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Improving the consumer properties of compression knitwear with a given pressure based on modelling of nonlinear deformations

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Abstract. The article was devoted to the current problem of ensuring rational parameters of compression textile products, which affect the qualitative parameters of their functioning. The purpose of this work was to substantiate the pattern-making methods of compression clothing, taking into account individual features of the human body structure, anisotropy of materials, deviations from linear laws of deformation, and large deformations that have values similar to geometric dimensions. Discrete-continuous model was developed, which represented a conditionally continuous compression textile material in the form of cells, the elements of which have certain characteristics determined based on macro experiments. The individual geometry of the human body was determined by 3D scanning methods. The use of a structural model allowed the creation of a pattern that ensured a given pressure on the human body. The proposed approach allowed the creation of patterns of compression clothing to ensure a given pressure on the human body. The created discrete model for simulating textiles used additional structural elements, which allowed for taking into account the material's resistance to shear stress and the anisotropy of the textile material. The deviation from the linear law of deformation of the textile material was provided by the characteristics of the structural elements. Significant deformations of the product were taken into account with compiling the system of nonlinear equations. Experimental studies had proven the adequacy of the results obtained. The proposed model allowed for the first time to take into account all real effects during the deformation of textile materials, which ensured the adequacy of the results in the process of creating compression clothing. The obtained results allow the creation of compression textile products with specified pressure parameters along the length

Keywords: textile medical materials; compression textile; discrete model; pattern making; 3D surface

Introduction

There is a tendency in the world to increase research in the field of medical use of textile products as was shown by S. Grycuk & P. Mrozek (2023). Among such products, a special place was occupied by compression textile products that can be used both in medical and sports clothing. This fact was noted by C.S. Buset *et al.* (2021). O. Kyzymchuk *et al.* (2020) noted, that the creation of compression clothing should be based on ensuring the necessary pressure between the clothing and the human body. In particular, special measuring devices have been developed for this purpose, which controlled the real parameters of the interaction, although real recommendations for construction taking into account the elastic characteristics of textile materials were given in the study of C. Ho *et al.* (2024).

Study of K.M. Bourne *et al.* (2021) claimed a positive effect of compression garments in the treatment of translational orthostatic tachycardia. Real studies were conducted on the effect of compression in different places of the human body. Leveling of heart rate and blood

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pressure was noted. The study of M. Lozo *et al.* (2021) offered basic approaches to the design of compression products. An attempt was made to provide real pressure values. However, this study does not take into account the real mechanical characteristics of stocking materials. The article of L. Zhang *et al.* (2019) was devoted to the determination of pressure distribution during the process of compression clothing use. At the same time, loads of ready-made clothes were determined without proposals for the actual design of the products to ensure the necessary parameters. Quite high hopes for the prospects of using compression textiles, including in the design of smart clothes, can be placed on systems of intimate textiles. D.B. Datta & P. Seal (2022) noted that this type of clothing at the present moment was not only an element of functional necessity or style.

Modern requirements for intimate clothing include, first of all, hygienic properties, which, in particular, were largely provided using compression textiles. The compressive properties of these materials can additionally have an aesthetic role of improving the appearance of the human body figure using intelligent intimate clothing. Considering the problems of intimate clothing in some publications, the problems of breast support with bras were solved by L. Haworth *et al.* (2022). Moreover, this problem was considered both from a medical point of view and for aesthetic purposes. The use of incorrect structures affected several biomechanical reactions, worsed the condition, and affected well-being. The use of compression textile materials made it possible to create designs of smart clothes with adjustable compression and support.

The analysis of research on the problems of creating compression clothing indicated the need to implement design methods that were based on the real mechanical characteristics of materials, including taking into account anisotropy and nonlinear effects. An attempt at such modelling was made in the study of M. Riabchykov *et al.* (2024). Such methods weren't take into account the real structure of textile materials. So, geometric modelling wasn't fully ensured compliance with the real characteristics of materials.

The purpose of this study was to substantiate the improvement of consumer properties of compression clothing based on modelling real material properties.

Materials and Methods

Requirements for materials for compression products determined a complex of elastic, durable, hygienic properties. In this research, knitted fabrics with a content of 73% polyamide and 27% elastin were used. Specification of the fabric was done in Table 1.

Table 1. *Specification of the fabric used in investigations*

Specification	Meaning
Fabric structure	Warp knitted fabric
Content	73% polyamide and 27% elastin
Fabric mass (g/m^2)	98
Yarns density	5.5 tex. (50 denier)/24 filaments
Elasticity modulus in longitudinal direction, N/cm	11
Elasticity modulus in longitudinal direction, N/cm	4.3

Source: *developed by the author based on N. Kankariya (2022)*

The overpayment of the material (Fig. 1) provided the necessary elastic characteristics, in particular, the transformation of forced during stretching into pressure on the body. At the same time, the pressure parameters required from compression clothing were taken into account. These can be textile products of the first compression class (provide pressure from 2.4 kPa to 2.9 kPa), second class (pressure from 3 kPa to 4.3 kPa), third class (pressure from 4.4 kPa to 6 kPa) (Lee *et al*., 2020).

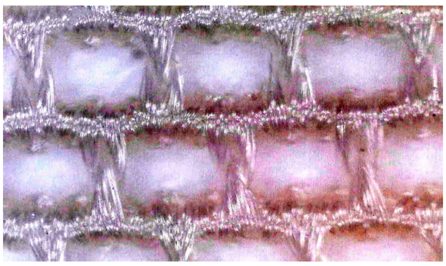

Figure 1. *Structure of compression textile material*

Source: *developed by the author*

The construction of a mathematical model was based on finite element approaches, which involved considering a conditionally continuous material as a complex of individual components. Such models more often used linear models, which weren't always take into account the effect of changing the real geometry of the textile material, as well as its real physical characteristics. Such model was developed by H.F. Siddique *et al.* (2022). Meanwhile, any data on textile materials showed a pronounced deviation from the linear relationship of elongation and load, which can significantly affect the construction of a real model (Fig. 2).

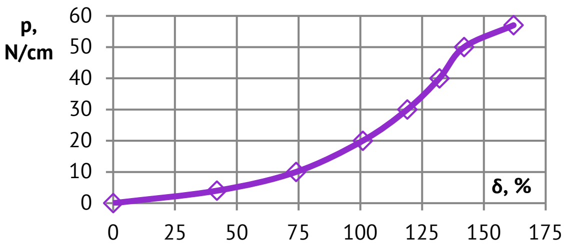

Figure 2. *The relationship between the specific force acting on the compression material, p, and its elongation, δ*

Source: *developed by the author based on H.F. Siddique et al. (2022)*

Deformations in different directions of the textile material caused different elastic forces, which made it necessary to take into account the effects of anisotropy. At the same time, standard characterisation experiments must be reorganised. The new approach should exclude marginal effects from the experiments and provide valid characteristics of the entire material (Fig. 3). This approach allowed to determine the elongation and narrowing of the material during testing it in two perpendicular directions. The main characteristics of the materials as a result of the experiment can be written in the form:

$$\begin{cases} p_x = K_{11}(\varepsilon_1 + \mu_{21} \cdot \varepsilon_2) \\ p_y = K_{22}(\mu_{12} \cdot \varepsilon_1 + \varepsilon_2), \end{cases} \quad (1)$$

where p_x, p_y – specific load per unit width of the material in the longitudinal and transverse directions, N/m; ε_1, ε_2 – relative deformation in the longitudinal and transverse directions; K_{11}, K_{12} – modules of elasticity for two directions; μ_{12}, μ_{21} – Poisson's ratios for two directions.

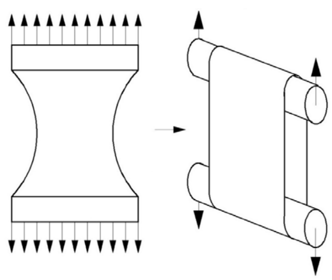

Figure 3. *Methods of determining the real characteristics of compression textile materials*

Source: *developed by the author*

The change in the geometry of the material cells indicated rather large deformations. As a rule, in models using finite element methods, the condition of small deformations was assumed. This fact, in particular, was implemented in the replacement of such trigonometric functions as sinus, and tangent with values of angles, which allowed for reducing the problem to a system of linear equations. Real compressions knitted materials in the process of deformation acquired noticeable deformations, which significantly affected the geometric characteristics of the cells (Fig. 4). At the same time, the rectangular cells significantly changed their geometry, which led to nonlinear dependencies.

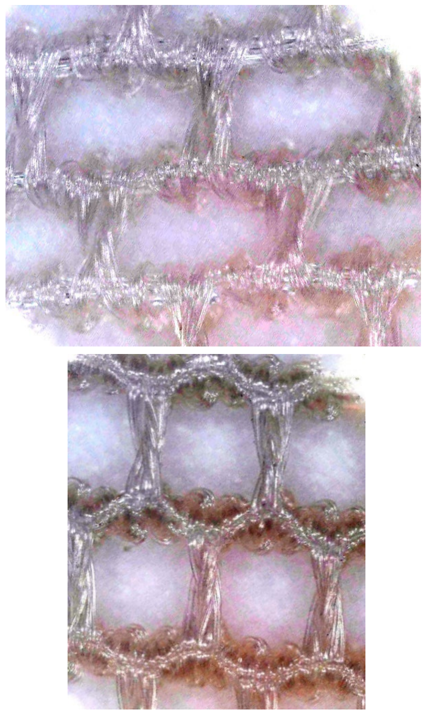

Figure 4. *Deformation of the compression material in the longitudinal and transverse directions*

Source: *developed by the author*

These facts demonstrated the need to improve existing models in the direction of taking into account their real structural, geometric, and physical characteristics. The main requirement, in this case, was to ensure the necessary pressure of compression clothing. It was desirable to take this requirement into account at the stage of pattern making, bearing in mind the real physical and geometric parameters of compression textile materials. At the same time, as mentioned by W. Xi *et al.* (2020), constant pressure over the entire surface of the compression product may be required, as well as variable pressure to help the body to move blood properly. Together with the constructed deformation model and real pattern-making methods, experiments were used by M. Riabchykov *et al.* (2023) to determine the pressure between the human body and compression clothing to assess the adequacy of the developed methods. Body-garment pressure measurements using pressure sensors provided the full range of data-predicted values required of compression garments.

Mathematical modelling methods allowed determining the deformations of compression clothing elements under conditions of nonlinear physical and geometric processes. This led to the need to solve systems of nonlinear equations. Iteration methods were used to solve them. As a first approximation, solutions of a linear problem for a square cell were chosen.

Results and Discussion

It worth to start with the real problem of designing compression medical clothes to provide constant pressure for an individual case. The real structure of the compression textile material (Fig. 1) showed undoubted discreteness. This confirmed the possibility of creating a model in the form of discrete elements with the possibility of determining real deformations.

A deeper analysis, meanwhile, demonstrated certain limitations of using a direct geometric interpretation in the form of rectangular cells with a hinged combination (Fig. 5, a). At the same time, the stiffness parameters of elements 1 and 2 should be chosen based on the real characteristics of the material. Such a model cannot take into account the behaviour of the material in the case of complex loading, in particular, the resistance of the material to shear deformations.

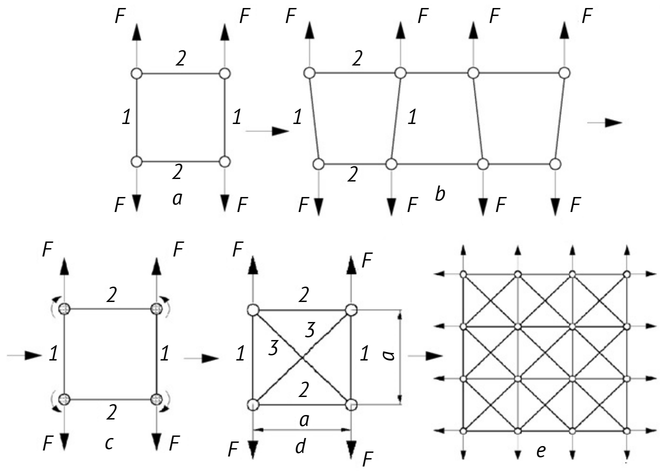

Figure 5. *A discrete model of compression textile material*

Note: *a – rectangular cells with a hinged combination; b – trapezoid element; c – replacement od hinged models with the ability to perceive moments; d – diagonal element conditionally added to the cells; e – replacement of textile material with a system of cells*
Source: *developed by the author*

The ability to catch shear deformations can be taken into account by changing the geometry of the cells, for example by changing the shape of a rectangle to a trapezoid (Fig. 5, b). Such a proposal excluded the unification of elements and complicated the consideration of geometric characteristics. Another way to take into account the shift factor can be to replace hinged models with the ability to perceive moments (Fig. 5, c). Such a scheme corresponded most closely to the real structure of the material, but it required taking into account additional components, when determining deformations and adding unknowns during mathematical modelling. As a result, the complexity of calculations increased significantly. In this study, an artificial step was proposed. To take into account the possibilities of displacement, element 3 was conditionally added to the cells, which ensured the perception of arbitrary deformations. At the same time, the compression textile material was replaced by a system of cells (Fig. 5, e). At the same time, the real characteristics of cell elements were determined from real macro-experiments for textile materials.

The first step in creating the model was the case of a linear isotropic material that has the same elastic characteristics in all directions. The modelling condition should be to ensure the same characteristics for the macro experiments and the calculated discrete model. In the case of an isotropic structure, such requirements lead to the conditions for determining the stiffness indicators of structural elements:

$$g1 = g2 = \frac{\sqrt{2} \cdot E \cdot a}{1+\mu};$$
$$g3 = \frac{\sqrt{2}\mu \cdot E \cdot a}{1-\mu^2}, \qquad (2)$$

where E – modulus of elasticity; μ – Poisson's ratio; a – sell dimension; $g1$ – stiffness of horizontal element; $g2$ – stiffness of horizontal element; $g3$ – stiffness of diagonal element.

The structure for simulating anisotropy replaces square cells with rectangular ones as shown in Figure 6.

Anisotropy will be provided by the correct choice of the ratio of longitudinal and transverse elements. Taking into account the data of the experiments according to the scheme of Figure 3, the diagonal angle of the rectangular element, which provided the necessary anisotropy indicators, should be determined from the condition:

$$tg\alpha = \frac{0{,}77-0{,}35\cdot\mu_{12}+0{,}35\cdot\mu_{21}-0{,}2\cdot\mu_{12}\cdot\mu_{21}}{\varsigma^{0{,}4+0{,}1\cdot\mu_{12}+0{,}9\cdot\mu_{12}\cdot\mu_{21}}}. \qquad (3)$$

The formula defined μ_{12} – Poisson's (compression) ratio in the transverse direction stretched in the longitudinal direction; μ_{21} – Poisson's ratio in the longitudinal direction stretched in the transverse direction; $\varsigma = E1/E2$, $E1$ – modulus of elasticity in the longitudinal direction; $E2$ – modulus of elasticity in the transverse direction.

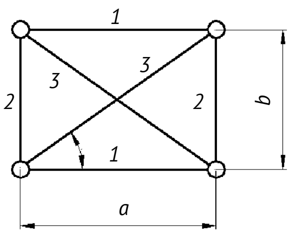

Figure 6. *Rectangular element for modelling anisotropic structure*

Note: *1 – longitudinal member; 2 – transverse member; 3 – diagonal member; a – longitudinal member length; b – transverse member length*
Source: *developed by the author*

The physical characteristics of the stiffness of the elements were determined based on real experimental data. The proposed structure can take into account the effects of geometric nonlinearity. In the case of deformations, the values of which were comparable to the cell sizes, the equilibrium equations must take this fact into account. The rationale for the methods of determining nonlinear effects was shown in Figure 7. At the same time, the cell acquired longitudinal Δx and Δy transverse deformations, the magnitudes of which were comparable to the cell sizes. The angle of inclination of the diagonal varies significantly and this must be taken into account, when constructing the equilibrium equations.

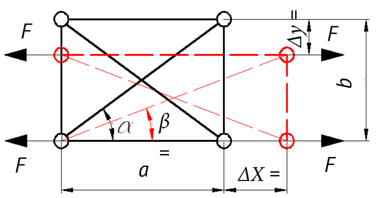

Figure 7. *Taking into account the effects of geometric nonlinearity*

Note: *a – longitudinal member length; b – transverse member length; F – strength in the element*
Source: *developed by the author*

For this case, the force-dependent deformations were determined by a system of nonlinear equations based on the methods that have been developed and were indicated as used in this study:

$$\begin{cases} \Delta x = \dfrac{F}{g1} - \dfrac{g3}{g1}\dfrac{\sqrt{(a+\Delta x)^2+(b-\Delta y)^2}-\sqrt{a^2+b^2}}{\sqrt{1+\left(\frac{a+\Delta x}{b-\Delta y}\right)^2}} \\ \Delta y = \dfrac{g3}{g2}\dfrac{\sqrt{(a+\Delta x)^2+(b-\Delta y)^2}-\sqrt{a^2+b^2}}{\sqrt{1+\left(\frac{b-\Delta y}{a+\Delta x}\right)^2}}, \end{cases} \qquad (4)$$

where a – longitudinal size of the cell; b – transverse size; $g1$, $g2$, $g3$ – stiffness parameters determined by formula (2).

This formula allowed, based on iterative approaches, to determine the real deformations of elements along the abscissa axis Δx, and along the ordinate axis Δy of compression clothing under the action of load F. It can be seen from the system that the values of the deformations depending on the applied forces were from both parts of the equation in the transcendental form. The real deformations for this case were determined by solving these equations using the iteration method.

To achieve the greatest effect, compression clothing should provide individual characteristics of a person (Richards *et al.*, 2020). The real geometric characteristics of the body element can be obtained by 3D scanning methods (Fig. 8, a). The resulting digital model allowed to determine the coordinates of individual points of clothing elements, in particular, the structure in the form of separate sections (Fig. 8, b).

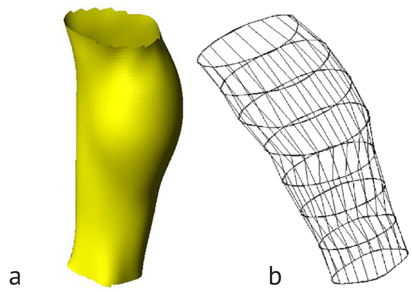

Figure 8. *3D surface for designing compression clothing*

Note: *a – real geometric characteristics of the body element; b – digital model of the body element*
Source: *developed by the author*

Determining the lengths of the cross-section lines and taking into account the distances between them allowed the creation of the scan of the surface of an element of the human body. At the same time, linear models of deformation allowed for determining negative allowances during pattern creation. The task was to build a pattern of compression clothing that provided the necessary pressure, taking into account the real physical characteristics of materials and real nonlinear characteristics of deformations. Such a problem can be solved within the framework of the proposed model. At the same time, the forces in the elements of the cells were transformed into the effect of pressure as shown in Figure 9. The initial sizes of the material cells were increased to the size of the human body in a separate section. Efforts were determined based on equilibrium equations taking into account nonlinear physical and geometric effects. Efforts were listed in the pressure parameter. If the pressure parameters wasn't match the required values, corrections were made to the geometry of the proposed structure.

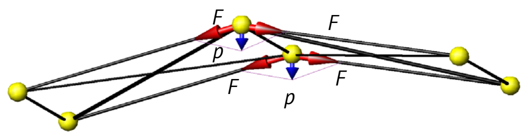

Figure 9. *Dependence of pressure on forces in the cells*

Note: *F – force in the element; p – pressure on the limb*
Source: *developed by the author*

The proposed technique was tested for the task of ensuring constant pressure over the entire surface. The results of building patterns for such conditions were shown in Figure 10. At the same time, the figure showed the difference between the initial sweeps of the surface of the body element, the proposed pattern on the base of the linear arrangement, and the required geometry taking into account nonlinear and anisotropic effects.

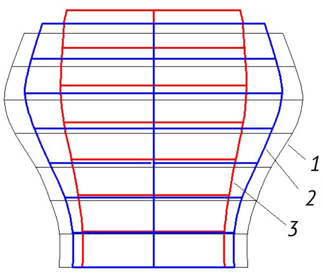

Figure 10. *Patterns to ensure constant pressure of compression clothing*

Note: *1 – stretching of the surface of the limb; 2 – the required geometry of the knitted fabric based on the linear arrangement; 3 – the required geometry of the knitted fabric taking into account nonlinear and anisotropic effects*
Source: *developed by the author*

These results determined the necessary geometric parameters of compression clothing, which provided the necessary pressure for an individual consumer. The requirements of the variable pressure length can be taken into account by the corresponding changes as a result of calculations according to the proposed model. The experiment used a conical rubber element 1, which imitated an element of the human body (Fig. 11). Compression product 2, designed according to the developed methods, was put on the conical element. Wires to pressure sensors 3, which were located on the surface of the rubber element, were passed through the holes in the rubber element. Eight sensors were located evenly around the circle in two cross-sections. For the pressure measurement sensor with limits up to 10 kPa was used in experiments. Pressure-sensing elements based on piezo resistive effect had sensitivity ±0.07 kPa^{-1}.

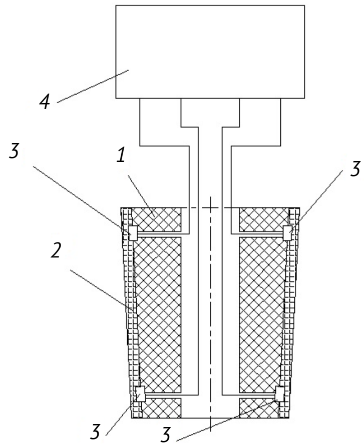

Figure 11. *Experimental studies of compression clothing*

Note: *1 – rubber element; 2 – compression product; 3 – pressure sensors; 4 – measuring console*
Source: *developed by the author*

The developed pattern according to the conical shape of the element imitating the limb of the body was made of compression material. Pressure values were taken from eight elements. After that, the compression textile was removed and unloading was carried out. The process was repeated four times, thus thirty-two pressure readings were obtained. The average value, variance, and root mean square deviation was determined. A total of three samples of compression garments were produced to provide different levels of pressure. The values obtained as a result of using the theoretical model, as well as the experimental data were given in Table 2.

Table 2. *Obtained pressure parameters for different samples of compression clothing*

Sample number	Theoretical pressure value, kPa	The average value of experimental data, kPa	Root mean square deviation, kPa	Real pressure values, kPa
1	2.8	2.97	0.08	from 2.73 to 3.21
2	3.6	3.86	0.11	from 3.53 to 4.19
3	4.5	4.64	0.13	from 4.25 to 5.03

Source: *developed by the author*

The results of the study proved the adequacy of the obtained calculation models and the possibility of their use in the processes of real pattern-making of elements of compression clothing. This study provided new results that can improve the consumer characteristics of compression garments. Comparison with known results demonstrated certain advantages of the proposed approaches and methods. It was possible to note the insufficient level of scientific substantiation of the parameters of compression clothing, taking into account the real values of the mechanical characteristics. The study of J. Lee & W. Do (2023) attempted numerical modelling of elastic clothing using the finite element method. In this study, an analysis of the influence of different pressure levels during wearing compression clothing was carried out. In contrast to this study, the proposed approaches allowed to take into account the effects of geometric and physical nonlinearity, which increased the accuracy of the modelling.

The structural-rod model of the textile material was developed in study of T. Yelina *et al.* (2022). Analysis of the proposed structure proved the possibility of its use in limited cases. Taking into account nonlinear and anisotropic properties in such a model caused great complications. This study used more precise approaches, which allowed for improved product characteristics. Attempts to take into account the anisotropic properties of textile materials were demonstrated in article of D. Wijesinghe & B.J. Roth (2022). In contrast to the results obtained in this study, these works weren't provide clear answers to the question of the correctness of using data from macro experiments to determine the mechanical characteristics of textile materials.

As noted by A. Tomaszewska & D. Reznikov (2025) attempts to analytically model the behaviour of textile materials in models of continuous environments can provide only separate solutions; they were quite difficult to apply to real problems. Modelling of structural and mechanical characteristics of knitted networks, taking into account morphological operations, was substantiated in the study of X. Li *et al.* (2022). The prospects for the development of such models were related to their connection to ensuring the mechanical characteristics of real textile products. Z. Jing & Z.M. Hua (2021) emphasised that the proposed models can be extended to design real clothing elements. Existing models of the mathematical design of clothing imply only geometric solutions without significant consideration of mechanical properties and deformations of textile materials, which were necessarily required in the design of compression textile products. The problems of real pattern computation taking into account mechanical and geometric parameters were solved in the study of W. Long *et al.* (2021). Researchers M. Riabchykov *et al.* (2023) developed a mathematical model of the surface with the determination of triangulation parameters and established that the accuracy of creating unfolding for further pattern making depends on the direction and number of geometric elements. In the context of medical research on bone prosthetics, the authors O. Zubkov & V. Torchynskyi (2024) noted the use of medical materials made of plastic. Overall, researchers noted that the use of such materials was reliable and durable. Real methods of designing a compression beam required consideration of nonlinear deformations, which weren't provided by the proposed methods. The real result of this study was developing methods for designing compression products to ensure a given pressure, taking into account anisotropy and nonlinear deformation effects.

Conclusions

This study provided a comprehensive approach to improving the design of compression clothing by integrating advanced modelling techniques that accounted for the real mechanical characteristics of textile materials. A significant contribution of this research lay in the development of a model that considered the anisotropic and nonlinear deformation properties of compression fabrics, addressing gaps in previous studies that primarily relied on simplified geometric or linear models.

By incorporating finite element methods and discrete structural modelling, the study successfully refined the accuracy of pressure distribution predictions in compression garments. Experimental validation using pressure sensors confirmed the reliability of the proposed model, demonstrating its applicability in real-world pattern-making for medical and athletic compression wear. The findings highlighted the necessity of tailoring compression clothing to individual anatomical characteristics, emphasising the role of 3D scanning in achieving a precise fit and optimal pressure distribution.

This study bridged the gap between theoretical modelling and practical garment design by integrating real material behaviours into the construction process. The ability to accurately simulate the effects of geometric deformations on pressure distribution allowed for the creation of garments that provided the necessary support, while maintaining comfort and functionality. The developed methodology has broad implications for both medical and sports applications, offering a pathway toward more effective, customised compression wear.

Future research could further refine these models by incorporating additional biomechanical factors, such as dynamic movement analysis, to enhance the adaptability of compression garments in varying conditions. The results of this study paved the way for innovations in smart textile applications, where compression clothing can be designed with embedded sensors to provide real-time physiological feedback for medical and performance-enhancing purposes.

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Conflict of Interest

None.

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Покращення споживних властивостей компресійного трикотажу із заданим тиском на основі моделювання нелінійних деформацій

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Анотація. Стаття присвячена актуальній проблемі забезпечення раціональних параметрів компресійних текстильних виробів, які впливають на якісні характеристики їх функціонування. Метою даної роботи було обґрунтування методів конструювання компресійного одягу з урахуванням індивідуальних особливостей будови тіла людини, анізотропії матеріалів, відхилень від лінійних законів деформації та великих деформацій, значення яких є порівняними з геометричними розмірами. Було розроблено дискретно-неперервну модель, яка представляє умовно неперервний компресійний текстильний матеріал у вигляді комірок, елементи яких мають певні характеристики, визначені на основі макроекспериментів. Індивідуальна геометрія тіла людини визначалася методами 3D-сканування. Використання структурної моделі дозволило створити лекало, що забезпечує заданий тиск на тіло людини. Запропонований підхід дозволив створювати викрійки компресійного одягу з урахуванням заданого тиску на тіло людини. Створена дискретна модель для моделювання текстилю використовувала додаткові структурні елементи, які дозволили враховувати опір матеріалу до зсувних напружень та анізотропію текстильного матеріалу. Відхилення від лінійного закону деформації текстильного матеріалу забезпечувалося характеристиками структурних елементів. Значні деформації виробу враховувалися при складанні системи нелінійних рівнянь. Експериментальні дослідження підтвердили адекватність отриманих результатів. Запропонована модель вперше дозволила врахувати всі реальні ефекти при деформації текстильних матеріалів, що забезпечило адекватність результатів у процесі створення компресійного одягу. Отримані результати дозволяють створювати компресійні текстильні вироби із заданими параметрами тиску вздовж довжини

Ключові слова: медичні текстильні матеріали; компресійний текстиль; дискретна модель; конструювання лекал; 3D-поверхня