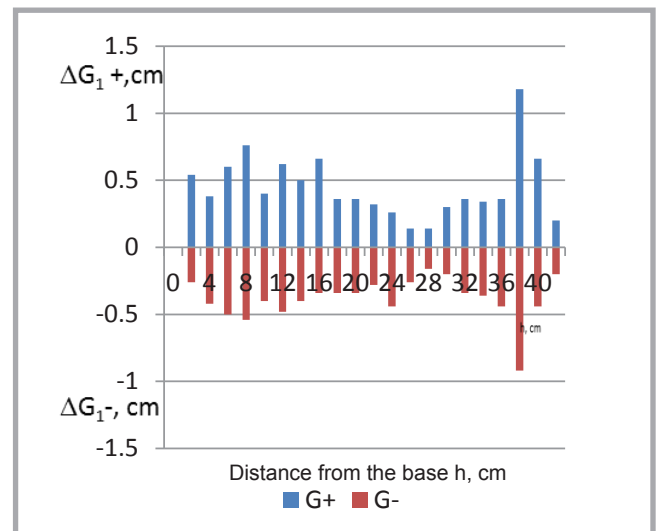

Figure 10. Dimensional tolerances of a female figure for subsequent circumferences measured with a 3D scanner without a compression product (hand).

circumference and the minimum and maximum values were determined (*Figures 9* and *10*). For many circumferences the differences between the average value and the minimum and maximum ones exceeded $\Delta G_1 \pm 1$ cm. The effect of the dimensional tolerance adopted $\Delta G_1 \pm 1$ cm on the changes in unit pressure depending on body circumferences and the longitudinal rigidity of the knitted fabric is illustrated in *Figure 11*. From the analysis of *Figure 11* it can be concluded that the smaller the value of the circumference and the greater the longitudinal rigidity of the fabric, the greater the influence of tolerance $\Delta G_1 \pm 1$ cm on the value of unit pressure. It also increases the deviation of the unit pressure from the intended value P = 20 hPa.
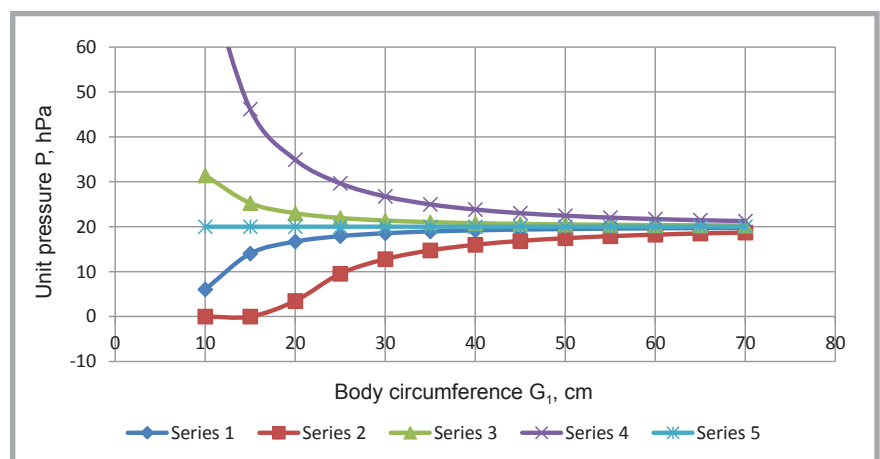

Figure 11. Influence of dimensional tolerance of a human body $\Delta G_1 \pm 1$ cm on changes in unit pressure depending on the circumferences values. Calculation parameters: 1÷2 – longitudinal rigidity a = 200÷1000 cN/cm, series 3÷ 4– longitudinal rigidity c1 = 200÷1000 cN/cm, series 5 – intended value of unit pressure P = 20 hPa.

Conslusions

- Designing compression products on the basis of values of body circumferences without compres s ion clothing does not take into account the impact of body susceptibility on the value of unit pressure. Experi m entally documented changes in bod y circumferences under the influence of compression clothing are on e of the reasons for the differences between the actual value of unit pressure and the intended one.

- Based on our study, determining body circumferences with single 3D scanning is insufficient in the design of compression products supporting the process of external treatment. It should be preceded by estimating measurement inaccuracy and determining the necessary number of measurements in order to eliminate dimensioning errors. In order to increase the accuracy, reliability and reproducibility of determining circumferences, positioning of the human body is necessary, by introducing support points for the figure and moving parts of the body.

- The use of knitted fabrics with high longitudinal rigidity for small circumferences $G_1 < 40$ cm is the reason for the differences between the actual unit pressure exerted on the body and its intended value, due to the unavoidable dimensional tolerances of the human figure. For instance, for an intended value of unit pressure $P = 20$ hPa, longitudinal rigidity of the knitted fabric a = 1000 cN/cm and dimensional tolerance adopted for the calculations $\Delta G_1 = \pm 1$ cm, the unit pressure for $\Delta G_1 = 1$ cm increases progressively from 23 to 46 hPa in the circumference range <15; 40 cm > and decreases degressively from 0 to 23 hPa for $\Delta G_1 = -1$ cm.

Acknowledgements

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