Stiffness change of abdominal prosthesis Optomesh™ under cyclic loading

Cite as: AIP Conference Proceedings **2077**, 020058 (2019); https://doi.org/10.1063/1.5091919
Published Online: 21 February 2019

Agnieszka Tomaszewska, Szabolcs Szinvai, and Krzysztof Żerdzicki

Stiffness Change of Abdominal Prosthesis Optomesh^{TM} Under Cyclic Loading

Agnieszka Tomaszewska[1,a)], Szabolcs Szinvai[2,b)] and Krzysztof Żerdzicki[1,c]

[1]*Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, Department of Structural Mechanics, Narutowicza 11/12, 80-233 Gdańsk, Poland*
[2]*Budapest University of Technology and Economics, Faculty of Civil Engineering, Műegyetem rakpart 3, 1111 Budapest, Hungary*

[a)]Corresponding author: atomas@pg.edu.pl
[b)]szinvaiszab@gmail.com
[c)]krzysztof.zerdzicki@pg.edu.pl

Abstract. Abdominal prostheses are used in humans for abdominal wall strengthening or reconstruction. From the mechanical point of view they are membranes, so their basic mechanical property is tensile stiffness. This property is experimentally identified for a selected implant, Optomesh^{TM}. The obtained results are described herein. Uni-axial simple and cyclic tension tests are a basis for the analysis. Both kinds of tests allowed to distinguish two states of the material, namely: baseline and preconditioned. In the preconditioned state the material reveals approximate two-fold increase of tensile stiffness in comparison to baseline state. In both states the material demonstrate orthotropy. Both features are typical for knitted synthetic abdominal implants, however, the first one is not, while the other is desired from the mechanical point of view of operated hernia.

INTRODUCTION

Abdominal prostheses are used in humans for different purposes related to the need of abdominal wall strengthening. In particular they are applied to prevent hernia occurrence in post-operational scar or to reconstruct abdominal tissue in a case of hernia. Hernia (e.g. ventral, periumbilical, inguinal) is a serious medical problem. It occurs when a continuity of connective tissue is broken and internal pressure pushes intestines outside. A bulk in abdominal wall is a visible proof of a sickness, the other is pain. Untreated hernia can enlarge its diameter. It can lead to serious health complications and also to death.

There are numbers of abdominal prostheses (meshes) available in medical market. Scientific papers report on their biochemical, physical and mechanical properties [1], [2], [3], [4], [5]. There is also an extensive bibliography on medical reports concerning reliability of hernia management made with the use of different prostheses and joints, see e.g. [6], [7]. This wide discussion is a result of still new materials proposed by the producers, but also it is connected with various medical outcome of different medical procedures and materials. [8] report for incisional hernia in United States a 20% recurrence rate, related to mesh device or suture failure. Also authors in [9] describe 20% recurrence rate of ventral hernia operated with the use of selected prosthesis and joint. Other authors discuss lower level of the sickness recurrence, e.g. 4.4% [10] or 1.2% [11]. The recurrence rate obviously depends on medical protocol and materials utilized. Each paper in the field of hernia repair deepens the knowledge on medical and mechanical issues in the subject and contributes to the improvement of medical solutions.

In this paper some mechanical properties of Optomesh^{TM} ThinLight prosthesis (TRICOMED SA, Świętojańska 5/9 St., 93-493 Łódź, Poland) are discussed. The material tension stiffness is determined for its basic and preconditioned state. The stiffness increase caused by the material preconditioning is discussed and compared to the results obtained by the author for other abdominal mesh DynaMesh®-IPOM (FEG Textiltechnik mbH, Aachen,

Scientific Session on Applied Mechanics X
AIP Conf. Proc. 2077, 020058-1–020058-7; https://doi.org/10.1063/1.5091919
Published by AIP Publishing. 978-0-7354-1805-9/$30.00

Germany) [12]. Both meshes are knitted structures, however with different pattern. The results shown in this paper broadens the state of knowledge on knit abdominal implants.

MATERIALS AND METHODS

Optomesh^{TM} Thin Light Material

The mesh is non-absorbable material, knitted of monofilament polypropylene yarn in a way which makes 3-dimensional complex structure. The implant is visible in Fig. 1. The mesh pores are mostly irregular quadrangles and some have triangular shapes. It can be observed that in the direction close to parallel to the knitting pattern the threads forming the pores sides are made of a single thread while in the direction close to perpendicular to the former one the pores sides are made of two threads. This solution may result in obtaining orthotropic properties of the implant. The pores sizes are between 1 and 2 mm.

The mesh reveals high tolerance by human organism. It is dedicated to abdominal, inguinal, femoral, preumbilical and post-operative hernia operations. For ThinLight and Macropore variants of Optomesh the producer declares surface mass between 60 and 85 g/m^2, and mesh thickness between 0.4 and 0.8 mm. The higher values concern the Macropore version, as discussed in [13]. Tension stiffness of the material is not discussed in the literature so far.

Experiments

Previous works discuss orthotropic properties of meshes knitted of polypropylene yarns [12], [14], [15], [5]. Typically, the orthotropy axes are parallel and perpendicular to the knitting pattern. The construction of the considered mesh suggests such a setup also in this case. Thus, two kinds of rectangular samples have been prepared. Their size is 120 × 30 mm with the longer dimension oriented parallel to the knitting pattern (direction '1' of the mesh) – these samples are denoted as 'kind 1' or with the longer dimension oriented perpendicular to the knitting pattern (direction '2' of the mesh) – these samples are denoted as 'kind 2'. Five pieces of each sample kind have been prepared. One piece of each kind has been subjected to uni-axial simple tension test in order to determine limit load as well as to decide on load levels in cyclic tests. The other four samples of both kinds have been subjected to cyclic uni-axial tension tests. Ten loading cycles have been performed each time. Different load ranges have been set in subsequent tests. They respond to physiologically possible load of the mesh joints, discussed in [4]. The samples have been tested with constant strain ratio of 0.003 1/s. The specification of the performed experiments is presented in Table 1 and the example samples are shown in Fig. 1. Zwick Roell Z020 strength machine with video-extensometer has been used. Clamp-to-clamp distance of 90 mm has been preserved while the samples mounting in order to prevent uni-axial tension state in central part of each sample. Strains of this central part, with an approximate initial length of 30 mm, have been measured by the video-extensometer whose resolution reaches 0.25μ. Force and strains are collected by the testing system. Force measuring accuracy is below 0.1 N.

TABLE 1. Sample labelling and force applied in experiments.

Orientation of the sample	Sample label	Force range in cyclic test [N]	Failure load [N]
'1'	1.0	simple tension test	82
	1.1	0.5-10	100
	1.2	0.5-20	85
	1.3	0.5-40	80
	1.4	0.5-60	105
'2'	2.0	simple tension test	106
	2.1	0.5-10	110
	2.2	0.5-20	110
	2.3	0.5-40	100
	2.4	0.5-60	110

Tension Stiffness Identification

It is proved in literature that knitted synthetic meshes become stiffer when preconditioned [16], [17]. Preconditioning may happen in patient's body while cyclic stretching of abdominal wall. Thus, the following two states of the Optomesh^{TM} are considered here: baseline (as produced) and preconditioned (just formerly stretched). Tension stiffness is identified as a tangent to cross-sectional force to strain relations obtained experimentally. It is worth to explain that abdominal prostheses do not have any bending stiffness - from the mechanical point of view they are membranes. Due to their small thickness not stress is determined but cross-sectional force, expressed in [N/m], which is a relation of a force to sample width [18].

In the baseline state tension stiffness is identified based on simple tension test. The material stiffness in the preconditioned state is identified based on cyclic tension tests. In this case elastic modulus is determined in loading path of each experimental hysteresis. The obtained elastic modulus values are then plotted against load cycle number and approximated by rational function to obtain estimation of the value for one-hundredth load cycle. This estimated value is accepted as the elastic modulus of the mesh in the preconditioned state in the strain range covered by the analyzed cyclic tests. The detailed procedure is explained in the paper [12].

RESULTS

The experimentally obtained relations of cross-sectional forces to engineering strains are drawn in Fig. 2. The elastic modulus values identified for the two distinguished directions of orthotropy are presented in Fig. 3 and in Table 2. Uncertainties of elastic modulus values are determined based on force and strain measurements accuracy, according to scatter transferring rules [19].

TABLE 2. Elastic modulus values identified for both directions of the material orthotropy and for the two considered material states.

Orientation of the sample	The mesh state	Strain range	Elastic modulus value [N/mm]
'1'	baseline	0.00-0.45	2.02 ± 0.01
		0.45-0.75	6.26 ± 0.02
	preconditioned	0.15-0.26	5.25 ± 0.08
		0.26-0.45	7.90 ± 0.06
		0.45-0.55	11.30 ± 0.09
		0.55-0.64	15.90 ± 0.11
'2'	baseline	0.00-0.28	3.07 ± 0.02
		0.28-0.48	13.17 ± 0.05
	preconditioned	0.07-0.13	5.00 ± 0.09
		0.13-0.20	10.30 ± 0.13
		0.2-0.28	17.00 ± 0.15
		0.28-0.37	21.00 ± 0.15

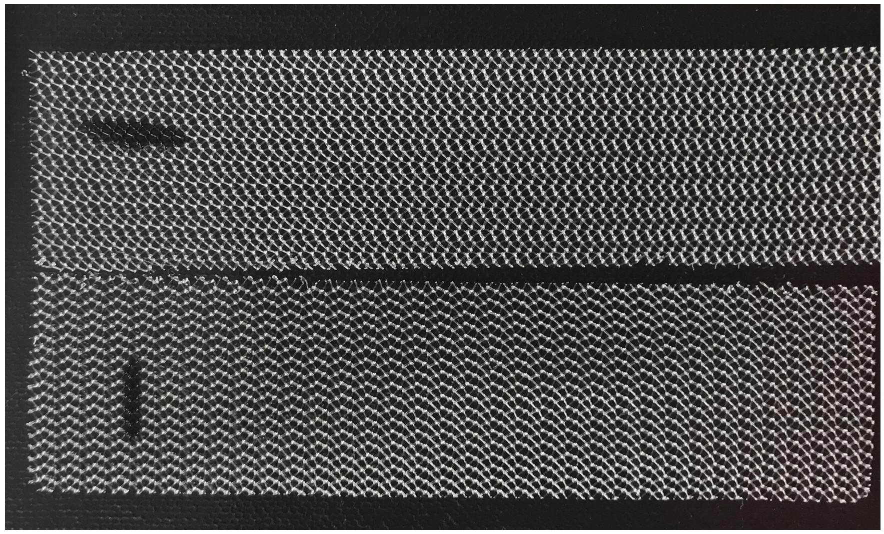

FIGURE 1. Samples prepared for the tests; top view: sample cut along the mesh knitting pattern, bottom view: longer dimension of the sample is perpendicular to the mesh knitting pattern.

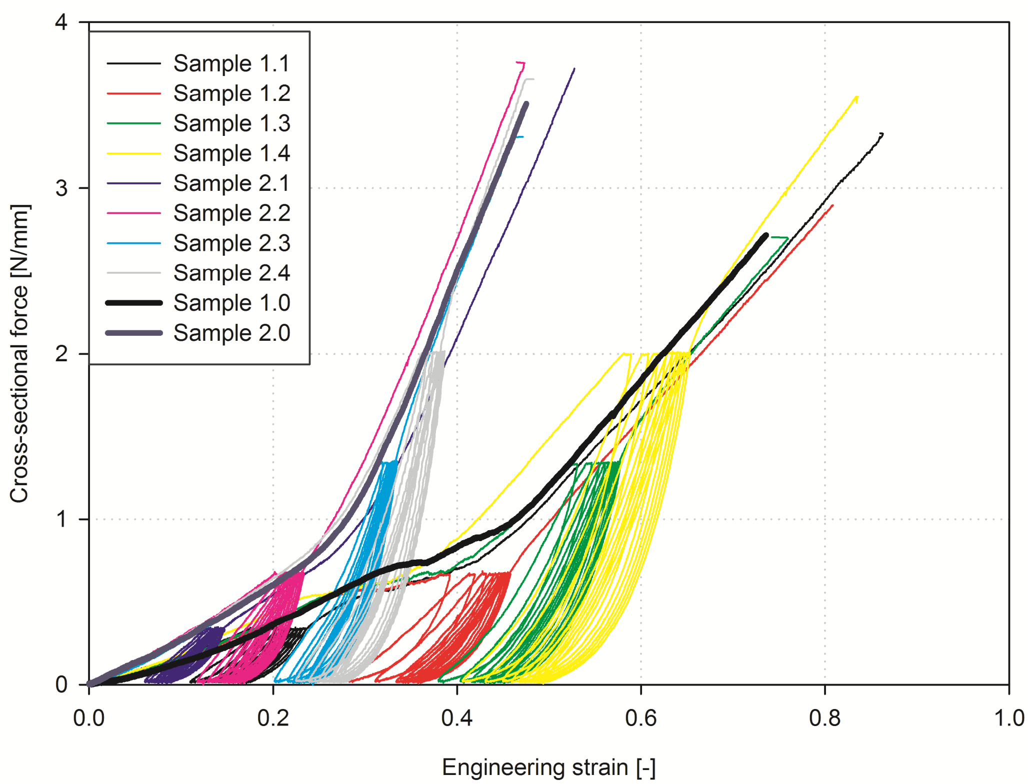

FIGURE 2. Experimental cross-sectional force vs strain for all samples.

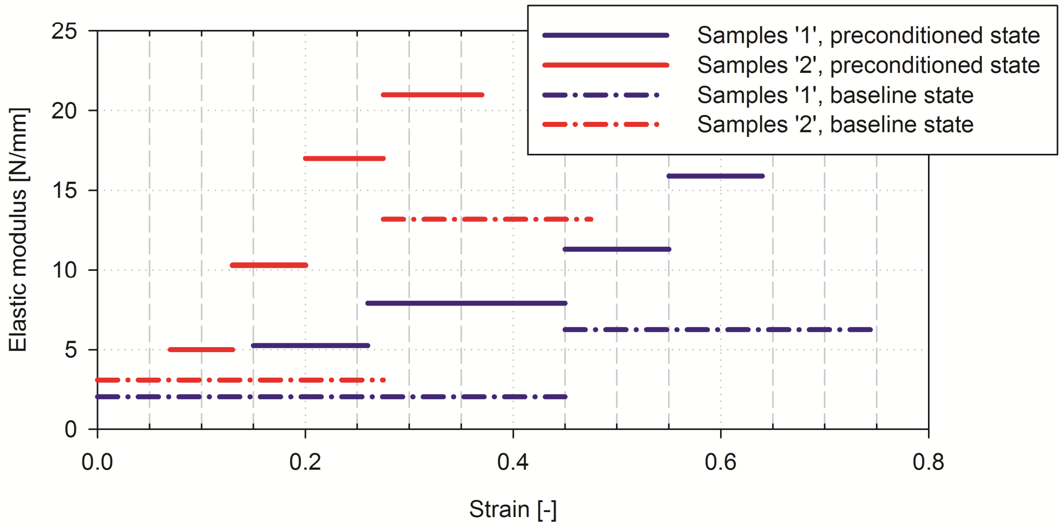

FIGURE 3. Elastic modulus values for two material states and two directions of orthotropy identified for strains covered by mechanical tests.

DISCUSSION

Performing simple and cyclic tension tests allows to observe some mechanical properties of abdominal implant. In this paper the material tension stiffness is of the greatest interest. At first, one can notice a similarity of cross-sectional force vs strain relations obtained for samples subjected to cyclic loading to the relations obtained for the same kinds of samples in simple tension (samples 1.0 and 2.0). This similarity is visible before hysteresis loops, which is obvious as this is the first loading path, but also after all hysteresis loops, when samples are stretched until rupture after loading cycles. On the other hand, elastic modulus of the prosthesis determined from loading paths of hysteresis loops is higher than the one determined for the same strain ranges in simple tension. Literature states that this phenomenon has two reasons. The first is the yarn mobility in knitted fabrics – during tension the yarns tighten in knots during stretching and thus the mesh becomes stiffer [20]. The other is strain hardening of the yarn substance, which is a result of increase of the polymer crystallinity due to introduced stress [21]. From the two above mentioned observations it may be concluded that the material has its baseline stiffness for the first-applied stress level and it is in the preconditioned state for the repeated stress level. As proved in [12] for DynaMesh®-IPOM, polypropylene knitted mesh can restore its baseline state from the preconditioned one, unless plastic strain occur (which is for sufficiently high deformation).

The observed stiffening effect is not a desired feature of abdominal meshes, because an increased stiffness causes an increase of force in joints which fix the mesh in abdominal wall. The increased force may cause the junction break down and then the hernia recurrence is observed. Sensitivity analysis of the junction force to various factors is described in [22], [23].

It is visible in Fig. 3 and in Table 2 that changing the material state from baseline to preconditioned causes at least doubling its tension stiffness. Such relation is observed also for DynaMesh®-IPOM [12]. However, when comparing tensile stiffness of Optomesh™ and DynaMesh®-IPOM in the directions '1' and '2', Optomesh is approximately twice stiffer than the other mesh in the baseline state and similarly in the preconditioned states of both materials. Also Optomesh is stiffer in the direction perpendicular to the knitting pattern than in the direction parallel to it, which is typical for abdominal implants, which should suit to orthotropic properties of abdominal wall [4], [5], [24], [25].

CONCLUSIONS

Tension stiffness of Optomesh™ implant dedicated to hernia operations is discussed in this paper. Two states of the material can be distinguished, namely: baseline and preconditioned, in which the material has different stiffness. In the preconditioned state the material is approximately twice stiffer than in the baseline one. This feature of the mesh is not desired in practise, as increased stiffness raises the risk of the hernia recurrence. However, such stiffness increase due to load history is typically observed in synthetic knitted abdominal meshes [17], [16], [12]. Thus, the preconditioned state of implants should be considered in calculating the necessary fixation strength in order to reduce the risk of the hernia recurrence.

Limitations of the study

Our research is dedicated to the case right after an operation, when the mesh is not yet incorporated with fascia, so no tissue overgrowth is considered. That is justified by the medical observations of most frequent hernia recurrences occurring shortly after the operation.

ACKNOWLEDGMENTS

This work has been partially supported by the National Science Centre (Poland) [grant No. UMO-2017/27/B/ST8/02518].

REFERENCES

1. E. R. Saberski, S. B. Orenstein, and Y. W. Novitsky, "Anisotropic evaluation of synthetic surgical meshes.," *Hernia*, vol. 15, no. 1, pp. 47–52, Feb. 2011.
2. B. Hernández, E. Peña, G. Pascual, M. Rodríguez, B. Calvo, M. Doblaré, and J. M. Bellón, "Mechanical and histological characterization of the abdominal muscle. A previous step to modelling hernia surgery.," *J. Mech. Behav. Biomed. Mater.*, vol. 4, no. 3, pp. 392–404, 2011.
3. A. Ciritsis, A. Horbach, M. Staat, C. K. Kuhl, and N. A. Kraemer, "Porosity and tissue integration of elastic mesh implants evaluated in vitro and in vivo," *J Biomed Mater Res Part B*, no. 106B, pp. 827–833, 2018.
4. A. Tomaszewska, I. Lubowiecka, C. Szymczak, M. Smietański, B. Meronk, P. Kłosowski, and K. Bury, "Physical and mathematical modelling of implant-fascia system in order to improve laparoscopic repair of ventral hernia.," *Clin. Biomech. (Bristol, Avon)*, vol. 28, no. 7, pp. 743–51, Aug. 2013.
5. C. R. Deeken and S. P. Lake, "Mechanical properties of the abdominal wall and biomaterials utilized for hernia repair," *J. Mech. Behav. Biomed. Mater.*, vol. 74, no. April, pp. 411–427, 2017.
6. F. E. Muysoms, S. a. Antoniou, K. Bury, G. Campanelli, J. Conze, D. Cuccurullo, a. C. de Beaux, E. B. Deerenberg, B. East, R. H. Fortelny, J.-F. Gillion, N. a. Henriksen, L. Israelsson, a. Jairam, a. Jänes, J. Jeekel, M. López-Cano, M. Miserez, S. Morales-Conde, D. L. Sanders, M. P. Simons, M. Śmietański, L. Venclauskas, and F. Berrevoet, "European Hernia Society guidelines on the closure of abdominal wall incisions," *Hernia*, vol. 19, no. 1, pp. 1–24, Jan. 2015.
7. T. Stetsko, K. Bury, I. Lubowiecka, C. Szymczak, A. Tomaszewska, and M. Śmietański, "Safety and efficacy of a Ventralight ST echo ps implant for a laparoscopic ventral hernia repair – a prospective cohort study with a one-year follow-up," *Pol. Przegl. Chir.*, vol. 88, no. 1, pp. 7–14, 2016.
8. M. M. Ibrahim, L. P. Poveromo, R. R. Glisson, A. Cornejo, A. E. Farjat, K. Gall, and H. Levinson, "Modifying hernia mesh design to improve device mechanical performance and promote tension-free repair q," *J. Biomech.*, vol. 71, pp. 43–51, 2018.
9. M. Pawlak, R.-D. Hilgers, K. Bury, A. Lehmann, R. Owczuk, and M. Śmietański, "Comparison of two different concepts of mesh and fixation technique in laparoscopic ventral hernia repair: a randomized controlled trial.," *Surg. Endosc.*, Jul. 2015.
10. V. K. Bansal, M. C. Misra, S. Kumar, Y. K. Rao, P. Singhal, A. Goswami, S. Guleria, M. K. Arora, and A. Chabra, "A prospective randomized study comparing suture mesh fixation versus tacker mesh fixation for laparoscopic repair of incisional and ventral hernias.," *Surg. Endosc.*, vol. 25, no. 5, pp. 1431–8, May 2011.
11. S. Sauerland, M. Walgenbach, B. Habermalz, S. Cm, and M. Miserez, "Laparoscopic versus open surgical techniques for ventral or incisional hernia repair (Review)," *Cochrane Libr.*, no. 3, pp. 1–62, 2011.

12. A. Tomaszewska, “Mechanical behaviour of knit synthetic mesh used in hernia surgery,” *Acta Bioeng. Biomech.*, vol. 18, no. 1, pp. 77–86, 2016.
13. A. Niekraszewicz, M. Kucharska, M. H. Struszczyk, A. Rogaczewska, and K. Struszczyk, “Investigation into Biological, Composite Surgical Meshes,” *FIBRES Text. East. Eur. January*, vol. 16, no. 6, pp. 117–121, 2008.
14. C. Szymczak, I. Lubowiecka, K. Szepietowska, and A. Tomaszewska, “Two-criteria optimisation problem for ventral hernia repair,” *Comput. Methods Biomech. Biomed. Engin.*, vol. 5842, no. March, pp. 760–769, 2017.
15. N. Sanbhal, L. Miao, R. Xu, A. Khatri, and L. Wang, “Physical structure and mechanical properties of knitted hernia mesh materials : A review,” *J. Ind. Text.*, vol. 48, no. 1, pp. 333–360, 2017.
16. S. Velayudhan, D. Martin, and J. Cooper-White, “Evaluation of dynamic creep properties of surgical mesh prostheses--uniaxial fatigue.,” *J. Biomed. Mater. Res. B. Appl. Biomater.*, vol. 91, no. 1, pp. 287–96, Oct. 2009.
17. X. Li, J. Kruger, J. Jor, M. Nash, V. Wong, and P. Dietz, “Characterizing the ex vivo mechanical properties of synthetic polypropylene surgical mesh,” *J. Mech. Behav. Biomed. Mater.*, vol. 37, pp. 48–55, 2014.
18. A. Ambroziak and P. Kłosowski, “Mechanical properties for preliminary design of structures made from PVC coated fabric,” *Constr. Build. Mater.*, vol. 50, pp. 74–81, Jan. 2014.
19. J. R. Taylor, *An Introduction to Error Analysis. The Study of Uncertainties in Physical Measurements.*, II. Sausalito, California: University Science Books, 1997
20. A. A. A. Jeddi, M. R. T. Otaghsara, and H. R. Alibabaei, “Investigation of fatigue behaviour of warp knitted fabrics under cyclic tension,” *Plast. Rubber Compos.*, vol. 33, no. 4, pp. 141–149, 2004.
21. M. El Fray and V. Altsta, “Fatigue behaviour of multiblock thermoplastic elastomers . 3 . Stepwise increasing strain test of poly (aliphatic / aromatic-ester) copolymers,” vol. 45, pp. 263–273, 2004.
22. C. Szymczak, I. Lubowiecka, A. Tomaszewska, and M. Śmietański, “Modeling of the fascia-mesh system and sensitivity analysis of a junction force after a laparascopic ventral hernia repair,” *J. Thoretical Appl. Mech.*, vol. 48, no. 4, pp. 933–950, 2010.
23. I. Lubowiecka, C. Szymczak, A. Tomaszewska, and M. Śmietański, “A FEM membrane model of human fascia – synthetic implant system in a case of a stiff ventral hernia orifice,” in *Shell Structures. Theory and Applications*, 2010, pp. 311–314.
24. I. Lubowiecka, K. Szepietowska, C. Szymczak, and A. Tomaszewska, “A preliminary study on the optimal choice of an implant and its orientation in ventral hernia repair,” *J. Theor. Appl. Mech.*, vol. 54, no. 2, pp. 411–421, 2016.
25. K. Junge, U. Klinge, A. Prescher, P. Giboni, M. Niewiera, and V. Schumpelick, “Elasticity of the anterior abdominal wall and impact for reparation of incisional hernias using mesh implants,” *Hernia*, vol. 5, no. 3, pp. 113–118, Sep. 2001.