KAUNAS UNIVERSITY OF TECHNOLOGY

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STRUCTURE INFLUENCE TO THE PROPERTIES OF KNITTED COMPRESSION SUPPORTS

Summary of Doctoral Dissertation

Technological Sciences, Materials Engineering (T 008)

2019, KAUNAS

This doctoral dissertation was prepared at Kaunas University of Technology, Faculty of Mechanical Engineering and Design, Department of Material Engineering during the period of 2015–2019. The studies were supported by the Research Council of Lithuania.

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Editor: Armandas Rumšas (Leidykla „Technologija“)

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The official defence of the dissertation will be held at 10 a.m. on 1st October, 2019 at the public meeting of Dissertation Defence Board of Materials Engineering Science Field in Dissertation Defence Hall at Kaunas University of Technology.

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Summary of doctoral dissertation was sent on August 30 2019.
The doctoral dissertation is available on the internet at http://ktu.edu and at the library of Kaunas University of Technology (K. Donelaičio 20, LT-44239, Kaunas, Lithuania).

KAUNO TECHNOLOGIJOS UNIVERSITETAS

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STRUKTŪROS ĮTAKA MEGZTŲ ORTOPEDINIŲ KOMPRESINIŲ ĮTVARŲ SAVYBĖMS

Daktaro disertacijos santrauka

Technologijos mokslai, medžiagų inžinerija (T 008)

2019, KAUNAS

Disertacija rengta 2015-2019 metais Kauno technologijos universiteto Mechanikos inžinerijos ir dizaino fakulteto Medžiagų inžinerijos katedroje. Mokslinius tyrimus rėmė Lietuvos mokslo taryba.

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Medžiagų inžinerijos mokslo krypties disertacijos gynimo taryba:
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Disertacija bus ginama viešame medžiagų inžinerijos mokslo krypties disertacijos gynimo tarybos posėdyje 2019 m. spalio 1 d. 10 val. Kauno technologijos universiteto Disertacijų gynimo salėje.

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Disertacijos santrauka išsiųsta 2019 m. birželio 29d.
Su disertacija galima susipažinti internetinėje svetainėje http://ktu.edu ir Kauno technologijos universiteto bibliotekoje (K. Donelaičio St. 20, 44239, Kaunas, Lithuania)

INTRODUCTION

Research Problem Justification and Relevance of the Work. The area of design of medical textile products requires high accuracy. It is not surprising that the quality of products for healthcare has to be excessively high. Knitted orthopaedic compression supports which are classified as non-implanted medical textile products are not an exception. In order to produce a high quality product that fulfills the medical, comfort, aesthetic and other requirements, it is important to consider all the stages of the design and production processes. Although scientific interest in the field of knitted orthopaedic compression braces has increased in the last decade, there is still lack of research in this field. For a long time, the greatest interest in knitted compression products has been directed towards the research and development of compression stockings. Knitted orthopaedic compression supports have not gained enough scientific attention, and the design of these products or their distribution into compression classes is based on the manufacturing or classification methodologies of compression stockings. There are a number of different compression assessment methods, and many of them are created to evaluate compression stockings. In addition, most of the compression evaluation methods are based on the value of compression generated during product stretching, regardless of the possible compression changes during wearing. It is important to note that the construction, purpose and indications of orthopaedic supports and compression socks are different, and that these products are common only by the demand of compression. According to it, the design and manufacture processes of knitted orthopaedic supports are possibly performed not in the optimal way. Thus over-production of raw materials, manpower and time, as well as failure to fulfill compression requirements is likely to happen.

The areas of application and the scale of production of knitted compression products are extremely wide. There are many companies producing compression supports in Lithuania (for example, AB *Ortopedijos technika*, UAB *Ortopagalba*, UAB *Pirmas žingsnis*, etc.), and there are numerous world-renowned brands, such as Sigivaris®, Bauerfriend®, GmbH OttoBock, etc.

Currently, the distribution of compression orthopaedic products into compression classes is adapted from the compression stockings methodology. Essentially, these classes are also suitable for compression supports, but there are different definitions of compression classes in different countries. This means that, depending on the different standards, the same product may belong to different compression classes in different countries. In addition, there is no precise definition of preventive, sporting, and healing compression supports. Since the production area of compression supports does not have any defined history and can be considered to be relatively new, the need for research is not fulfilled, and the design and production processes are also not standardized, either. This means that the internal standards of different countries or different companies are not interrelated. Thus, when purchasing a product, the consumer is not necessarily convinced that the product possesses the required properties.

Recently, the control of objects of human health or human well-being items has been systematically increasing. Raising consumer awareness, the desire to lead a healthier life and live in a sustainable and more environmentally friendly environment promotes the development of various research. In this case, the field of medical textiles, as an object of health or prevention, is analyzed in various aspects. Over the last few decades, the areas of use and production volumes of compression medical textiles have significantly increased. As the scale of production is constantly increasing, it is important to pay attention to the sustainability of manufacturing processes, the reduction of waste, or to inadequate production, i.e. to supports that do not fulfill the compression requirements and which are often difficult to recycle due to the mixed fibre composition.

In this way, inaccurate design of the supports can lead not only to overuse of raw materials, but also to inappropriate execution of production processes, reduction of the sustainability and environmental friendliness of the production and its activities. For these reasons, the relevance of compression medical textile research is extremely high.

The aim of the dissertation is to determine the influence of various structures of knitted compression materials on compression and wear comfort, and to create more accurate methodologies of compression and air permeability evaluation.

The objectives of the research:

1. To determine the influence of the stabilization process on the properties of compression knitted materials.
2. To determine the influence of the product structure on the generated compression.
3. To investigate the influence of long-term and short-term relaxation on the alteration of the generated compression.
4. To determine alteration of air permeability of compression knitted products during wearing.
5. To develop compression and air permeability evaluation methods of orthopaedic compression supports by evaluating the alteration in properties during use.
6. To create a recommendable design process of compression support and to develop a recommendations set for evaluating compression and comfort parameters.

Scientific novelty and practical importance. The demand for compression orthopaedic supports determines the increasing interest of researchers in this field. Although Lithuanian and global researchers have analyzed various elastic properties of knitted fabrics, research results have not been summarized yet into a single set of recommendations. In addition, in order to create the optimal and consistent integral methodology for knitted orthopaedic compression supports, there is still lack of research in this field. According to the investigation of this dissertation, a basic set of recommendations for compression and comfort properties evaluation and prevision during the design process of knitted compression supports was created.

According to the results of our investigations, a new approach to evaluating compression generated by compression products is essential, while taking into account the tensile stress losses during relaxation. Experimental results show that the proposed compression assessment methodology is appropriate and useful for both finite products and product elements with different elongation values belonging to the zone of low extensions. In the previous research, the impact of rigid elements of various relative areas on the generated compression values it was investigated. This dissertation presents a much wider and more detailed assessment of the influence of rigid elements, while taking into account not only the relative area, but also the previously unexplored features – the influence of the shape or direction of the element that has not been studied yet. Another aspect that has not been studied yet is the evaluation of the comfort properties of knitted orthopaedic compression supports. The dissertation states that due to the changes in the knitted structure during wearing, air permeability should be evaluated in simulated wearing elongation. According to the obtained results, the design process of compression support would be performed more effectively, and optimisation of the manufacturing process would increase its economic indications and environmental friendliness.

Approbation of the research results. The results of this research were presented in 4 scientific publications in *Clarivate Analytics Web of Science* listed journals, (including three articles published in Q1 journals, Material Science, Textiles) and 10 international conferences.

Structure of the dissertation. The dissertation consists of an introduction, 3 chapters, conclusions, a list of references (176 positions), and a list of scientific publications.

CONTENT OF THE DISSERTATION

The Introduction presents the relevance of the dissertation topic, the aim of the work, the set of objectives, along with the scientific novelty and the expected practical value of the work.

The first chapter, *Literature Review*, introduces general information about compression therapy and compression textile products for medical purposes, the construction, composition and manufacturing of compression textile products, various methodologies of compression evaluation, mechanical properties and comfort parameters of knitted materials.

The second chapter, *Research Methodology*, describes the object of research and methodologies of experimental investigations.

Experimental materials.

In this research, complete knitted compression products (knee supports) and samples of the elements of knitted support were investigated (five different groups of samples). All types of knitting patterns and yarns used for the samples are presented in Table 1. All the sample groups were prepared in a variety of variants differing by parameters as presented in Table 2 and Table 3.

Table 1. Materials of the investigated samples

Type of the sample		Material and linear density of ground yarn	Material and linear density of elastomeric / inlay yarns
Complete supports	Knee support with two types of rigid elements (combined laid-in jacquard with elastomeric inlay-yarns)	PA6.6 (7.8 tex) + PU (31 tex) double covered with PA6.6 (2.2 tex)	PU (47 tex) double covered with PA6.6 (2.2 tex), total T = 55 tex
Elements of the support	I pattern (combined laid-in jacquard with elastomeric inlay-yarns)	PA6.6 (7.6 tex) + PU (5 tex), covered with PA6.6 (4.4 tex) and in different direction PA6.6 (4.4 tex)	PU (47.5 tex) covered with PA6.6 (11 tex) and viscose yarn (14.3 tex), total T = 70 tex
	II pattern (rib 1x1 with elastomeric inlay-yarns)	PA6.6 (7.8 tex) + PU (31 tex) double covered with PA6.6 (4.4 tex)	PU (47 tex) double covered with PA6.6 (2.2 tex), total T = 55 tex
			PU (47.5 tex) double covered with PA6.6 (2.2 tex) and cotton yarn (4,4 tex), total T = 70 tex
	III pattern (imitation of rib 1x1)	Cotton yarn, 30 tex	PU (45 tex) covered with PA (7.8 tex), total T = 120 tex
			PU (12 tex) covered with PA (7.8 tex), total T = 78 tex

Table 2. Variants of samples of complete supports and elements of support

Type of the sample		Sample code	Feature	Elastomeric inlay-yarn
Complete supports	Knee support	M	Size M	
		L	Size L	
		XL	Size XL	
Elements of the support	I pattern	E_ZA_4	Elastomeric yarn pretension in the yarn feeder 4 cN/tex	
		E_ZA_7	Elastomeric yarn pretension in the yarn feeder 7 cN/tex	
	II pattern	E_LA1_1/4	Inlay-yarn inserted in every fourth course	PU (47 tex) double covered with PA6.6 (2.2 tex), total T = 55 tex
		E_LA1_1/2	Inlay-yarn inserted in every second course	
		E_LA1_1/1	Inlay-yarn inserted in every single course	
		E_LA1_2/2	Two inlay-yarns in every second course	

Continuation of the Table 2. Variants of samples of complete supports and elements of support

Type of the sample		Sample code	Feature	Elastomeric inlay-yarn
Elements of the support	II pattern	E_LA2_0/0	Without inlay-yarn	PU (47.5 tex) double covered with PA6.6 (2.2 tex) and cotton yarn (4.4 tex), total T = 70 tex
		E_LA2_1/4	Inlay-yarn inserted in every fourth course	
		E_LA2_1/2	Inlay-yarn inserted in every second course	
		E_LA2_1/1	Inlay-yarn inserted in every single course	
	III pattern	E_LI_1	PU (45 tex) covered with PA (7.8 tex), total T = 120 tex	
		E_LI_2	PU (12 tex) covered with PA (7.8 tex), total T = 78 tex	

Table 3. Variants of samples of elements of support with rigid elements

Type of the sample		Sample code			Rigid element	
					Shape (height x width, mm)	Relative area, %
Elements of the support with rigid elements	I pattern	N_LA_1/1	N_LA_1/2	N_LA_1/4	Rectangular	10
		N_LA_1/1	N_LA_1/2	N_LA_1/4		15
		N_LA_1/1	N_LA_1/2	N_LA_1/4		20
		N_LA_1/1	N_LA_1/2	N_LA_1/4		25
	II pattern	N_ZA_68			Circle (d = 68)	18
		N_ZA_60x60			Square (60x60)	
		N_ZA_40x90			Rectangular (40x90)	
		N_ZA_80x45			Rectangular (80x45)	
		N_ZA_45x80			Rectangular (45x80)	

Experimental methodology.

All of the samples were kept for 24 hours in standard atmosphere for testing, and all the experiments were carried out in the same standard atmosphere for testing according to Standard LST EN ISO 139:2005, e.g., temperature (20 ± 2) °C, relative humidity (65 ± 5)%. The structure parameters of knitted samples were analyzed according to British Standard BS 5441:1998. The average values of the results of all the performed tests are presented in this work.

The stabilization process was performed according to Standard LST EN ISO 6330:2012 (water temperature 40 °C, duration 40 min, centrifugation frequency 500 min^{-1}, drying temperature 60 °C; detergents were not used).

Tensile force tests were performed by using a universal testing machine ZWICK/Z005 (with adapted clamps) according to Standard LST EN ISO 13934–1:2000. The tensile speed was set at 100 mm/min; pretension – 2 N, sensor – 5 kN. The g gauge length of 100 mm was set for the elements of support testing, and a specially designed frame was used for complete testing of supports.

Stress relaxation tests were performed with the same universal testing machine ZWICK/Z00 and same initial parameters as were set during the tensile force tests in accordance with standard LST EN ISO 13934-1:2000. The relaxation process was investigated by the fixed elongation method, and stress was recorded as a function of time. Long-term and short-term relaxation processes were performed, and the selected regimes are presented in Table 4.

Table 4. Regimes of stress relaxation process

Type	Sample type	Duration, sec	Elongation, %
Long-term relaxation	Complete supports	36000	11,5
	Elements of the support. Pattern II	200000	30
Short-term relaxation	Elements of the support. Pattern II	300	30
	Elements of the support. Pattern III		15
	Elements of the support with different shape rigid elements. Pattern II		20

Compression calculations were performed by using Laplace equation (Bartels, 2011):

$$P = \frac{2\pi F}{L_N \cdot h}; \tag{1}$$

where: P – compression, Pa, F – tensile force, N, $L_N \cdot h$ – area of the sample, m^2.

Air permeability tests were performed with a L14DR device according to Standard LST EN ISO 9237:2007. The airflow rate was measured at a differential pressure of 200 Pa in the 5 cm^2 circle-shaped area of the natural state of a knitted material and at 10% and 20% elongation. Air permeability was calculated according to equation (Matukonis A., Palaima J., Vitkauskas A., 1989):

$$R = \frac{\overline{q_v}}{S_B} \cdot 167; \tag{2}$$

where: R – air permeability, dm^3/(m$^2 \cdot$s); q_v –, airflow rate, dm^3/min (l/min); S_B – tested area, cm^2; 167 – calculation from dm^3/(cm$^2 \cdot$min) to dm^3/(m$^2 \cdot$s) coefficient.

The third chapter, *Results of Investigations*, presents the results of the performed experimental investigations and their analysis.

Investigation of the influence of stabilization on the mechanical properties of knitted materials

The obtained results show that the parameters of the knitted structure changed during the stabilization process: the density in the course and wale directions increased up to 7.45%, and the length of the elastomeric thread in the knitting report decreased up to 10.66%, depending on the group of the samples. Stabilized knits performed up to 3.22–4.54% higher (depending on the sample group) tensile force values than raw state samples (Fig. 1).

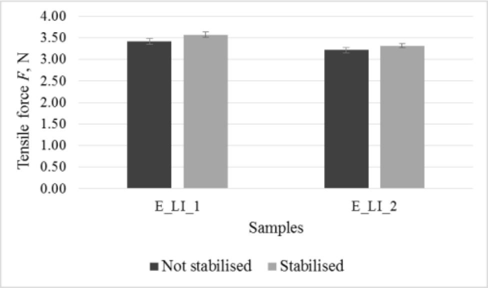


Figure 1. Tensile force alteration after stabilization

Lower tensile force alteration after stabilization was observed in the samples with a lower linear density of the elastomeric yarn. According to the data, possible tensile force changes during stabilization must be taken into account during the design or compression evaluation process, and compression products must be stabilized during the manufacturing process.

Investigation of the influence of products' structure on the tensile force and generated compression.

Compression generated by the product increases by inserting inlay-yarns into the knitted structure, and different insertion densities can be used for changing the generated compression in different parts of the product. Studies show that the report of elastomeric inlay-yarns insertion into the knitted material determines the value of the tensile force, but the character of this effect is not linear (Fig. 2).

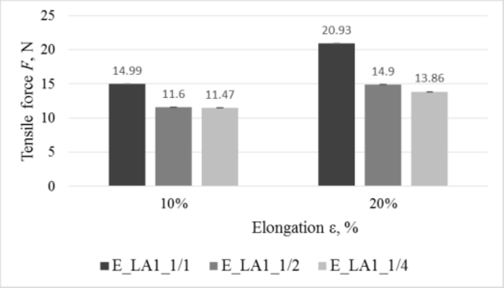


Figure 2. Correlation of tensile force and amount of inlay-yarn at 10% and 20% elongations

The highest tensile force values were observed in the knits with highest inlay-yarn insertion density (inserted into every single course). The tensile force values of the samples with two times reduced inlay-yarn insertion density (inserted into every second course) were observed from 22.62 to 28.81% lower (at 10% and 20% elongation, respectively). However, the decrease of tensile force values of the samples with two times more reduced inlay-yarn insertion density (inserting in every fourth course) were observed only from 0.87 to 4.97% (at 10% and 20% elongation, respectively) compared with the samples with inlay-yarns in every second course.

It was found that not the absolute amount of elastomeric inlay-yarns in the knitted suture but its distribution exerts main influence on the tensile force values: the tensile force values of the samples with one inlay-yarn inserted into every single course is 23.88–27.86 % higher (depending on the elongation) than the tensile force of the samples with two inlay-yarns inserted into every second course (Fig. 3). The observed tendencies are particularly relevant for the design processes of the compression product and compression pre-assessment.

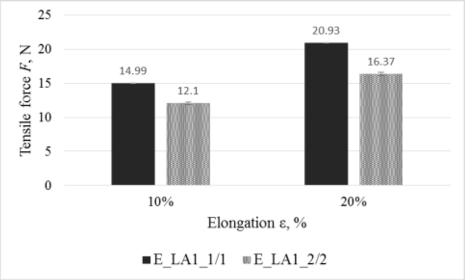


Figure 3. Correlation of tensile force and inlay-yarn insertion density at 10% and 20% elongations

The linear density of the core element (PU) of the elastomeric yarn is a significant factor forming and determining the mechanical behavior of the knitted fabrics without inlay-yarns. However, the linear density of the core element of the elastomeric yarn is not directly proportional to the tensile force of the knitted fabric: by increasing the linear density of the core element by 3.75 times, the tensile force increased only from 6.4% to 7.8%, depending on the stabilization status of the samples (Fig. 4). Thus it is necessary to accurately estimate the proper amount of elastomeric yarn and its linear density during the design process of compression supports.

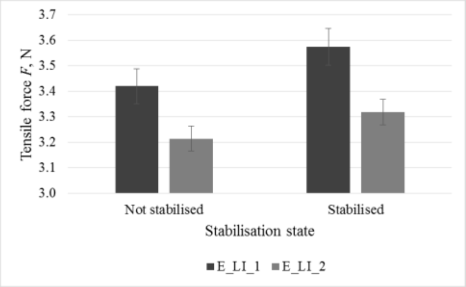


Figure 4. Correlation of tensile force and linear density of elastomeric yarn

Pre-tension of the elastomeric yarn in the yarn feeder also has significant influence on the tensile force values of the knitted fabric – there was 16.5% difference observed between the tensile force values of the samples with 4 cN/tex and 7 cN/tex elastomeric yarn pre-tension in the yarn feeder (Fig. 5).

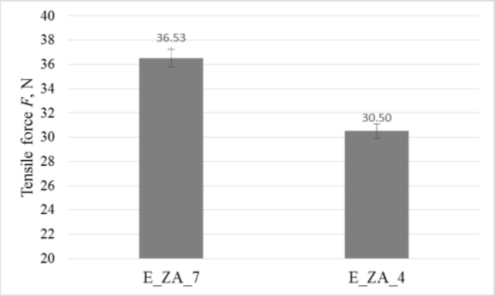
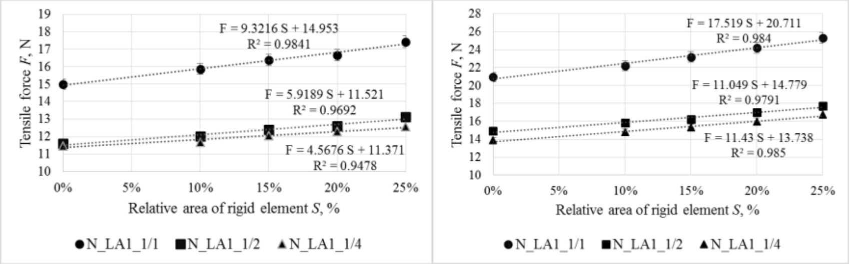


Figure 5. Correlation of tensile force and pre-tension of elastomeric yarn in the yarn feeder at 30 % fixed elongation

It was found that the rigid element that occupies 25 % relative area of the sample can increase the tensile force values up to 16.21% at 10% fixed elongation and even up to 20.93% at 20% fixed elongation. The compression generated by the sample is linearly proportional to the relative area occupied by the rigid element – by increasing the relative area occupied by the rigid element, the compression generated by the sample increases linearly, irrespectively of the inlay-yarns insertion density (R^2 = 0.9478–0.985) (Fig. 6).



a) b)

Figure 6. Correlation of tensile force and relative area of the rigid element at different elongations: a) 10%; b) 20%.

There is a correlation between the length of the vertical edge of the same area rectangular rigid element and the tensile force of the sample: the tensile force increases by increasing the length of the rigid element (Fig. 7). It was also discovered that the shape or direction of the same relative area rigid element affects the tensile force and the generated compression (Fig. 8). The obtained data allows a more accurate and more suitable prediction of the compression generated by the orthopaedic support.

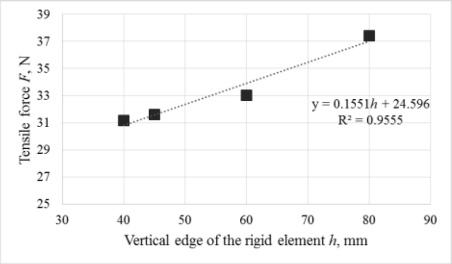


Figure 7. Correlation of tensile force and length of vertical edge of the rectangular rigid element

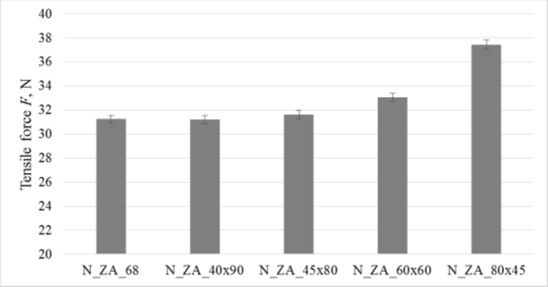
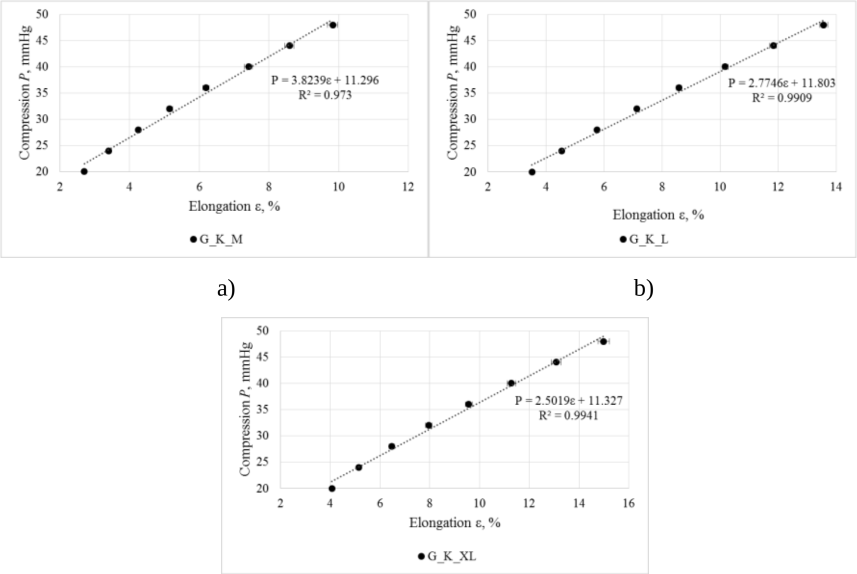


Figure 8. Correlation of tensile force and shape/ direction of the rigid element

Investigation of the influence of anthropometric data on generated compression. According to the analysis of the obtained data, it can be stated that it is necessary to evaluate not only the structure and mechanical characteristics of the knitted material, but also the parameters of the finite product: the planned size and compression class of the support, its structure, dimensions, and the relevant area of the rigid elements. Additional rigid elements usually are one size, therefore, by inserting them into products of different sizes, the decrease of the relative area of the elastic textile part is different. It was observed that in order to achieve the required compression value, different sizes of orthopaedic compression supports require different elongation values (Fig. 9): the investigated supports were stretched from 2.7% elongation (M size support, first compression class) to 15% elongation (XL size support, fourth compression class). Thus in order to generate the required compression, the value of elongation for a specific body size or different positions must vary. By adapting one size support to different compression classes, different elongation is also required for each class. Dependence between elongation and compression generated by the support can be described by linear equation. The evaluation of the generated compression must be performed separately for each size of the support with all the accessories specific to the finished product.



a) b)

c)

Figure 9. Correlation of tensile force and elongation of supports of: a) size M; b) size L; size) XL

<u>Investigation of the influence of the relaxation process on the generated compression</u>.

A new approach to the compression assessment method is required evaluating the decrease of the tension force during stress relaxation. Almost a half (49%) of the tensile force decrease during long-term stress relaxation (36000 sec) of complete supports was observed during the first 100 sec. Differences of the generated compression at the initial time of relaxation and after 120 sec varied from 2 to 4 mmHg depending on the support's size and the compression level (Fig. 10).

The tendency of the results of long-term (200,000 sec) stress relaxation of 'I' pattern knitted samples were similar: 26.72–42.81% of the tensile force loss was observed during the first 100 sec, and almost a half (47.15–57.31%) of the total tensile force loss was observed during the first 500 sec depending on the sample group. Also, tensile force values consistently decrease during stress relaxation regardless of the pre-tension in the yarn feeder of the elastomeric inlay-yarn.

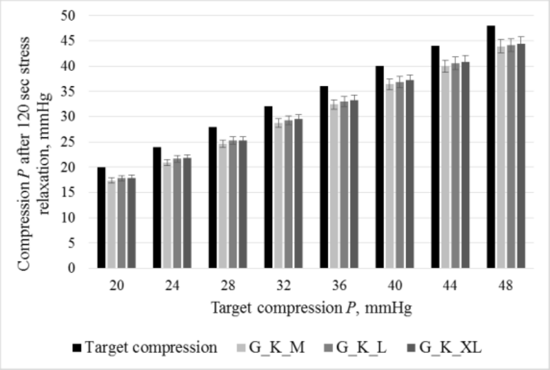


Figure 10. Differences between compression values at the initial strain time and at the time after 120 sec relaxation

In case of long-term (200,000 sec) relaxation, knits with the higher elastomeric inlay-yarn pre-tension in the yarn feeder are found to exhibit the higher tensile force loss during relaxation (in the investigated case – 28.67%) compared with the samples with lower elastomeric inlay-yarn pre-tension (in the investigated case – 23.74%) (Fig. 11), and the influence of elastomeric yarn pre-tension in the yarn feeder to the tensile force values gradually decreases – the difference between the tensile force values of these samples at the initial point of relaxation was 20%, but after long-term stress relaxation the tensile force values were similar. It was observed that the tensile force changes during the short-term stress relaxation (100–500 sec) are the subject for improved compression assessment.

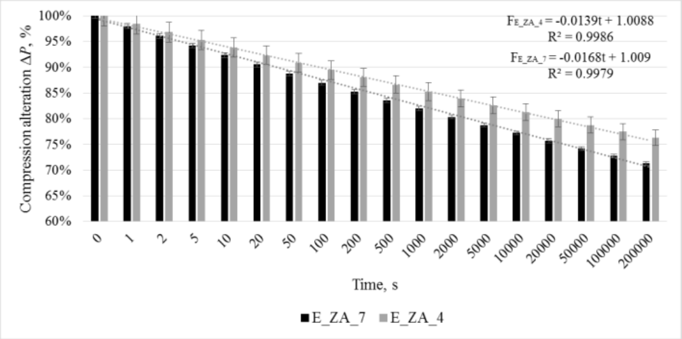


Figure 11. Compression alteration during long-term (200,000 sec) stress relaxation (‘I’ pattern)

It was found that during the short-term (300 sec) stress relaxation, as well as in the case of long-term stress relaxation, the specimens of the ‘I’ pattern knitted material with higher pre-tension of the elastomeric inlay-yarn appeared to show higher compression loss, but the process of short-term stress relaxation does not reveal a decrease of the influence of elastomeric yarn pre-tension in the yarn feeder to the tensile force value (Fig. 12).

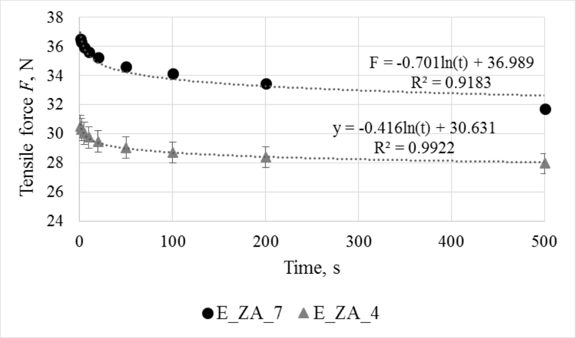


Figure 12. Compression alteration during the first 500 sec of long-term stress relaxation (‘I’ pattern)

In the case of short-term relaxation, 59.91–69.19% of the total tensile force decrease was observed during the first 50 sec of the process, and even 71.51–81.05% of the total decrease during the first 100 sec of relaxation (depending on the sample group) was observed (Fig. 13).

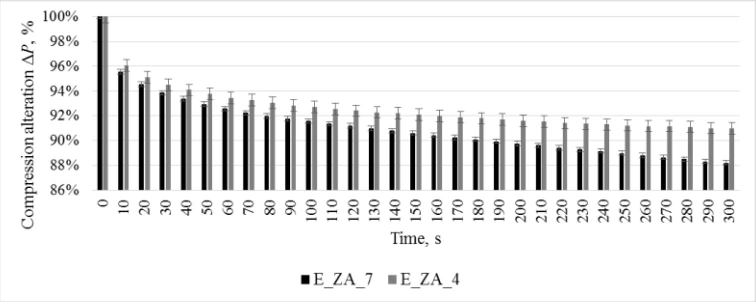


Figure 13. Compression alteration during short-term (300 sec) stress relaxation (‘I’ pattern)

The tendency of the short-term stress relaxation process of the specimens of the ‘II’ pattern knitted fabric with a different elastomeric inlay-yarn insertion density remains similar regardless of the elastomeric inlay-yarn insertion density 88.6–91.7% of the total tensile force decrease was observed during the first 100 sec depending on the sample group. It was found that the higher inlay-yarn insertion density determines lower relative compression loss during short-term relaxation (in the investigated case – up to 3.4%). The obtained results are presented in Figure 14.

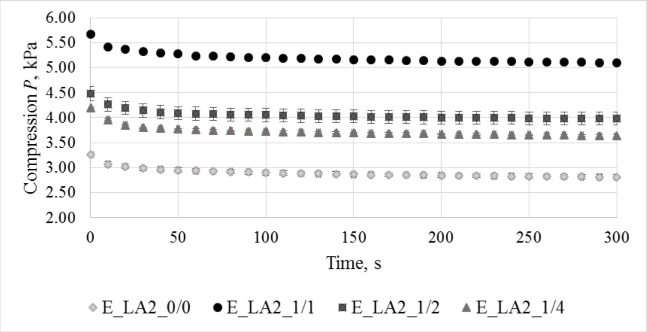
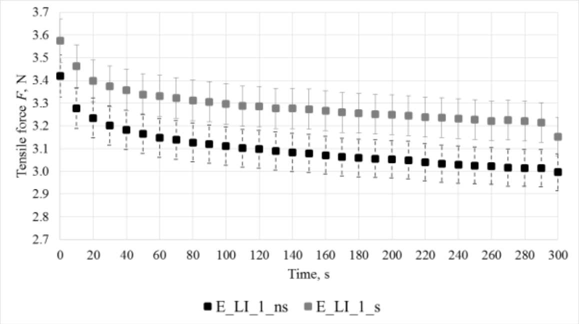


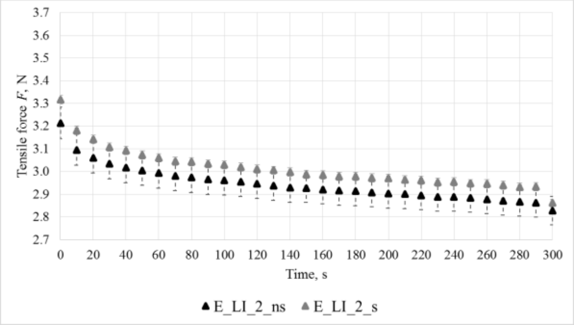
Figure 14. Compression alteration during short-term (300 sec) stress relaxation (‘II’ pattern)

Specimens of the ‘III’ pattern knitted fabric without elastomeric inlay-yarns and with a higher linear density of elastomeric yarns exhibited a faster relaxation process compared with the samples with the lower linear density of elastomeric yarns – the decrease of the values of the tensile force was 53.59–60.10% of the total tensile force loss during the first 50 sec, and 63.32–72.79 % of the total tensile force loss during the first 100 sec depending on the sample group. It was also observed that the tendency of the stress relaxation process remains similar regardless of the stabilization status of the samples. The obtained results are presented in Figure 15.



a)

Figure 15. Compression alteration during short-term (300 sec) stress relaxation of the raw state and stabilized samples: a) E_LI_1



b)

Continuation of Figure 15. Compression alteration during short-term (300 sec) stress relaxation of the raw state and stabilized samples: b) E_LI_2

The tendency of the stress relaxation process remains similar regardless of the shape of the rigid element: the alteration of the tensile force between the analyzed sample groups during the relaxation process was only 1.02–1.55% depending on the sample group and the moment of the relaxation process (Fig. 16). It was observed that even 57.75–61.40% of the total tensile force loss of the samples with rigid elements occurs during the first 20 sec of the relaxation process, and even 83.45–85.49% of the total tensile force loss is detected during the first 100 sec depending on the group of samples.

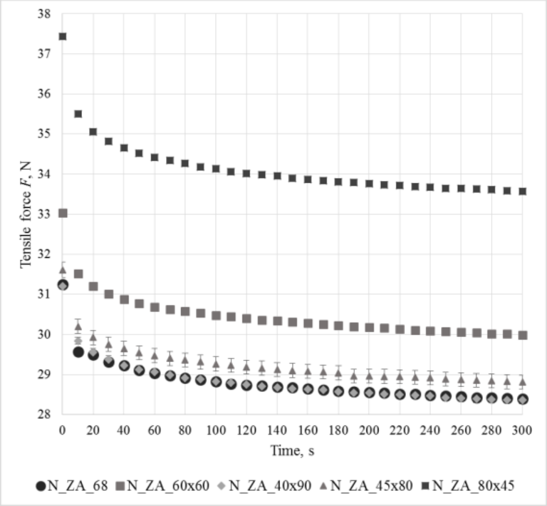


Figure 16. Compression alteration during short-term (300 sec) stress relaxation (‘I’ pattern with rigid elements)

The proposed methodology of tensile force and generated compression assessment evaluating tensile force changes during 120 sec of stress relaxation, is suitable for both finished products and elements of the product regardless of their pattern or structure. During the first 120 sec of relaxation, the decrease of the tensile force of the samples were: ‘I’ pattern: 74.56–84.24%, ‘II’ pattern: 84.96–88.17%, ‘III’ pattern 67.4–74.1%, ‘II’ pattern elements with rigid elements: 86.27–88.34% compared with the total decrease of the tensile force during short-term (300 s) stress relaxation depending on the group of the samples. Thus the proposed methodology of compression estimation evaluating the tensile force changes during not less than 120 sec of stress relaxation is suitable for different structure compression supports and can be used in the compression product design algorithm; it can be applied to evaluate compression at different stages of the product.

Investigation of the comfort parameters of the knitted compression product.

It was found that air permeability is closely related to the knitting pattern and the amount of elastomeric yarn in the structure – by increasing the elastomeric inlay-yarn density, the air permeability decreases. Thus the structural parameters of knitted materials have high influence on the air permeability. However, the dependence of the absolute amount of elastomeric inlay-yarns and air permeability is not linear. As it is presented in Figure 17, when relieving the elastomeric inlay-yarn insertion density, the values of the air permeability vary by 14–49% thus making a major impact on the product comfort.

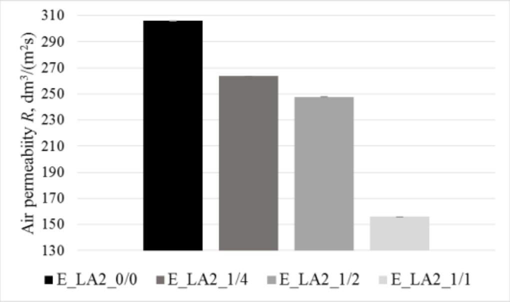


Figure 17. Influence of the structural parameters of ‘II’ pattern knitted samples on the air permeability

Air permeability of the stretched samples (at 10% and 20% fixed elongation) with different elastomeric inlay-yarns insertion report was also investigated, and the obtained results (presented in Figure 18) showed a similar tendency as in the case of non-stretched specimens.

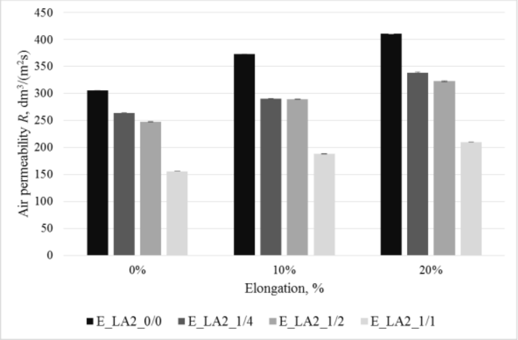


Figure 18. Influence of elongation to air permeability of ‘II’ pattern knitted samples with different inlay-yarn insertion report

Samples with elastomeric inlay-yarn inserted into every single course appeared with 48.8–49.5% lower air permeability compared with the samples without inlay-yarns depending on elongation. The air permeability of the samples with two times lower insertion density of the elastomeric inlay-yarn (inserted into every second course) was from 21.4% to 22.5% lower compared with the samples without inlay-yarns depending on elongation. Finally, the air permeability of the samples with four time lower insertion density of the elastomeric inlay-yarn (inserted into every fourth course) was 14.5–22.3% lower compared with the samples without inlay-yarns depending on the elongation. Also, despite the fact that the values of air permeability at 20% fixed elongation are higher in comparison with values at 10% fixed elongation, it was observed that the percentage alteration between the samples with different inlay-yarn insertion is reported to be lower.

These results are particularly relevant for the improvement of the methodology of compression product comfort parameters – it is recommended to perform air permeability tests at not less than the minimal specific elongation.

Recommendations for evaluation of compression and air permeability of orthopaedic compression supports.

According to the obtained results and the analysis of the works of previous researchers, the methods and recommendations for evaluating the generated compression and comfort properties (air permeability) of the compression orthopaedic support were formed. It is proposed to evaluate the generated compression after a stress relaxation period of at least 120 sec. It is recommended to perform experimental tests of air permeability at no less than the minimum specific elongation. A complex evaluation of these properties was also suggested – evaluations should be performed during the assessment of the theoretical properties and during experimental tests. The design process of the compression orthopaedic product and the basic recommendation(s) of the impact of the parameters of compression orthopaedic support on the compression and comfort properties of the product were proposed.

CONCLUSIONS

1. It was found that the increase in the tensile strength and the generated compression during the stabilization process in the investigated case of up to 4.5%, is significant and should be assessed during the prediction of compression generated by the product. Experimental compression tests should be performed after the stabilization process.
2. It was found that elastomeric inlay-yarns insertion into the knitted structure increases the value of the generated compression, but the dependence of the tensile force in the course direction and insertion density of elastomeric inlay-yarns is not linear. By reducing the insertion density from insertion into every single course to insertion into every second course, the tensile force decreases by 22.62–28.81%, while the insertion density reduction from insertion into every second course to insertion into every fourth course leads to the alteration of the tensile force of only 0.87–4.97% depending on the elongation.
3. It was found that not the total amount of elastomeric inlay-yarn but its insertion density determines the value of the generated compression: samples with the same amount of elastomeric inlay-yarn but two times lower insertion density in the structure showed the tensile force in the course direction values from 23.88% to 27.86% lower (depending on the elongation).
4. Parameters of elastomeric yarns determine the behavior of a knitted fabric under the stretching to the course direction:

- By increasing elastomeric inlay-yarn pre-tension in the yarn feeder by 1.75 times, the tensile strength increases by 16.5% at 30% fixed elongation, but this effect gradually decreases during long-term stress relaxation. Therefore, the compression properties of the long-term wearable products cannot be predicted based only on the value of the elastomeric yarn pre-tension in the yarn feeder.
- By increasing the linear density of the core element of the elastomeric yarn, the tensile strength of the knitted material increases, but the linear density of the elastomeric yarn core is not directly proportional to the tensile strength. In the investigated case, by increasing the linear density of the core element by 3.75 times, the tensile force increased only by 6.4–7.8% (depending on the stabilization status of the samples).

5. By increasing the relative area occupied by the rigid element in the product, the compression generated by the product increases linearly regardless of the elastomeric inlay-yarns insertion density. While the rigid element occupies 25% relative area, the tensile force in the course direction increases to 16.21% at 10% fixed elongation, and up to 20.93% at 20% fixed elongation.
6. It was found that the direction of the rigid element or its orientation in the product exerts influence on the tensile force and the generated compression –

the influence of the same relative area rigid elements but a different shape or direction on the tensile force varies up to 20%. It was found that the tensile force in the course direction increases by increasing the height of the rigid element in the stretching direction.

7. It was found that in order to achieve the required compression value, orthopaedic compression supports of different sizes or positions require different elongation values. The evaluation of the generated compression must be performed separately for each size of the support with all the additional elements specific for the finished product due to the uneven decrease of the relative area of the viscous part of the support by inserting the rigid elements of the standard size.
8. It was found that the tensile force of the knitted compression product or its elements decreases during the stress relaxation, and major changes of the tensile force occur during the first 100–200 s. Therefore, the compression generated by compression products must be evaluated not earlier than after 120 s of stress relaxation.
9. It was found that the different insertion density of the elastomeric inlay-yarn may change air permeability up to 49%. At 20% fixed elongation in the course direction, the air permeability of compressive knits increases up to 25.9%, thus air permeability must be evaluated at the minimal specific elongation of the material.
10. According to the obtained results, a basic recommendation for compression and comfort properties of compression orthopaedic support parameters was formed, and the design process of the compression orthopaedic product was developed.

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REZIUMĖ

Tiriamosios problemos pagrindimas ir darbo aktualumas. Medicininės tekstilės gaminiai - sritis, kurioje būtinas didelis projektavimo tikslumas. Natūralu, kad su žmogaus sveikata susijusių gaminių kokybei yra keliami itin aukšti reikalavimai. Ne išimtis ir megzti ortopediniai kompresiniai įtvarai, kurie yra priskiriami medicininės tekstilės neimplantuojamų gaminių grupei. Norint pagaminti aukštos kokybės gaminį, atitinkantį keliamus medicinos, komforto, estetikos ir kitus reikalavimus, svarbu atsižvelgti į visus projektavimo ir gamybos etapus. Nors pastarąjį dešimtmetį atliekama vis daugiau megztų ortopedinių kompresinių įtvarų mokslinių tyrimų, jų vis dar nepakanka. Ilgą laiką didžiausias susidomėjimas megztais kompresiniais gaminiais buvo susijęs su kompresinių kojinių ypatybių tyrimo ir tobulinimo klausimais. Mokslininkai gana ilgai neskyrė gana dėmesio megztiems ortopediniams kompresiniams įtvarams. Minėti gaminiai dažniausiai buvo projektuojami ar skirstomi į kompresijų klases remiantis kompresinių kojinių gamybos ar skirstymo metodika. Yra žinoma daug skirtingų kompresijos vertinimo metodų, sukurtų vertinti kompresines kojines. Be to, daug kompresijos vertinimo metodikų yra pagrįstos gaminio ištempimo metu generuojamos kompresijos verte, neatsižvelgiant į dėvėjimo metu galimus kompresijos pokyčius. Paminėtina, kad ortopedinių įtvarų ir kompresinių kojinių sandara, paskirtis ir indikacijų priežastis yra skirtinga, o šiuos gaminius vienija tik apspaudimo jėgos poreikis. Tai leidžia teigti, kad megztų ortopedinių įtvarų projektavimas ir gamybos procesas galimai nėra optimaliausi. Taigi tikėtinas žaliavų, darbo jėgos ir laiko pereikvojimas bei gaminiams keliamų reikalavimų netenkinimas. Atsižvelgus į minėtas priežastis, trūksta mokslinių tyrimų, skirtų kompresiniams ortopediniams įtvarams analizuoti. Itin aktualus optimalesnis ir tikslesnis projektavimas bei kompresijos ir kitų savybių vertinimas.

Megztų kompresinių gaminių panaudojimo sritys įvairios, o gamybos apimtys didelės. Lietuvoje ir visame pasaulyje veikia daug šią produkciją gaminančių įmonių: Lietuvoje įsikūrusios įmonės AB „Ortopedijos technika“, UAB „Ortopagalba“, UAB „Pirmas žingsnis“ ir kt. Be minėtų įmonių produkcijos, vartotojus dažnai pasiekia ir pasaulyje gerai žinomų prekės ženklų gaminiai, pavyzdžiui, „Sigivaris®“, „Bauerfriend®“, GmbH „OttoBock“ ir t. t.

Šiuo metu megzti kompresiniai ortopediniai gaminiai yra skirstomi pagal kompresinėms kojinėms pritaikytas kompresijos klases. Iš esmės, šios klasės tinka ir kompresiniams įtvarams skirstyti, tačiau skirtingose Europos ar pasaulio valstybėse egzistuoja įvairios kompresijos klasių apibrėžtys. Tai reiškia, kad, atsižvelgus į skirtingus galiojančius standartus, skirtingose valstybėse tas pats gaminys gali priklausyti skirtingoms kompresijos klasėms. Be to, nėra tikslios prevencinių, sportinių ir gydomųjų kompresinių įtvarų apibrėžties. Kadangi kompresinių įtvarų gamyba nėra ilgametė ir gali būti laikoma santykiškai nauja, o mokslinių tyrimų poreikis yra didelis, tad kompresinių įtvarų projektavimo ir gamybos procesai taip pat nėra standartizuoti. Tai reiškia, kad skirtingų šalių ar

skirtingų įmonių vidiniai standartai tarpusavyje nesusiję. Taigi vartotojas, įsigydamas produktą, nebūtinai yra įsitikinęs, kad šis atitinka savybes, kurių jis pageidauja.

Pastaruoju metu žmogaus sveikata ar jos gerovės užtikrinimas tampa vis griežčiau kontroliuojamu objektu. Šiuo atveju įvairiais aspektais, kaip sveikatinimo ar prevencijos objektas analizuojama medicininės tekstilės sritis. Kadangi įvairios paskirties medicininių tekstilės gaminių gamyba nuolat auga, svarbu atkreipti dėmesį ir į gamybos procesų tvarumą, atliekų ar netinkamos produkcijos kiekių mažinimą. Per pastaruosius kelis dešimtmečius itin padidėjo kompresinių medicininės tekstilės produktų gamybos apimtys ir padaugėjo panaudojimo sričių. Įtvarus, neatitinkančius keliamų reikalavimų generuojamai kompresijai dėl mišrios pluoštinės sudėties, dažnai sudėtinga perdirbti. Todėl netikslus įtvarų projektavimas gali nulemti ne tik žaliavų pereikvojimą, bet ir netikslingą gamybos procesų vykdymą, ir taip sumažinti gaminamos produkcijos ir gamybos tvarumą bei draugiškumą aplinkai. Dėl šių priežasčių kompresinių medicininės tekstilės gaminių tyrimų aktualumas yra itin didelis.

Darbo tikslas – nustatyti skirtingos kompresinių mezginių struktūros įtaką generuojamai kompresijai, dėvėjimo komfortui ir sukurti tikslesnius kompresijos ir laidumo orui vertinimo metodus.

Darbo uždaviniai:

1) nustatyti stabilizavimo proceso įtaką kompresinių mezginių savybėms;
2) nustatyti gaminio struktūros įtaką generuojamai kompresijai;
3) ištirti ilgalaikės ir trumpalaikės įrąžos relaksacijos įtaką generuojamos kompresijos pokyčiui;
4) nustatyti kompresinio mezginio laidumo orui pokyčius dėvėjimo metu;
5) sukurti ortopedinių kompresinių įtvarų generuojamos kompresijos ir laidumo orui vertinimo metodus, įvertinant savybių pokytį eksploatajos metu;
6) sudaryti rekomenduojamą ortopedinio kompresinioci įtvaro projektavimo eigą ir kompresinių bei komforto savybių vertinimo rekomendacijų rinkinį.

Mokslinis darbo naujumas. Kompresinių ortopedinių įtvarų paklausa nulemia didėjantį mokslininkų susidomėjimą šia sritimi. Nors Lietuvos ir pasaulio tyrėjai yra nagrinėję įvairias tampriąsias megztinių medžiagų savybes, tyrimų rezultatai nėra apibendrinti viename rekomendacijų rinkinyje. Be to, siekiant parengti optimalią ir vientisą megztų ortopedinių kompresinių įtvarų projektavimo metodiką, vis dar trūksta tam tikrų tyrimų. Disertacijos rengimo metu atlikti tyrimai ir jų metu suformuotos išvados leido sukurti kompresinių gaminių generuojamos kompresijos ir komforto savybių vertinimo bazinį rekomendacijų rinkinį, vartotiną gaminių projektavimo metu. Šios disertacijos rengimo metu atlikti tyrimai įrodė, kad, norint įvertinti kompresinių gaminių generuojamą kompresiją, būtinas naujas požiūris, atsižvelgiant į įrąžos relaksacijos metu patiriamus tempimo jėgos nuostolius. Eksperimentiniai rezultatai atskleidė, kad siūloma kompresijos vertinimo metodika yra tinkama ir vartotina tiek vertinti baigtinius gaminius, tiek gaminį sudarančius elementus, esant skirtingoms ištįsos vertėms, priklausančioms mažų ištįsų zonai. Ankstesniuose mokslininkų darbuose buvo pradėti skirtingo santykinio ploto netąsių elementų įtakos generuojamos kompresijos vertėms tyrimai. Šioje disertacijoje pateikiamas gerokai platesnis ir detalesnis netąsių elementų įtakos vertinimas, atsižvelgiant ne tik į santykinio ploto, bet ir iki šiol neanalizuotų savybių – elemento formos ar krypties – įtaką. Kitas iki šiol nenagrinėtas aspektas – megztų ortopedinių kompresinių įtvarų komforto savybių vertinimas. Disertacijoje teigiama, kad dėl įtvaro dėvėjimo metu pakintančių megztinės medžiagos struktūros parametrų laidumas orui turėtų būti vertinamas esant eksploatavimą imituojančiai ištįsai. Atsižvelgus į disertacijos rengimo metu gautus duomenis, kompresinio gaminio projektavimas turėtų būti vykdomas tiksliau ir našiau, o optimizuojant gamybos procesą, turėtų būti pagerinti jo ekonominiai rodikliai ir ekologiškumas.

IŠVADOS

1. Nustatyta, kad stabilizavimo proceso metu patiriamas gaminio tempimo jėgos ir generuojamos kompresijos padidėjimas, tirtuoju atveju siekiantis iki 4,5 %, yra gana reikšmingas ir turi būti įvertinamas gaminio kompresijos prognozavimo metu. Eksperimentiniai kompresijos nustatymo tyrimai turi būti vykdomi bandinius apdorojus stabilizavimo procese.
2. Nustatyta, kad ataudinių siūlų įterpimas į gaminį padidina generuojamos kompresijos vertes, tačiau tempimo jėgos eilučių kryptimi ir ataudinio elastomerinio siūlo įterpimo į medžiagą raporto tankumo priklausomybė nėra tiesinio pobūdžio. Ataudinio elastomerinio siūlo kiekį sumažinus nuo įterpimo kiekvienoje eilutėje iki įterpimo kas antroje eilutėje, tempimo jėga sumažėja 22,62–28,81 %, o sumažinus nuo įterpimo kas antroje eilutėje iki įterpimo kas ketvirtoje eilutėje, tempimo jėgos pokytis siekia tik 0,87–4,97 %, priklausomai nuo ištįsos dydžio.
3. Nustatyta, kad ataudinio siūlo įterpimo raportas, o ne absoliutinis kiekis nulemia generuojamos kompresijos dydį: esant tam pačiam elastomerinio siūlo kiekiui, tačiau dvigubai retesniam įterpimui į struktūrą, tempimo jėga eilučių kryptimi sumažėjo net 23,88–27,86% (priklausomai nuo ištįsos dydžio).
4. Elastomerinio siūlo parametrai nulemia mezginio elgseną tempimo eilučių kryptimi metu:

- Elastomerinio ataudinio siūlo įtempį mezgimo metu padidinus 1,75 karto, tempimo jėga išauga 16,5 %, esant 30 % fiksuotai ištįsai, tačiau ilgalaikės įrąžos relaksacijos metu ši įtaka laipsniškai nyksta. Todėl ilgalaikiam dėvėjimui skirtų gaminių kompresinių savybių negalima prognozuoti remiantis tik elastomerinio siūlo įtempio mezgimo metu verte.
- Didėjant elastomerinio siūlo šerdinio komponento ilginiam tankiui, didėja medžiagos tempimo jėga, tačiau elastomerinio siūlo šerdinio elemento ilginis tankis nėra tiesiogiai proporcingas tempimo jėgos dydžiui. Tirtuoju atveju šerdinio

elemento ilginį tankį padidinus 3,75 karto, tempimo jėga padidėjo tik 6,4–7,8 % (priklausomai nuo bandinių stabilizavimo būsenos).

5. Didinant netąsaus elemento užimamą plotą gaminyje, gaminio generuojama kompresija tiesiškai didėja, neatsižvelgiant į ataudinio siūlo įterpimo tankumą. Netąsiam elementui užimant 25 %, tempimo jėga eilučių kryptimi padidėjo iki 16,21 %, esant 10 % fiksuotai ištįsai, ir iki 20,93 %, esant 20 % fiksuotai ištįsai.
6. Nustatyta, kad netąsaus elemento forma ar orientacijos gaminyje kryptis turi įtakos tempimo jėgai ir generuojamai kompresijai – vienodo ploto, bet skirtingos formos ar krypties netąsių elementų įtaka tempimo jėgai skyrėsi net iki 20 %. Nustatyta, kad tempimo jėga eilučių kryptimi didėja, didėjant netąsaus elemento aukščiui tempimo kryptimi.
7. Nustatyta, kad, norint pasiekti reikiamą kompresijos vertę, skirtingų dydžių ar pozicijų ortopediniams kompresiniams įtvarams būtinos skirtingos ištįsos vertės. Generuojamos kompresijos vertinimas turi būti atliekamas atskirai kiekvieno dydžio įtvarui su visais baigtam gaminiui būdingais priedais, dėl skirtingo tąsios įtvaros dalies santykinio ploto sumažėjimo, įterpus standartinio dydžio netąsius elementus.
8. Nustatyta, kad įrąžos relaksacijos metu megzto kompresinio gaminio ar jo elementų tempimo jėga mažėja, o didžiausi tempimo jėgos pokyčiai įvyksta per pirmąsias 100–200 s. Todėl kompresinių gaminių generuojama kompresija turi būti vertinama ne anksčiau, nei po 120 s įrąžos relaksacijos.
9. Nustatyta, kad skirtingas ataudinio elastomerinio siūlo įterpimas gali pakeisti laidumą orui iki 49 %. Esant 20 % ištįsai eilučių kryptimi, kompresinių mezginių laidumo orui vertės padidėja net iki 25,9 %, todėl laidumas orui turi būti vertinamas esant minimaliai dėvėjimo metu patiriamai medžiagos ištįsai.
10. Įvertinus gautus rezultatus, sudaryta bazinė kompresinio ortopedinio įtvaro parametrų gaminio kompresinėms ar komfortinėms savybėms vertinimo rekomendacija ir kompresinio ortopedinio gaminio projektavimo eiga.

PADĖKA

Esu labai dėkinga savo mokslinei vadovei prof. dr. Daivai Mikučionienei už perduotas žinias ir patirtį, skatinimą tobulėti, neribotus patarimus ir konsultacijas, įvairiapusę pagalbą ir palaikymą visų studijų metu.

Dėkoju dr. Gintai Laureckienei už suteiktas žinias, pagalbą, skirtą laiką ir palaikymą bei kitiems KTU dėstytojams ir darbuotojams už patirtį ir žinias, įgytas studijų metu.

Labai dėkoju savo šeimai ir artimiesiems už kantrybę, visapusį palaikymą ir pagalbą studijų ir disertacijos rašymo metu. Esu itin dėkinga savo vyrui už supratingumą ir pagalbą suderinant doktorantės ir mamos vaidmenis.

UDK 677.075.017.4 + 615.477](043.3)
SL344. 2019-06-17, 2 leidyb. apsk. l. Tiražas 50 egz.
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