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Designing Seamless Compression Products Supporting the Process of External Treatment on Numerically Controlled Flat Knitting Machines

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Abstract
The paper presents a procedure for the design of seamless compression products with an intended value of unit pressure on numerically controlled flat knitting machines. Based on the algorithms developed, some important stages of product design are discussed, i.e. dimensioning of body parts by 3D scanning, selection of proper longitudinal rigidity of the fabric, and manufacturing the tolerance of the product in the form of five-finger gloves with covered and exposed fingers. An important stage in the design procedure is the selection of a knitted fabric with appropriate longitudinal rigidity in dependence on the anatomy of the hand.

Key words: *flat knitting machines, compression products, knitted fabric – optimisation and properties, unit pressure, Laplace's law, 3D scanner, longitudinal rigidity of a knitted fabric.*

Introduction

Products available on the market used in therapies supporting the process of external treatment are either joined by seams or seamless. Most of them are finished products, available in various sizes. However, products designed for individual body dimensions are more useful for medical reasons because they ensure an intended compression value, provided they are designed based on the dependencies resulting from Laplace's law [1-4]. It should be noted, however, that according to this law, cylindrical models of human body parts are used for design purposes. Consequently variable pressure is exerted by the product along the circumference of the user's body part whose geometry deviates from the circle [4, 5].

The traditional technique of constructing compression products joined by seams, based on the manual dimensioning of body parts and making patterns of individual product elements, is both time-consuming and fraught with large material losses of up to 20-30%. New technological possibilities of manufacturing compression products are provided by numerically controlled flat knitting machines, on which products are obtained by the seamless technique, practically without material losses.

In the process of designing compression products, regardless of the technique, the following factors are important and influence the intended value of unit pressure:
- dimensioning accuracy of body circumferences G1 and their distance from the base [6, 7]
- selection of proper longitudinal rigidity of the knitted fabric, depending on the type of therapy and the circumferences of body parts
- accuracy of determining the mechanical characteristics of the knitted fabric in the form of the relationship between the force and relative elongation [8, 9]
- body susceptibility to pressure [10].

Review article [11] presents different aspects of the design and modeling of compression products.

Relatively high accuracy in determining the value of G1 circumferences can be obtained by using 3D scanners [12-18], which eliminate some of the reasons for scatter in the results, caused by the manual methods of taking the measurements. An important stage in the design of compression products is considering the mechanical characteristics of the knitted fabric, in the form of complex relations between the force F and relative elongation ε in dependance on the stretching range [9].

The aim of this work is to present the problem of designing personalised seamless products on numerically controlled flat knitting machines. Based on the algorithms developed, some important stages of product design will be discussed, especially the dimensioning of body parts by 3D scanning, selection of appropriate longitudinal rigidity of the knitted fabric, and manufacturing the tolerance of the products in the form of five-finger gloves with covered or exposed fingers, also covering the forearm.

Research program and methodology

The procedure for designing seamless compression products with an intended value of unit pressure was based on a general algorithm developed for determining input parameters for the Stoll M1plus program and model-experimental tests. The selection of five-finger gloves with covered or exposed fingers, also covering the forearm, was connected with the fact that the design procedure for this type of product is more complex than for products protecting other body parts. Measurements of hand and forearm circumferences were made by the 3D scanning technique for a 4-year-old boy. The choice of the product size resulted from the lack of seamless compression gloves for children on the market, and according to literature sources [21], the demand for compression products for people affected by burns is 400.000 per year, 50-80% of which are children aged 2-4.

A spatial structured light scanner was used for the measurements.

The scanning head performs a rotational motion around the scanned object. Scanner configuration:
- two monochrome cameras 1.3 MPix,
- DLP 1280 x 1024 projector
- FlexScan3D software ver. 3.1

Evaluation of the scanning accuracy was carried out on the basis of the VDI/VDE 2634 standard, part 2 "Optical 3D measuring systems – Optical systems based

Figure 1. 3D scanner with devices for measuring limbs.

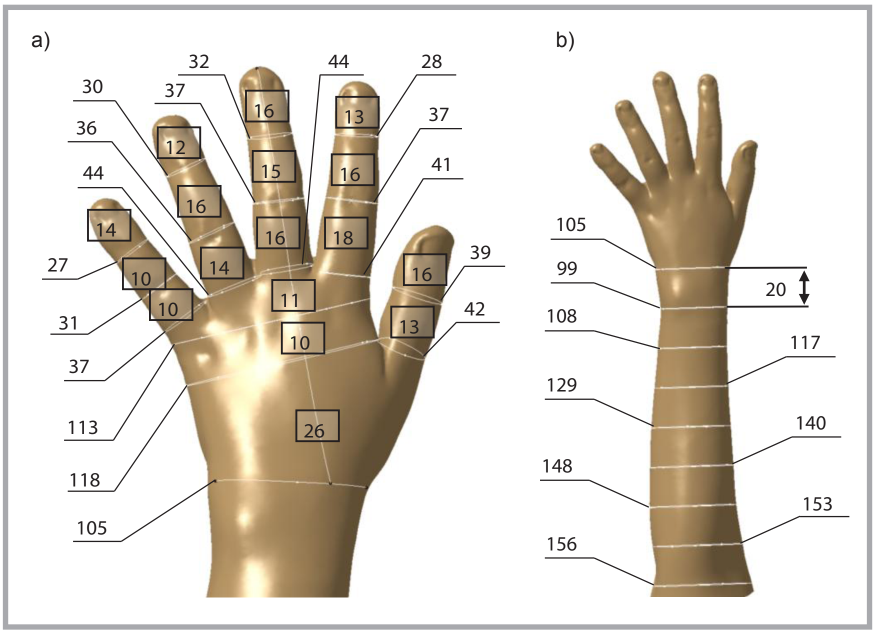

Figure 2. a) Hand dimensions of a child G_i in mm, b) Forearm dimensions of a child G_i in mm.

on area scanning". The accuracy was assessed by using two balls fixed to the base. The diameter of the test ball was 44,629 ± 0.005 mm and the distance between them 120,093 ± 0.005 mm.

Scanning measurements were made for 7 positions of the balls in the measurement space, in accordance with the recommendations given in the standard. The average error over the length equaled 0.062 mm, which, in relative terms, means that the errors fall within ± 0.1%.

The patient's body was digitised by combining the scans performed during the scanner rotation (scanner shown in ***Figure 1***). In order to measure the circumferences of the patient's body in the cross-sections selected, the scanning results were processed by a specially developed computer program implementing the algorithm of a convex hull in a 3-dimensional space. The results of hand and forearm scans are shown in ***Figure 2.a*** and ***2.b***.

An important stage in the design process of seamless compression products in the form of gloves is the selection of proper longitudinal rigidity of the knitted fabric. The main reason for selecting the longitudinal rigidity of the fabric for the purpose of designing a compression glove is the fact that the circumferences of the four fingers measured at the finger base $\sum_{i=1}^{4} G_i$ are longer than the hand circumference below the fingers (i.e., $\sum_{i=1}^{4} G_i > G_D$). Therefore it is necessary to fulfil condition (1) by choosing proper longitudinal rigidity of the compression fabric for the intended value of unit pressure. This condition will be fulfilled when the circumference of the knitted fabric girdlingthe fingers in a relaxed state $\sum_{i=1}^{4} G_{0i}$ directly at the finger base is smaller than the hand circumference. This rule results from the boundary conditions of the knitting process, where the number of needles forming the middle part of the hand should be equal to that forming the fingers.

Pre-selection of the longitudinal rigidity of the compression fabric based on the linear model was performed on the basis of the algorithm developed (***Figure 3***).

The main element of the calculations is the fulfillment of the following condition.

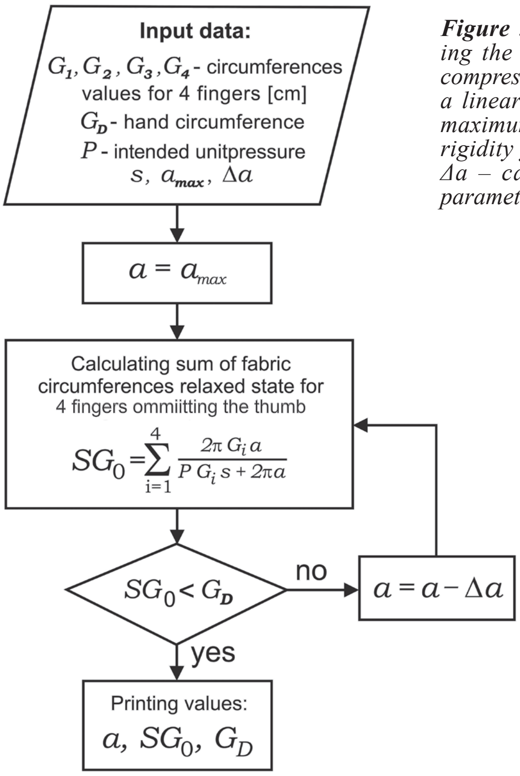

Figure 3. Algorithm for selecting the longitudinal rigidity of compression fabric according to a linear model, where: amax – maximum value of longitudinal rigidity for a given fabric, and Δa – calculation accuracy of parameter a.

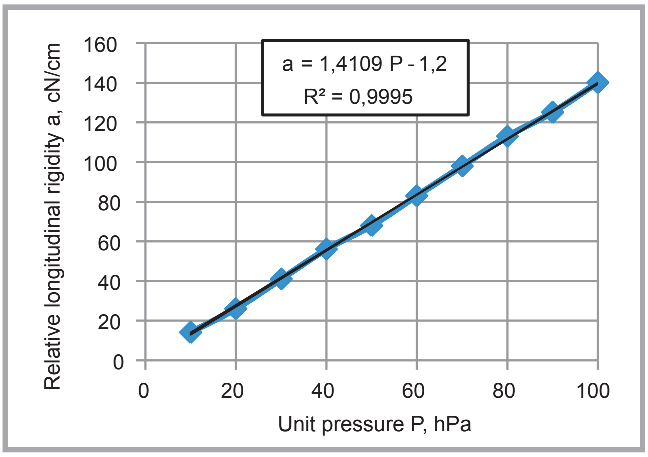

Figure 4. *Influence of unit pressure P on longitudinal rigidity a when dependence $\sum_{i=1}^{4} Go_i < G_D$ is satisfied.*

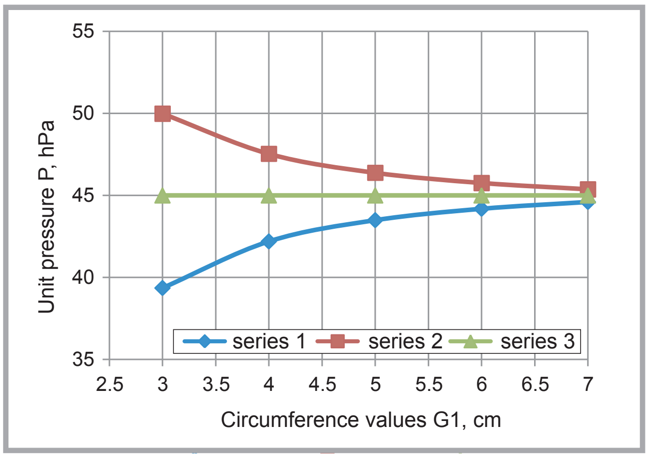

Figure 6. *Changes in unit pressure P under the effect of manufacturing tolerance $\Delta G_0 = \pm 0.139$ cm in dependence on body circumferences G_1 for the longitudinal rigidity of the knitted fabric a = 62 cN/cm. Series 1 – P for $G_0 + 0.139$ cm, series 2 – P for – 0.139 cm, series 3 – for P = 45.*

$$SG_0 = \sum_{i=1}^{4} \frac{2\pi G_i a}{P G_i s + 2\pi a} < G_D \qquad (1)$$

Where: SG_0, cm – the sum of fabric circumferences in a relaxed state for four fingers, ommitting the thumb,
G_i, cm – circumferences of four individual fingers,
P, hPa – intended value of unit pressure,
a, cN/cm – longitudinal rigidity of the fabric,
G_D, cm – hand circumference below the fingers.

Calculation results of longitudinal rigidity a [cN/cm] in dependence on the value of unit pressure P, taking into account the fingers and hand circumferences, as well as the fulfillment of dependence $\sum_{i=1}^{4} \mathrm{Go_i}$ indicate the linear characteristic of relationship a = f(P) (***Figure 4***).

According to literature data [19-20], in the case of the treatment of post-burn scars, the unit pressure applied falls in the range between 5 and 35 mmHg (7 ÷ 45 hPa). In the case analysed, the upper value P = 45 hPa was adopted for the tests, because for this value condition can be easily fulfilled. In this case, the longitudinal rigidity of the knitted fabric is a = 62 cN/cm. Choosing the upper value of unit pressure was also connected with the dimensional tolerance of the product, which is particularly important for fabric dimensions in a relaxed state for small body circumferences e.g. fingers.

The difference between the values of finger circumferences G_i and fabric circumferences in a relaxed state G_{0i} should be as high as possible, which increases with a decrease in the longitudinal rigidity of the knitted fabric and increase in unit pressure *P* (***Figure 5***).

A relatively large difference between the fingers' circumferences and the circumference of the knitted fabric in a relaxed state is observed in the case of knitted fabric with longitudinal rigidity in the range a = 50 ÷ 100 cN/cm. However, the permissible value of unit pressure narrows the range of values of relative longitudinal rigidity.

Another factor which indirectly influences the manufacturing tolerance of product elements for body parts, such as fingers, is the needle gauge of the knitting machine. The smaller the needle gauge, the greater the dimensional accuracy of the product; henceit is possible to obtain knitted fabrics with narrower wales.

In the process of narrowing/widening the product, the manufacturing tolerance of the fingers of the glove is closely related to the warp density of the knitted fabric. In the case of double-sided narrowing/widening by one needle on both needle beds of the knitting machine, the difference between the calculated value G_{0i} and the result obtained is due to rounding the error to the total number of needles forming the circumference.

Hence the maximum difference, according to the equation, equals $\Delta G_{0i} = \mp \frac{100}{Pk} n$, where n – the number of needles for two-sided narrowing/widening by one needle on two needle beds. For the fabric made during the experiment $\Delta G_{0i} = \pm 0{,}139\ cm$.

As expected, changes in unit pressure *P* decrease with increasing body circumferences G_1 (***Figure 6***).

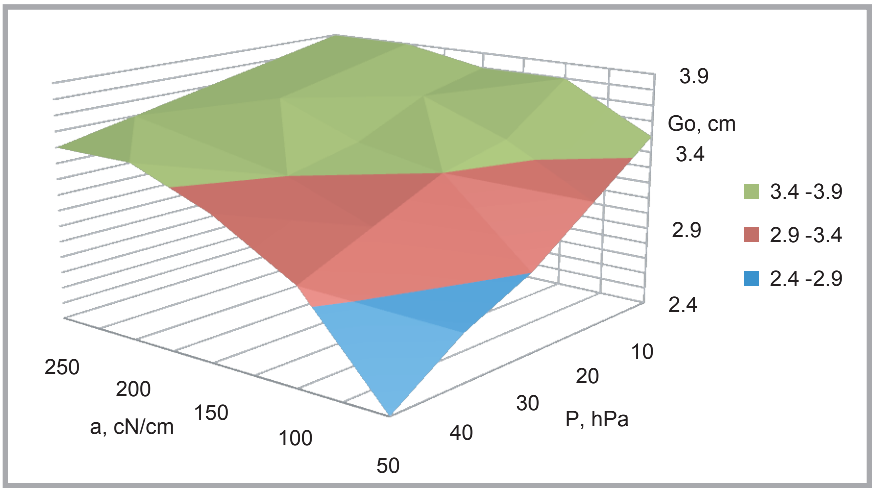

Figure 5. *Influence of longitudinal rigidity a and unit pressure P on the fabric circumference in a relaxed state G_0 for finger circumference G_1 = 4 cm.*

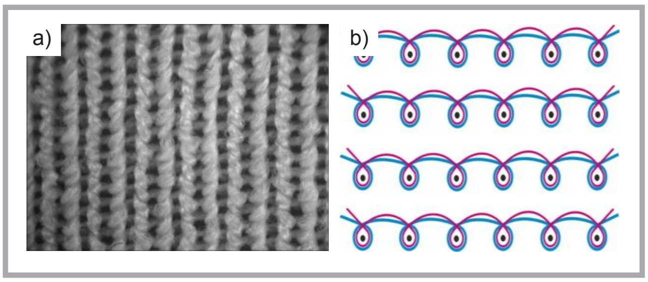

***Figure 7.** a) View of the face of a weft-knitted fabric plated with elastomeric yarns, b) Schematic record of the stitch of a weft-knitted fabric plated with elastomeric yarns.*

Summarizing it should be noted that in the final selection of the longitudinal rigidity of the knitted fabric, quality parameters of the fabric, such as the stitch density, strength parameters and organoleptic qualities. should also be taken into account. The production of "delicate" fabrics characterised by low values of longitudinal rigidity – suitable for small circumferences such as fingers – also limits the possibility of processing yarns with low linear mass densities on numerically controlled flat knitting machines, due to their needle gauges.

Knitted fabric was made on a numerically controlled flat knitting machine – Stoll CMS 530 HP 8.2. with plain stitch consisting of a connecting stitch made of textured polyamide silk with a linear mass density of 78 dtex f128 x 1, plated with elastomer with a braid of linear mass density of 78 dtex + Lycra 44 dtex, characterised by the following parameters (***Figure** 7*).

Fabric properties:
Course density Pr = 245/10 cm
Wale density Pk = 144/10 cm
Surface density M = 288 g/m^2

In order to determine the actual mechanical characteristics in the form of the relationship between the force and relative elongation, the compression fabric was tested for the relative elongation range ε 0÷1.0 in separate stretching ranges increased by 0.1 of relative elongation. Adopting the relationship of force and relative elongation based on the force values determined in the relaxation phase, after stopping the stretching process for different stretching sub-ranges, eliminates the causes of errors in the design of compression products with an intended value of unit pressure. It is due to the fact that it takes into account differences in the relations between values F and ε in dependence on the stretching range and rheological properties of the compression fabrics tested.

Considering the conditions of use of compression products, which are often applied in relatively long-term therapies [22] and are mostly used while the patient is at rest, the values of forces in the relaxation phase, i.e. at standstill after the stretching process stops in the sixth hysteresis loop for individual stretching sub-ranges, were used to describe the function of force and relative elongation. The final mechanical characteristics of the knitted fabric in the form of the relationship between the force and relative elongation with respect to a knitted strip of width s = 1 cm are described by the following function: $F = 97{,}284\varepsilon^3 - 161{,}41\varepsilon^2 + 118{,}41\varepsilon$, $R^2 = 0{,}989$. A detailed method of function designation, together with justification based on the rheological model, were presented in publication [9].

As illustrated in ***Figure 8***, in practice, a knitted fabric with elastomeric threads is characterised by a non-linear relationship of force and relative elongation, and consequently variable longitudinal rigidity, depending on the relative elongation value (***Figure 9***). Values of longitudinal rigidity $a = dF/d\varepsilon$, cN/cm (***Figure 9***) determined for the knitted fabric produced on the knitting machine used for the tests fall within the range 120 ÷ 30 cN/cm.

Theoretical part

The aim of the theoretical considerations was to develop an algorithm and then a computer program based on it that could merge data from a 3D scanner in the form of circumferences G_i and distances Y_i of these circumferences from the base, taken as a reference point. The aim of the calculations is to determine input data for the Stoll M1plus computer program controlling the work of the knitting machine in the production of seamless products.

Assumptions

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

- the relationship between the unit pressure P, circumferential force F in a knitted fabric of width s and the body circumference G_1 is described by Laplace's law,

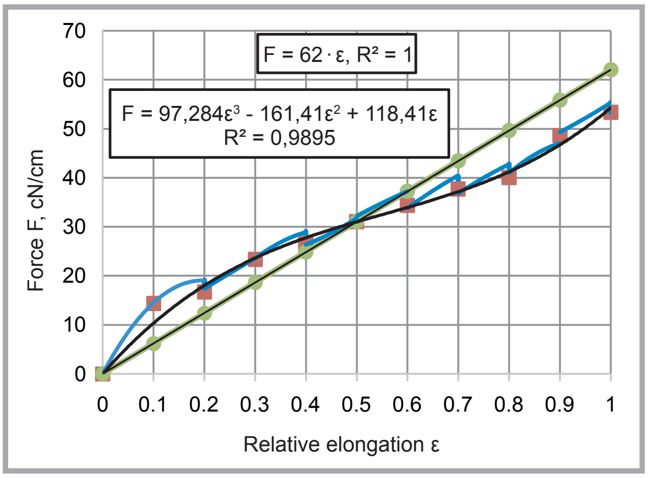

***Figure 8.** Force values as a function of relative elongation in the 6th hysteresis loop for different fabric stretching ranges. Series 1 ■ – experimental curve. Series 2 ● – according to linear model*

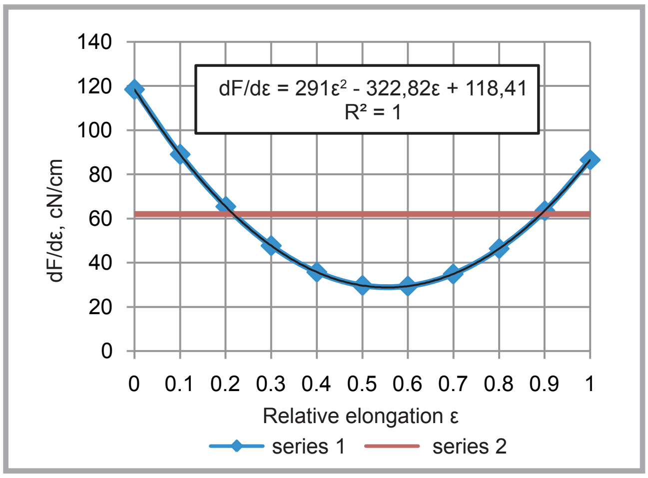

***Figure 9.** Values of longitudinal rigidity dF/dε, cN/cm in dependence on relative elongation ε. Series 1 – experimental values. Series 2 – dF/dε = 62,cN/cm – according to linear model*

- the relationship between the force and relative elongation of the knitted fabric is determined on the basis of experimental characteristics for the tension phase of the fabric in the 6th hysteresis cycle and for different stretching ranges,
- the forces *F* in the knitted fabric along the circumference of the human body are constant, as they are equalised during use,
- the body's susceptibility to unit pressure is neglected.

The program developed makes it possible to calculate values of fabric circumferences in a relaxed state G_{0i} for individual hand and forearm circumferences G_i. Depending on the values of body circumferences G_i and the intended value of unit pressure P, the force values are calculated according to Laplace's law.

$$Fi = \frac{P \cdot G_i \cdot s}{2\pi} \quad \text{for i = 1, 2... n} \quad (2)$$

Next, on their basis, the relative elongation of the knitted fabric and fabric circumferences in a relaxed state are determined according to the equation:

$$Go_i = \frac{G_i}{\varepsilon + 1} \quad = \text{for i = 1, 2... n} \ (3)$$

After calculating the fabric circumferences in a relaxed state G_{0i}, the distances between the circumferences, fabric parameters and its mechanical characteristics in the form of the relation between force and elongation, it is possible to determine the number of needles *I*, the number of knitted courses between circumferences *R*, the number of narrowings/widenings *N,* and the number of courses between subsequent narrowings/widenings of the product *NR*.

A detailed calculation diagram of the above-mentioned parameters used to determine input data for the Stoll M1plus program in the production of seamless compression products is shown in ***Figure 9***. The input parameters for model calculations for gloves include the following: circumferences of the parts of the hand and forearm – G_i, the distance between the circumferences and base – Y_i, the intended pressure value –P_i, regression coefficient of the function of the force and relative elongation of the knitted fabric – *a*, *b* and *c*, the calculation accuracy factor of relative elongation – $\Delta\varepsilon$, and the maximum fabric elongation Coefficients and indicate the range within which the relative elongation is searched for. At the beginning this range is < 0, ε_{max} > (ε_{max} can be 1 or more), and it should

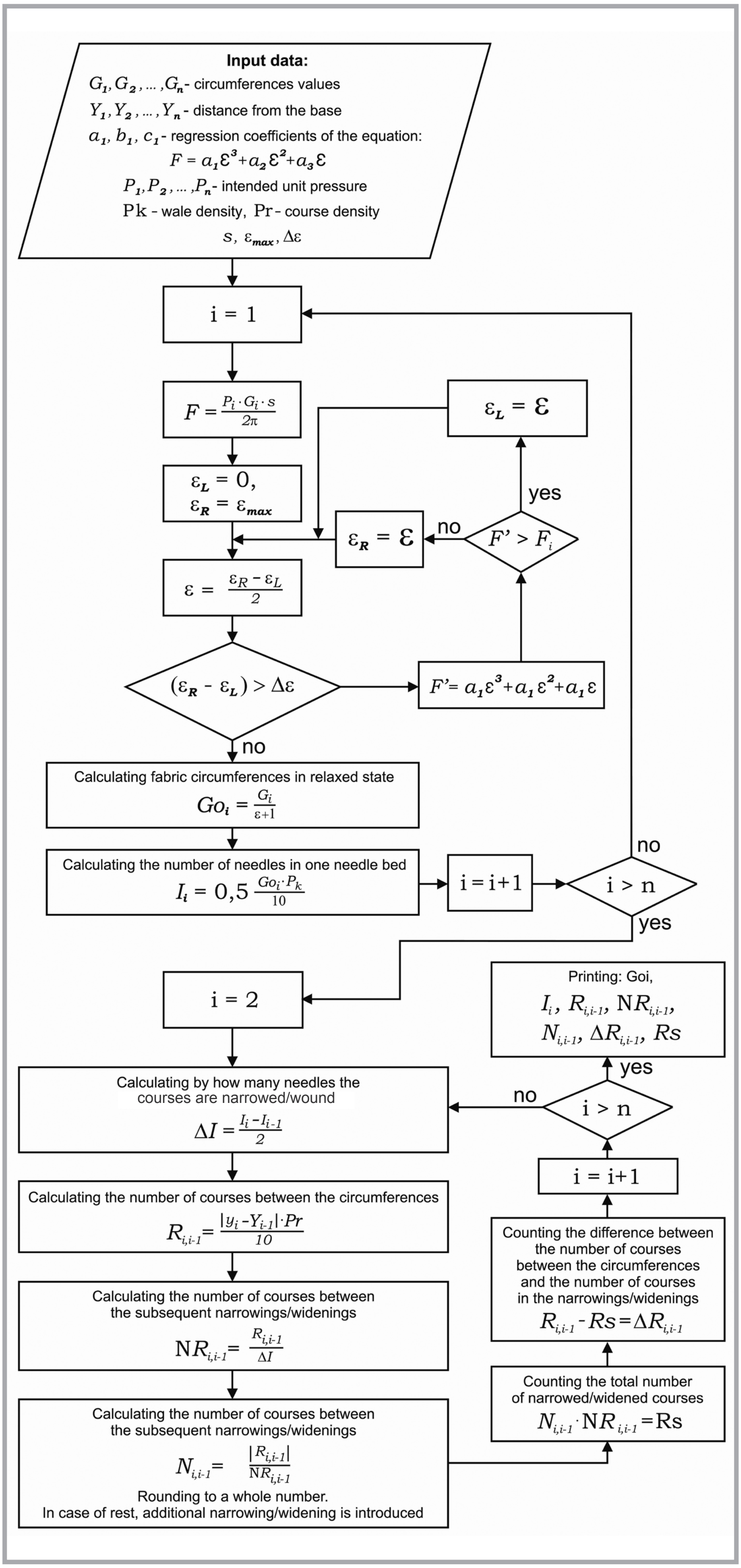

Figure 10. *Algorithm for determining input data for the Stoll M1plus program for the production of seamless compression products.*

correspond to the relative useful elongation of the knitted fabric. In the next steps the range is narrowed using a bisection method, by changing ε_L or ε_R, respectively. Since ε has to be determined with accuracy to the specified delta, the range is divided until its size is smaller than the delta. Finally the value of relative elongation ε is chosen from the middle of the range.

It should be noted that it is impossible to ensure the intended value of unit pressure for all hand zones. The geometry of the middle part of the hand deviates from the cylindrical model, which is why the intended value of unit pressure can only be obtained for the edges of the hand, where the radii of curvature are close to those of the curvature of the fingers' circumferences. This is of practical importance only when post-burn wounds are situated in this part of the hand. For the palm and back of the hand, the intended pressure value can be obtained by inserting layers of specific thickness made of medical foam, silicone patches or distance knitted fabrics

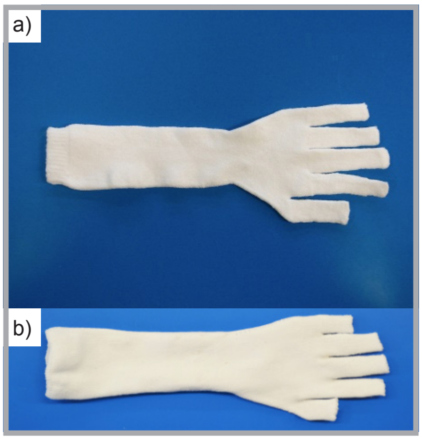

***Figure 11.** Examples of gloves made using seamless technology with a) covered and b)exposed fingers.*

***Figure 12.** Example of glove made using seamless technology with exposed fingers.*

***Table 1.** Input data of the algorithm for determining input parameters for the Stoll M1plus program for the example of hand and forearm (**Figure 2**).*

	a1	a2	a3	Pr	Pk	Eps Max	Delta Eps	n		
	97.284	**-161.41**	**118.41**	**245**	**144**	**3**	**0.001**	**30**		
	G_i cm	Y_i cm	P hpa	G_{0i} cm	I	R	NR	N	deltaR	Rs
Little finger	2.7	0	45	2.2	16					
	2.7	1.4	45	2.2	16	34		0	34	0
	3.1	2.4	45	2.4	18	24	24	1	0	24
	3.7	3.4	45	2.6	19	24		0	24	0
Ring finger	3	0	45	2.4	17					
	3	1.2	45	2.4	17	29		0	29	0
	3.6	2.8	45	2.7	19	39	39	1	0	39
	4.4	4.2	45	2.9	21	34	34	1	0	34
Middle finger	3.2	0	45	2.5	18					
	3.2	1.6	45	2.5	18	39		0	39	0
	3.7	3.1	45	2.7	19	37		0	37	0
	4.4	4.7	45	2.9	21	39	39	1	0	39
Index finger	2.8	0	45	2.3	16					
	2.8	1.3	45	2.3	16	32		0	32	0
	3.7	2.9	45	2.7	19	39	20	2	-1	40
	4.1	4.7	45	2.8	20	44		0	44	0
Thumb	3.9	0	45	2.8	20					
	3.9	1.6	45	2.8	20	39		0	39	0
	4.2	2.9	45	2.9	21	32		0	32	0
Middle part	11.8	0	2.5	11.3	82					
	11.8	2.1	2.5	11.3	82	51		0	51	0
Forearm	10.5	4.7	20	6.6	48	64	-4	-16	0	64
	9.9	6.7	20	6.5	47	49		0	49	0
	10.8	8.7	20	6.7	48	49		0	49	0
	11.7	10.7	20	6.9	49	49		0	49	0
	12.9	12.7	20	7.2	52	49	24	2	1	48
	14	14.7	20	7.5	54	49	49	1	0	49
	14.8	16.7	20	7.8	56	49	49	1	0	49
	15.3	18.7	20	7.9	57	49		0	49	0
	15.6	20.7	20	8	58	49		0	49	0

***Note:** G_i – lengths of subsequent circumferences, Y_i – distance from the base, a_1, a_2, a_3 – regression coefficients of the function of the force and relative elongation of the knitted fabric, Pr – course density, Pk – wale density, EpsMax – maximum relative elongation of the fabric, DeltaEps – accuracy of elongation calculations, G_0 – fabric circumference in a relaxed state, I – number of needles in one needle bed, R – number of courses between successive circumferences, NR – number of courses between subsequent narrowings/widenings, N – number of narrowings/widenings, deltaR – difference between the number of courses between the circumferences and the number of courses in the narrowings/widenings, Rs – total number of narrowed/widened courses.*

Experimental verification of unit pressure

Based on the functions obtained defining the relation between the force and relative elongation for the analysed fabric used for the glove and on Laplace's law, the lengths of the compression bands in a relaxed state G_0 were calculated, with the intended values of unit pressure $P = 20$ hPa, for a cylindrical body model with circumference $G_1 = 9{,}4 \div 15{,}7$ cm.

The unit pressure was measured using a PICOPRESS device by MICROLAB ELEKTRONICA, with measurement resolution 1 mmHg.

The differences between the intended values of unit pressure and those measured should be attributed to the manufacturing tolerance of the band, which equals 0,139 cm, and to the manual method of applying bands onto the cylinder, which does not ensure an even distribution of circumferential forces on the surface of the cylinders. The maximum percentage difference between the intended and measured value equals 5.6%.

Conslusions

1. The selection of proper longitudinal rigidity of knitted fabric is an important stage in the design procedure of seamless compression products for the following reasons:

  - the relation between the values of the finger circumferences and the circumference of the middle part of the hand
  - techniques for manufacturing products on numerically controlled flat knitting machines
  - dimensional tolerance of the product
  - physical and mechanical parameters of the knitted fabric.
2. The algorithm developed for determining input parameters for the program controlling flat knitting machines allows – after calculating the fabric circumferences in a relaxed state G_{0i} – to specify the number of needles I, the number of knitted courses between the circumferences R, the number of narrowings/widenings N, and the number of courses between subsequent narrowings/widenings in the product NR. These parameters are determined on the basis of data from the 3D scanner, including the circumferences G_i and distances Y_i of these circumferences from the base, dimensional parameters of the knitted fabric Pk and Pr, intended pressure value and regression coefficients of the relation between the force F and fabric elongation ε.
3. Experimental verification of the unit pressure for selected body circumferences confirmed the correctness of the procedure adopted for designing and manufacturing seamless products on numerically controlled flat knitting machines.

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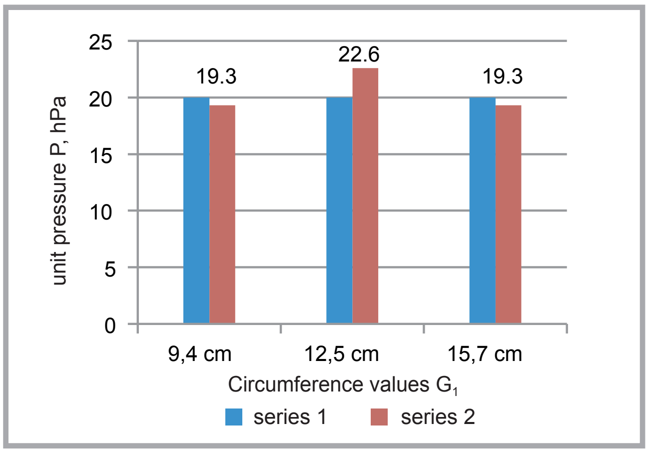
Figure 13. *Test results of unit pressure of compression bands on cylinder models with circumference* $G_1 = 9,4 \div 15,7$ *cm. Series 1 – Intended pressure value* $P = 20$ *hPa, Series 2 – pressure value measured.*



Acknowledgements

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