UDC 687.055.004.94:621.98
DOI: 10.15587/2706-5448.2025.327068

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DEVELOPMENT OF TEXTILE STRUCTURES USING 3D PROTOTYPING TECHNOLOGIES

The object of the research is pseudotextile mesh structures with three-dimensional hinged joints, manufactured by 3D prototyping methods. One of the main tasks in the field of 3D printing of textile materials is to ensure their flexibility, elasticity and adaptability to the shape of the human body. Materials produced by traditional 3D printing methods have high rigidity, which limits their application in the light industry. During the study, a concept for creating pseudotextile materials based on flexible network structures using spherical three-dimensional hinges was developed. The proposed structure allows for achieve the necessary flexibility and deformation capabilities characteristic of traditional textile materials. Modeling and experimental samples demonstrated that structures with three-layer hinged joints provide spatial variability of shape, while the use of eccentricity in the hinges allows to adjust the rigidity of the structures. The obtained results can be attributed to the use of three-level spherical hinge joints, which provide spatial mobility of individual elements of the structure, as well as numerical modeling to optimize the sizes of structural elements. The implemented models confirm that the mechanical properties of the synthesized structures can be controlled by changing their geometry. The developed structures can be utilized in the clothing production where high flexibility of the material is required, as well as in the creation of adaptive textile products for medical purposes, in particular for compression therapy or automated massage. Additionally, such materials can be used in the decorative design of fashion products.

Keywords: *3D prototyping, textile structures, additive manufacturing, spherical joints, pseudotextiles. material flexibility.*

Received: 19.01.2025
Received in revised form: 14.03.2025
Accepted: 05.04.2025
Published: 17.04.2025

How to cite
Mytsa, V., Riabchykov, M., Popova, T., Nikulina, A. (2025). Development of textile structures using 3D prototyping technologies. Technology Audit and Production Reserves, 2 (3 (82)), 18–23. https://doi.org/10.15587/2706-5448.2025.327068

1. Introduction

Digital technologies are actively penetrating all spheres of life, including garment manufacturing, where intensive implementation of innovations related to digitalization is observed. Digital methods in the sewing industry include three-dimensional measurement technologies [1], automated garment design tools [2], and the digitalization of production organization processes [3]. The set of digital solutions analyzed in studies [4, 5] contributes to the development of effective algorithms for designing garments with specified functional and aesthetic characteristics.

One of the key areas of digitalization in manufacturing is the use of rapid prototyping methods, which are implemented through 3D printing [6, 7]. Despite the significant potential of 3D printing in the light industry, its widespread adoption is limited by the requirements for the physico-mechanical and operational properties of materials. The first successful developments in this area have emerged in footwear manufacturing, where 3D printing is used to create individual structural components [8].

In garment production, 3D prototyping technologies are primarily applied to the manufacturing of sewing accessories [9, 10], as their mechanical characteristics do not require excessively high levels of flexibility, elasticity, and wear resistance, which are critical for textile materials.

According to [11], 3D printing technologies in garment manufacturing are still at an early stage of development and are significantly constrained by the properties of the materials used in the sewing industry.

At the same time, a number of researchers highlight the potential for creating textile products using 3D printing [12, 13]. A particularly promising direction is the development of printed textile structures aimed at supporting the mobility of individuals with disabilities [14]. The study [15] examines the application of 3D printing for producing elements of specialized clothing, particularly lumbar support garments. Research presented in [16] focuses on the analysis of three-dimensional effects in the process of developing compression garments.

The development of textile structures utilizing 3D printing technologies, as presented in various publications, remains exploratory in nature and is currently at the stage of experimental research.

One of the key directions in this field is the integration of different fiber types into the 3D printing process. In particular, study [17] describes the application of fused deposition modeling (FDM) technology for the fabrication of textile materials using 3D printers, opening new perspectives for the development of functional clothing.

3D printing technologies enable the direct integration of smart elements into garments [18] and the creation of smart textile systems [19]. Study [20] examines the mechanical properties of various materials intended for 3D-printed textile structures, while the process of fiber formation, similar to natural fibers, using 3D prototyping is described in [21].

The deposition of printed materials onto textile substrates, investigated in [22], allows the fabrication of printed textile structures based on traditional fibers. The adhesive properties of materials during 3D prototyping in interaction with textile materials are analyzed in [23].

An optimization model for forming woven-like textile structures is presented in [24]. Study [25] proposes specialized structures that mimic the properties of textile materials, demonstrating significant similarity to woven fabrics.

The challenges associated with 3D printing of fibers and other flexible structures are explored in [26]. Additionally, study [27] analyzes various 3D-printed structures capable of altering the draping properties of textile materials.

Several studies [28] have attempted the direct fabrication of garments based on 3D scanning; however, the compliance of the obtained characteristics with real-world performance requirements has not been demonstrated. Study [29] discusses a methodology for forming textile structures using 3D scanning and 3D tomography.

The work in [30] demonstrates the possibility of creating printed three-dimensional textile structures with enhanced properties. Methods for decomposing continuous textile structures into substructures with varying curvature were developed based on research [31].

Examples of spatial rod-like structures are well known in mechanical engineering and are described in detail in [32]. Study [33] proposes an approach for developing three-dimensional mechanical structures using spherical joint connections.

The analysis of existing research reveals discrepancies between the potential capabilities of 3D printing technologies, the significant differences in the properties of printed materials compared to traditional textile structures, and the necessity to develop constructions that meet the requirements of garment manufacturing.

The aim of this research is to justify the methods of synthesizing three-dimensional textile structures with variable stiffness using 3D prototyping technologies.

2. Materials and Methods

For the modeling of textile structures in the 3D printing process, materials widely used in additive manufacturing were selected. The most common plastic, PET, was utilized in prototype samples due to its high rigidity and served as a reference material for comparative experiments. Elastan, characterized by its increased elasticity, was found to be suitable for 3D printing of flexible elements. The most elastic material used was FilaFlex, which has a density of 1215 kg/m^3 and an elongation at break of up to 700 %, significantly exceeding the performance of traditional textile materials.

For the three-dimensional modeling of textile structures, solid modeling software such as SolidWorks and AutoCAD was employed. MeshLab was used for geometry correction and conversion into formats compatible with 3D printing.

The 3D prototyping process was carried out using a Great Boot EE 3D printer with a 0.2 mm nozzle diameter and a minimum extrusion thickness of 0.1 mm. Printing was controlled by CreanWare 7.0.1 software, based on Slic3r, with settings adjusted to achieve a minimum extrusion size of 0.1 mm.

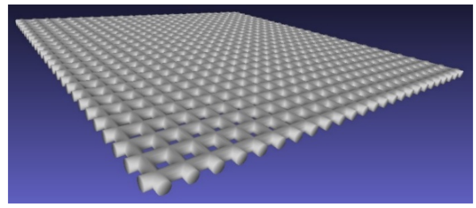
The structural parameters of the fabricated textile materials were determined using optical photogrammetry. The obtained materials were analyzed based on rigidity and air permeability. Air permeability was measured according to ISO 9073:15 under conditions of constant pressure differential. The air permeability range varied from 3 to 3000 cubic decimeters per minute (dm^3/(m^2·min)) at a pressure difference of 200 Pa.

During the creation of flexible pseudo-textile structures, methods from the theory of mechanisms were applied, taking into account the characteristics of spherical joints. Spatial bending of the structure was analyzed using coordinate system rotation matrices in the classical Euler form, with partial application of quaternion theory.

3. Results and Discussion

3.1. Creation of regular solid textile structures

The first stage of simulating regular textile structures involved modeling mesh constructions composed of cylindrical elements intersecting at right angles. Models were created with cylindrical elements of 0.2, 0.5, 0.8, and 1 mm in diameter (Fig. 1, *a*), as well as trapezoidal elements of similar dimensions but with varying aspect ratios (Fig. 1, *b*).



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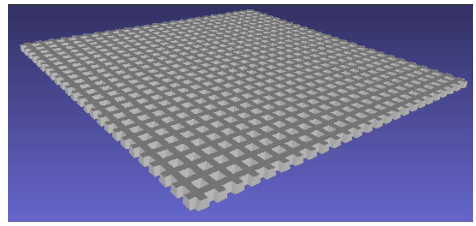


b

Fig. 1. Regular textile structures obtained through 3D prototyping: *a* – with circular cross-section structural elements; *b* – with trapezoidal cross-section structural elements

The fabricated textile structures do not fully meet the fundamental requirements for materials used in the light industry. At small diameters (0.2–0.3 mm), the resulting constructions exhibit high flexibility and can easily change shape and size, but they lack elasticity. Draping effects are not observed in these structures.

Increasing the thickness of the elements within the structure leads to a significant increase in stiffness and, consequently, a decrease in flexibility. According to the fundamental principles of elasticity theory, the deformation of elastic elements decreases in proportion to the moment of inertia of the cross-section of the rod-like element. For cylindrical elements, the moment of inertia is proportional to the fourth power of their diameter. Thus, for optimal textile structure imitation, the thickness of elements should be minimized.

Another significant drawback of such structures is the presence of rigid connections at nodal points, which significantly increase the overall stiffness of the system and prevent individual elements from freely deforming relative to one another.

At the same time, the designed structures can be optimized for air permeability, which is determined by the size, shape of structural elements, and the distance between them.

The study of air permeability in the obtained structures showed that the optimal airflow conditions are achieved when using trapezoidal structural elements. The orientation of the trapezoidal base relative to the direction of airflow is a crucial factor. Under conditions of equal cross-sectional area for both cylindrical and trapezoidal elements, and at constant spacing between them, it was found that positioning the trapezoid with its shorter side facing the airflow increases air permeability. For a trapezoidal aspect ratio of 1.4–1.6, an increase in air permeability of 22–26 % was observed. Conversely, when the larger side was facing the airflow, a decrease in air permeability of 16–18 % was recorded.

The density of structural elements also plays a critical role in determining air permeability characteristics.

The obtained results suggest that such structures can be recommended for use in decorative elements of clothing, as well as in ventilation inserts in garment areas requiring a certain level of air permeability.

3.2. Modeling of flexible thread-like structures using hinged connections

The results of the study on continuous network structures obtained through 3D printing revealed significant differences in mechanical properties, even for materials with high elasticity. The primary drawback of such structures is their inability to maintain shape when conforming to a surface. This limitation is critical for textile materials, which must adapt to the body's contours in garment manufacturing.

Structures produced through standard 3D printing methods exhibit predominantly elastic properties, meaning that after deformation, they return to their original shape and size. However, achieving the required flexibility solely through material selection has proven to be impossible.

At the same time, 3D printing presents a promising opportunity to create objects of arbitrary geometry and convert continuous structures into complex composite forms. In such cases, a traditional continuous structure must be transformed into a hinged structure, connected in the form of a chain.

The foundation of a flexible linear system can be a cylindrical hinge, as shown in Fig. 1, *a*. This construction connects two adjacent links and allows their mutual rotation. A long flexible object must exhibit continuity. To achieve a continuous flexible structure, the hinge of one link must serve as an extension of the hinge of the adjacent link. This requirement is met by the link presented in Fig. 2, *b*. It consists of: a cylindrical inner element 1 that freely fits into the opening of the shaped hinge ring 2: a connecting rod 3, which forms the link.

The length of the connecting rod determines the overall structural flexibility, while its cross-sectional diameter influences the linear density of the flexible structure. The hinged links, when connected, form a flexible chain, capable of imitating a textile thread-like element (Fig. 2, *c*).

Fig. 2, *d* presents the real structures fabricated using a 3D printer.

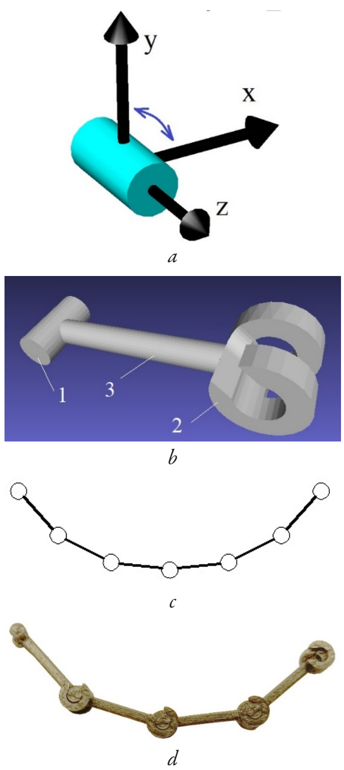


Fig. 2. Linear flexible structure fabricated using 3D prototyping methods: *a* – a cylindrical hinge; *b* – single link of the structure; *c* – flexible circuit diagram; *d* – the real structures fabricated using a 3D printer

The properties of the obtained structures correspond to those of flexible threads. In particular, under conditions of free suspension, such a structure forms a catenary curve. When the distance between the ends of the chain-like structure is *l*, it assumes the shape of a curve under its own weight, which is described by the corresponding mathematical function:

$$y=\frac{l}{2}\left(e^{x/l}+e^{-x/l}\right). \quad (1)$$

In the case of modeling flexible linear elements with inherent stiffness, the synthesized structure can simulate stiffness parameters by generating frictional forces in hinge joints. Specifically, in stiffness elements, the bending moment acting on the flexible element is proportional to its bending angle, with the proportionality coefficient determining the structural stiffness level.

When modeling a flexible structure in the form of a chain of hinge-connected elements manufactured using 3D prototyping methods, this dependency can be achieved by introducing an eccentricity of the inner cylinder *1* (Fig. 2, *b*). The eccentricity is incorporated directly during the 3D printing process. As the elements rotate with the specified eccentricity, the frictional moment increases proportionally to its magnitude, ensuring a linear dependence on the rotation angle.

3.3. Modeling networked textile surfaces using spherical three-dimensional hinges

The structure described in the previous section exhibits linear properties and cannot fully replicate textile materials suitable for garment manufacturing. Cylindrical hinges enable element bending only within a single plane, thereby limiting their capacity for spatial deformation. In contrast, spherical hinge joints allow individual elements to freely rotate and adjust their positions in three dimensions within predefined constraints.

The objective of the modeling process is to create a complex surface structure by integrating multiple elements into a unified system. To connect three adjacent elements at a single node, a triple spherical hinge was synthesized (Fig. 3, *a*). This mechanism consists of an inner sphere linked to the first rod element. The inner sphere is enclosed by an intermediate spherical component, which is connected to the second rod element. An outer sphere encapsulates the intermediate one and is linked to the third rod element.

The proposed three-level spherical hinge enables the mutual movement of three rod elements, thereby mimicking the multidimensional deformation capabilities of textile materials. Implementing a fourth-level hinge connection is significantly more complex, as additional levels may intersect, complicating the structure's functionality.

Further refinement of this structure can be achieved by expanding it through the attachment of additional elements with spherical hinges. However, connecting elements into triangular configurations is inefficient, as triangular structures are rigid and do not provide the necessary flexibility. Instead, combining four elements through spherical hinges enables the formation of flexible strips consisting of two parallel lines. To transform such strips into a continuous spatial structure, additional hinge connections must be incorporated at the corresponding nodal points.

The proposed structure can be schematically represented in Fig. 3, *b*. The first structural element (Fig. 3, *c*) features spherical components *1* at its ends, which serve as the internal elements of the three-level spherical hinge. In its central part, this element contains an additional sphere *2* that forms the inner part of a two-level spherical hinge. The core of the construction is a rod *3*, which defines the material's future structure.

The middle structural element (Fig. 3, *d*) has two hollow spheres *4* at its ends, specially designed with an elastic shape to function as the intermediate elements of the three-level hinge. The inner surface of these spheres has a contoured shape for connection with the inner sphere *1*, while the outer surface is designed to interact with the external part of the three-level hinge *5*.

The outer structural element (Fig. 3, *e*) features two hollow spheres *5* at its ends, which complete the three-level hinge. In the central part of this element, an additional sphere *6* is located, contributing to the formation of the two-level spherical hinge.

Together, the three rod elements – inner, middle, and outer – along with the three-level spherical hinge system, form a ribbon-like dual-line flexible structure. To integrate such ribbons into a single three-dimensional surface, additional connecting elements are used (Fig. 3, *f*). These connecting elements can be manufactured as separate components via 3D prototyping or directly integrated into a unified structure to achieve the desired geometric shape of the flexible surface.

The overall structure of the pseudo-textile material synthesized using the described methodology is shown in Fig. 3, *g*. Experimental samples produced using a 3D printer (Fig. 3, *h*) confirmed the viability of the proposed structure and demonstrated a high degree of elasticity during deformation.

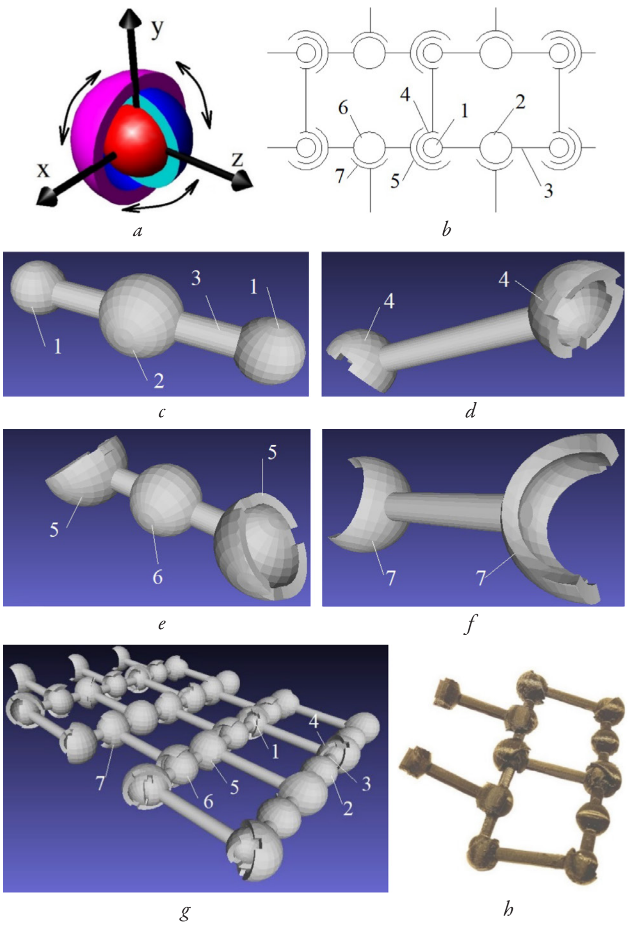


Fig. 3. Spatial textile structure created using 3D prototyping methods: *a* – a triple spherical hinge; *b* – diagram of the structure; *c* – the first structural element; *d* – the middle structural element; *e* – the outer structural element; *f* – additional connecting elements; *g* – the overall structure of the pseudo-textile material; *h* – experimental samples produced using a 3D printer

The resulting structure forms a surface capable of adopting any spatial shape. In Fig. 4, *a*, a scanned real human figure is presented. The surface of the shoulder area is a complex spatial object. The individual geodesic lines of this surface can be considered as spatial chains connected by spherical hinges.

The coordinates of each subsequent hinge are determined by the position of the previous hinge, taking into account the orientation angles in the local coordinate system. Considering the possibility of rotation of each subsequent link relative to the previous one, it is convenient to represent each link in its own spherical coordinate system (Fig. 4, *b*). The three-dimensional Cartesian coordinates of the ends of the link are defined based on the surface of the human body obtained through 3D scanning (Fig. 4, *a*).

An individual link, transformed into the global Cartesian coordinate system, is shown in Fig. 4, *c*. Let the global coordinates of the terminal hinge of the link be denoted as x_i, y_i, z_i, and the coordinates of the second end of the link as x_{i-1}, y_{i-1}, z_{i-1}. These coordinates define the position of the link in the textile 3D structure created using 3D printing methods.

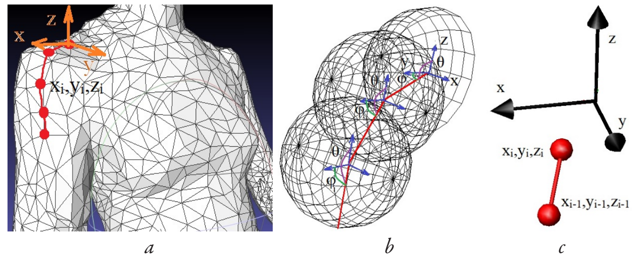


Fig. 4. Formation of a textile surface using 3D printing: *a* – a scanned real human figure; *b* – own spherical coordinate system; *c* – an individual link, transformed into the global Cartesian coordinate system

The surface formation is carried out by rotating the respective link in its own spherical coordinate system. The required rotation angles, ensuring the correct positioning of the link, are determined by solving the corresponding system of equations:

$$\begin{cases} \theta_i = \operatorname{arctg}\dfrac{\sqrt{\left(x_i - x_{i-1}\right)^2 + \left(y_i - y_{i-1}\right)^2}}{z_i - z_{i-1}}, \\ \varphi_i = \operatorname{arctg}\dfrac{y_i - y_{i-1}}{x_i - x_{i-1}}. \end{cases} \quad (2)$$

The inverse problem involves determining the coordinates of the surface points of the textile product, given the rotations of structural elements within the spherical hinges at specified angles:

$$\begin{cases} x_i = r\sum\limits_{j=1}^{i} \sin\theta_j \cos\varphi_j, \\ y_i = r\sum\limits_{j=1}^{i} \sin\theta_j \sin\varphi_j, \\ z = r\sum\limits_{j=1}^{i} \cos\theta_j. \end{cases} \quad (3)$$

The set of three-dimensional coordinates for all spherical hinges defines the surface function of the textile product. The calculated rotation angles and the arrangement of structural elements in the three-dimensional textile structure allow for specifying the necessary parameters for the 3D printer, ensuring the formation of a surface with the desired geometry (Fig. 5, *a*).

Experimental studies of real structures (Fig. 3, *h*), numerical modeling results, and structural analysis in 3D design software confirm the feasibility of creating an arbitrary flexible surface that mimics the mechanical properties of textile materials.

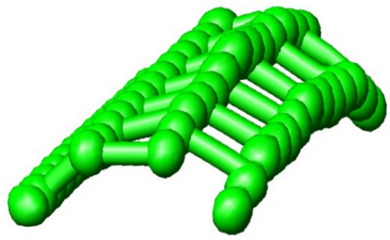
It should be noted that the developed three-dimensional structures were primarily aimed at modeling the structure and validating the methodology. To create a fully functional printed textile material, it is necessary to optimize the dimensions of the cells and spherical hinges, as well as refine the accuracy requirements for the 3D printer. The obtained results will help bring the characteristics of the fabricated material closer to those of real textile products.

Artificial intelligence was used to generate proposals for possible external forms of textile products made from the proposed materials (Fig. 5, *b*). Given the specific geometric properties of the created structures, such products could be used for decorative embellishments in fashion, adding unique volumetric elements to textile compositions.

Additionally, the presence of smooth spherical shapes on the material's surface – whose dimensions can be individually specified – creates

 ISSN-L 2664-9969; E-ISSN 2706-5448

opportunities for controlled mechanical effects on the skin or human body. This opens up prospects for using such structures in the field of medical textiles, particularly for automated massage or compression therapy applications.



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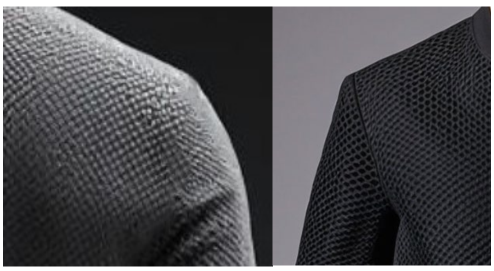

b

Fig. 5. Possible textile surfaces based on the synthesized structure (Fig. 5, *b* imagined with AI): *a* – three-dimensional textile structure; *b* – proposals for possible external forms of textile products

The results obtained in the course of the study have wide practical application in the field of textile production, in particular in the development of adaptive and functional textile materials using 3D printing technologies. The proposed textile materials with adjustable parameters of stiffness, air permeability and elasticity will allow the development of innovative clothing with improved performance characteristics, increasing its adaptability to specific operating conditions.

However, structures manufactured by the 3D prototyping method have limited flexibility and elasticity compared to traditional textile materials, which may affect their wearability. In addition, the properties of printed materials, in particular air permeability and stiffness, largely depend on the geometry of structural elements, which requires further research on design optimization. The introduction of 3D printing technology in the textile industry is also limited by the high cost of materials, the duration of the production cycle and the need to fine-tune printing parameters to ensure uniform product quality.

The martial law conditions in Ukraine significantly affected the conduct of the study, causing a number of restrictions related to both logistical support and organizational aspects of scientific work. In particular, difficulties arose due to interruptions in the supply of necessary materials for 3D printing, which complicated the process of testing various polymer compositions and affected the possibility of large-scale experimental analysis.

The prospects for further research are to expand the experimental base for optimizing the parameters of 3D prototyping of textile structures, taking into account mechanical, operational and aesthetic characteristics. It is advisable to conduct research on expanding the range of materials used for 3D printing of textile structures, in particular, the introduction of innovative polymer compositions with improved flexibility, wear resistance and air permeability. Further development of the direction also involves improving the technological aspects of 3D printing, in particular, research into methods for multilayer formation of textile structures and the influence of different printing modes on the operational characteristics of the material.

4. Conclusions

A methodology for creating textile structures based on 3D prototyping using spherical joints has been proposed. Modeling and experimental studies have confirmed the feasibility of developing pseudo-textile materials with controllable mechanical properties. The use of multi-level joint connections ensures sufficient mobility of structural elements, allowing them to adapt to the shape of the human body. Adding eccentricity to the joints enables the adjustment of material stiffness.

An optimal ratio of geometric parameters of structural elements allows for an increase in material air permeability by 22–26 %, depending on the orientation of the joint connections, making them promising for the development of ventilated textile products.

The research findings can be applied in the light industry sector, particularly for the creation of high-tech textile materials. The proposed structures have potential applications in medical textile manufacturing, adaptive clothing, and decorative elements in the fashion industry.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

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