This is an Accepted Manuscript of an article published by Taylor & Francis Group in COMPUTER METHODS IN BIOMECHANICS AND BIOMEDICAL ENGINEERING on 10/03/2015, available online: https://doi.org/10.1080/10255842.2015.1016004

Mechanical properties of mosquito nets in the context of hernia repair

Andrzej Ambroziak[1], Katarzyna Szepietowska[2] and Izabela Lubowiecka*

Department of Structural Mechanics, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Narutowicza 11/12, 80 - 233 Gdańsk, Poland

The paper deals with issue of applying mosquito nets as implants in hernia repair, which have already been used in resource-poor developing countries. Uniaxial tensile tests have been conducted on polyester mosquito meshes in two orthogonal directions. Non-linear elastic constitutive laws parameters have been identified to be applied in dense net material models. Mechanical performance of tested mosquito nets has been compared with properties of commercial implants used in treatment of hernia and with properties of human tissue. This study contributes to mechanical knowledge of hernia repair issue by investigation of cheaper alternative to commercial implants.

Keywords: hernia implants; mosquito net; mechanical properties; tensile test; Murnaghan model; dense net model

1. Introduction

A defect of fascia in the area of human abdomen causes a common medical problem called hernia. Although hernia repair is a known surgical procedure, recurrences still take place. Among different methods of hernia repair, the best results can be achieved by the use of a prosthetic mesh. The use of mesh to reinforce the abdominal wall in inguinal hernia repair is now accepted as the gold standard and led to recurrence rates below 5% (see, e.g., Frey et al. 2007; Sanders et al. 2013), which is a promising trend in surgery. However, the reduction of relapses and the medical costs, together with the improving of life comfort by reduction of postoperative pain, confirms the need of applying engineering methodology and physical or mathematical modelling to be used in surgery planning for its better efficiency (see e.g., Hernández-Gascón et al. 2011, Tomaszewska et al. 2013, Lubowiecka 2015a).

Even if the use of surgical meshes is the most efficient treatment, it often becomes unreachable for patients in resource-poor developing countries due to the high implant costs, so only the sutured repair with significantly inferior results can be applied. As reported in the literature (see, e.g., Sanders et al. 2013), the use of sterilised mosquito nets in hernioplasty can be a cheaper alternative in the healthcare for countries with the problem of endemic poverty. Following Clarke et al. (2009), the cost of an individual 10 cm × 15 cm mesh was estimated at US $0.0072–0.014, and the cost of sterilisation and packaging was US$1.46 per mesh.

The nylon and polyester mosquito nets have been tested previously with good results mostly in repairs of inguinal hernias in Africa. As reported by Freudenberg et al. (2006), there was neither significant difference in the clinical short-term outcome of the hernia treatment nor in the surgeons' comfort. Additionally, the polyester mosquito net mesh represents an alternative to commercial meshes, with a relatively low rate of early complications and similar short-term recurrence rate as with commercial implants (Clarke et al. 2009). The life quality index after surgery in both cases, using commercial implant and mosquito nets, is comparable, as shown in Freudenberg et al. (2006).

Properties of commercial implants have been tested and reported in the literature (see e.g., Saberski et al. 2011; Röhrnbauer and Mazza 2013). Some mechanical properties of polyethylene mosquito mesh without the identification of material model parameters were investigated and compared with properties of commercial implants by Sanders et al. (2013).

The present study describes the mechanical properties of some available polyester mosquito net meshes to be considered as a material for intracorporal implants in hernia repair. Tensile tests of the nets have been performed and the appropriate material models identified. The material models are particularly important when considering the mathematical modelling and simulation of implanted nets. The comparison of the mosquito nets properties with the commercial prosthetic meshes also provides necessary information about their compatibility with human abdominal wall (see e.g., Lubowiecka et al. 2014; Lubowiecka 2015b). This is a source of information for the surgeons about the mosquito net selection for efficient hernioplasty.

Mechanical behaviour of the considered mosquito nets within the tensile tests indicates their non-linear performance. Thus, some non-linear constitutive models for the mesh materials are identified and described. The multi-linear constitutive functions are defined and hyperelastic five-parameter Murnaghan material model is identified. The obtained parameters can be applied in dense net material model assumed in further finite element simulations of mosquito nets. Moreover, the obtained mechanical properties of mosquito nets are compared with the commercial surgical implants widely applied in hernia repair and with properties of fascia – the key layer of the abdominal wall in the context of hernia.

2. Materials and methods

2.1 Materials

Four polyester mosquito meshes have been investigated: Mako® (Sp. z o. o. , Skawina, Poland), FX (manufactured by BROS Sp. J, Poznań, Poland), Tesa® (SE – A Beiersdorf Company, Hamburg, Germany) and Coronet (Sp. z o. o., Mikołów, Poland). Within the paper there are called, MSQ1, MSQ2, MSQ3 and MSQ4, respectively.

All the nets structures are presented in Figure 1. The MSQ1, MSQ2 and MSQ4 (Figure 2(a)) have a structure different than MSQ3 shown in Figure 2(b). However, mesh pores of different mosquito nets are of different sizes. In MSQ3 it is hard to distinguish the directions of material structure with the unaided eye.

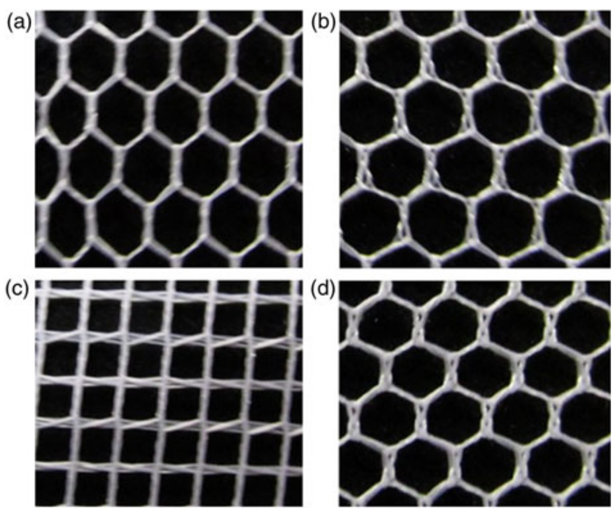

Figure 1. Photos of mosquito nets structures (zoom 100 ×): (a) MSQ1, (b) MSQ2, (c) MSQ3 and (d) MSQ4.

2.2 Concept of dense net model

In the analysis of technical fabrics, it is possible to apply the finite element in the plane stress state with the special substructure appropriate to describe behaviour of the thread families. This concept called the dense net model has been applied by Ambroziak and Kłosowski (2011) and Branicki (1969) and in the modelling of surgical implants by Lubowiecka (2015a and 2015b). It is easily applicable in self-made or commercial finite element codes and can be used with different types of material description of threads' behaviour. In this model, it is assumed that the forces in the thread families depend on the uniaxial strain in the same family only. The friction between thread families is neglected. Consequently, the thread force increment of the direction of d1 ($\Delta\sigma_1$) or direction of d2 ($\Delta\sigma_2$) is calculated from the following equations:

$$\begin{aligned} \Delta\sigma_1 &= F_1(\varepsilon_1)\cdot\Delta\varepsilon_1, \\ \Delta\sigma_1 &= F_2(\varepsilon_1)\cdot\Delta\varepsilon_1, \end{aligned} \tag{1}$$

where $F_1(\varepsilon_1)$ and $F_2(\varepsilon_1)$ represent the uniaxial material functions of the threads called longitudinal stiffnesses. For the definition of these functions, any type of the constitutive equation can be used.

Basing on the geometrical relationship, the thread force and strain can be expressed by the stress and strains components in the plane stress state as follows:

$$\boldsymbol{\varepsilon}_{\xi} = \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \cos^2\alpha & \sin^2\alpha & \sin\alpha\cos\alpha \end{bmatrix} \begin{Bmatrix} \varepsilon_{x_2} \\ \varepsilon_{x_2} \\ \gamma_{x_1x_2} \end{Bmatrix} = \mathbf{T}_{x\xi}\boldsymbol{\varepsilon}_x,$$

$$\boldsymbol{\sigma}_x = \begin{Bmatrix} \sigma_{x_1} \\ \sigma_{x_2} \\ \tau_{x_1x_2} \end{Bmatrix} = \begin{bmatrix} 1 & \cos^2\alpha \\ 0 & \sin^2\alpha \\ 0 & \sin\alpha\cos\alpha \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \end{Bmatrix} = (\mathbf{T}_{x\xi})^T\boldsymbol{\sigma}_{\xi}, \tag{2}$$

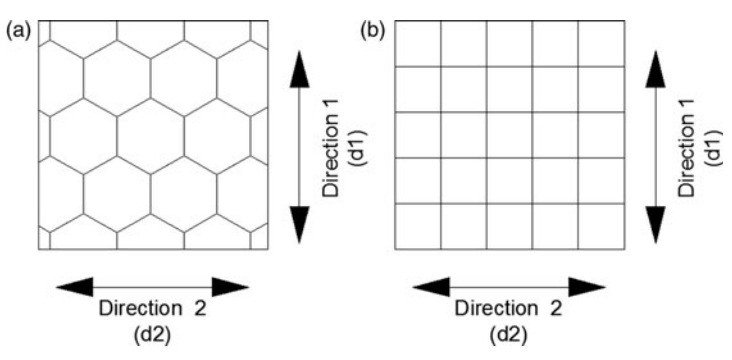

Figure 2. Scheme of knit structure of mosquito nets: (a) MSQ1, MSQ2 and MSQ4, and (b) MSQ3.

where α is the actual inclination angle between the thread families during the deformation process. The angle between thread families, α, changes during deformation and is calculated according to the current values of stress components σ_{x_2} and $\tau_{x_1x_2}$ in the fabric from the relation:

$$\alpha = \operatorname{arctg}\frac{\sigma_{x_2}}{\tau_{x_1x_2}}. \tag{3}$$

Consequently, the constitutive relation in the plane stress state of the whole element, expressed by the thread forces, takes the form of:

$$\boldsymbol{\sigma}_{xt} = \boldsymbol{\sigma}_{xt-\Delta t} + \Delta\boldsymbol{\sigma} = \boldsymbol{\sigma}_{xt-\Delta t} + \mathbf{D}_x \cdot \Delta\boldsymbol{\varepsilon}_x, \tag{4}$$

where $\boldsymbol{\sigma}_{xt}$ are the stress components in actual time increment t, $\boldsymbol{\sigma}_{xt-\Delta t}$ are the stress components in last increment $t-\Delta t$, $\Delta\boldsymbol{\sigma}$ and $\Delta\boldsymbol{\varepsilon}_x$ are the increments of stress and strain components, and $\mathbf{D}_x$ is the elasticity matrix which can be expressed as:

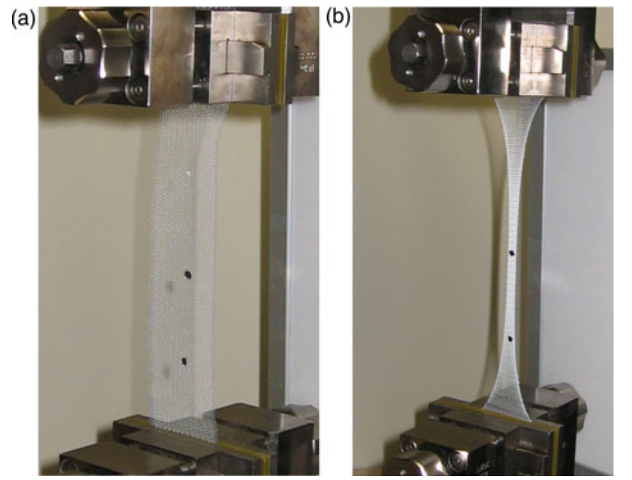

Figure 3. Specimen in strength machine: (a) before test (b) during the test.

$$\mathbf{D}_x = \begin{bmatrix} F_1(\varepsilon_{\xi 1}) + F_2(\varepsilon_{\xi 2})\cos^4\alpha & F_2(\varepsilon_{\xi 2})\sin^2\alpha\cos^2\alpha & F_2(\varepsilon_{\xi 2})\sin\alpha\cos^3\alpha \\ F_2(\varepsilon_{\xi 2})\sin^2\alpha\cos^2\alpha & F_2(\varepsilon_{\xi 2})\sin^4\alpha & F_2(\varepsilon_{\xi 2})\sin^3\alpha\cos\alpha \\ F_2(\varepsilon_{\xi 2})\sin\alpha\cos^3\alpha & F_2(\varepsilon_{\xi 2})\sin^3\alpha\cos\alpha & F_2(\varepsilon_{\xi 2})\sin^2\alpha\cos^2\alpha \end{bmatrix}. \tag{5}$$

2.3 Experiments: uniaxial tests description

In the uniaxial tensile tests the Zwick type, computer operated strength-testing machine was used. The 50 mm wide specimens of the dry mosquito net from the same batch of fabric in directions d1 and d2 (Figure 2) were cut according to PN-EN ISO 13934-1. The grip separation of 200 mm was taken for the test. The specimens were subjected to tension with displacement rate of grip of 20 mm/min in the room temperature (about +20°C). Tests were controlled by video extensometer with constant base (about 50 mm).

Three specimens for each directions d1 and d2 were exposed to uniaxial tension (Figure 3). The displacement–force relations obtained from the strength machine were transformed into strain–stress curves. It should be noted that in the study, the Cauchy strain and stress measures were assumed here to be consistent with the results for commercial implants used as a reference (Tomaszewska et al. 2013). Also, in most of the papers dealing with textile implants used for hernia repair, the Cauchy stress and strain measures are applied (see, e.g., Hernández-Gascón et al. 2011; Saberski et al. 2011) to present the stress–strain curves for the analysed material. Thus, the authors decided to assume Cauchy strain measure in the present analysis of the tensile test outcomes in order to provide a consistent comparison of the obtained stress–strain curves with the relations published in the literature.

The authors are aware of the simplification resulting from the application engineering strain measure. In the human body, mosquito net undergoes large strains. Hence, within Finite Element simulations of implanted mosquito net, the large strain measure will be applied in the future research. Presented results can be easily transformed to other strain/stress measures. The range of the strains observed in the human front abdominal wall during life activity does not exceed 25–30%. In this range, the Cauchy strains do not differ more than 7% from logarithmic strains (see Figure 4).

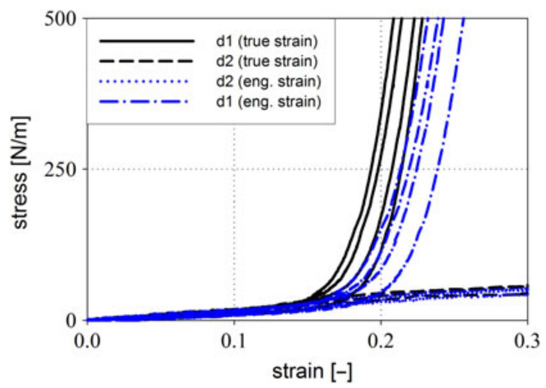

Figure 4. Cauchy strains vs. logarithmic strains for MSQ1.

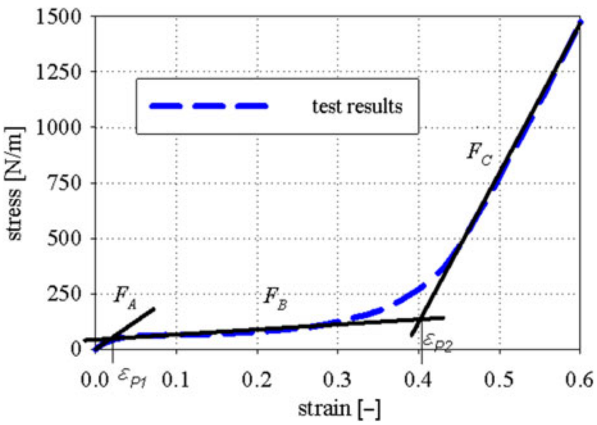

Figure 5. Graphical interpretation of the F parameters.

2.4 Non-linear elastic constitutive description

Analysing the stress–strain curves, one can observe characteristic points of distinct curvatures. Hence, a piecewise linear model can be applied to describe stress–strain relation. In this concept (see Figure 5), the coefficients (F_i) of a linear function and intersection points ε_i specifying the range of applicability of longitudinal elastic modulus should be set (see e.g., Ambroziak and Kłosowski 2014a, 2014b).

2.5 Murnaghan model-based description of a mosquito net behaviour

Due to the apparently non-linear behaviour of the mosquito net, the Murnaghan five-parameter model (see, e.g., Murnaghan 1951) is also applied to describe the mesh properties. This model depicts well the mechanics of textile structure (see, e.g., Ambroziak and Kłosowski 2014a, for polyvinylidene difluoride-coated fabric). In the Murnaghan solid model, the potential energy is described by the equation (Lurie 1990)

$$\Phi = \frac{\lambda + 2\mu}{2}(I_{\mathbf{E}})^2 - 2\mu II_{\mathbf{E}} + \frac{l + 2m}{3}(I_{\mathbf{E}})^3 - 2m(I_{\mathbf{E}})II_{\mathbf{E}} + nIII_{\mathbf{E}}, \tag{6}$$

$$\varepsilon_2 = \pm \frac{\sqrt{\left(\varepsilon_1^2\left((2m-n)^2 - 8l(3m-n)\right) + 4(\varepsilon_1(4l\mu - 2m(2\lambda+\mu) + n(\lambda+\mu)) + (\lambda+\mu)^2\right)}}{4(2l+m)} + - \frac{\varepsilon_1(4l - 2m + n) - 2(\lambda+\mu)}{4(2l+m)}. \tag{11}$$

where λ and μ are the Lame constants, l, m and n are the Murnaghan constants and $I_{\mathbf{E}}$, $II_{\mathbf{E}}$ and $III_{\mathbf{E}}$ are the invariants of the Lagrange-Green strain tensor. The stress $\boldsymbol{\sigma}$ is derived as the gradient of the energy Φ with respect to strain $\mathbf{E}$:

$$\boldsymbol{\sigma} = \left(\frac{\lambda - 2\mu}{3}I_{\mathbf{E}} - (2m-n)II_{\mathbf{E}} + l(I_{\mathbf{E}})^2\right)\mathbf{I} + (2\mu + (2m-n)I_{\mathbf{E}})\mathbf{E} + n\mathbf{E}^2. \tag{7}$$

In particular case of the uniaxial stress state, the potential energy Φ can be determined as

$$\begin{aligned}\Phi = {} & \frac{\lambda + 2\mu}{2}(\varepsilon_1 + 2\varepsilon_2)^2 - 2\mu(2\varepsilon_1\varepsilon_2 + \varepsilon_2^2) \\ & + \frac{l + 2m}{3}(\varepsilon_1 + 2\varepsilon_2)^3 + \\ & - 2m\left(2\varepsilon_1^2\varepsilon_2 + \varepsilon_1\varepsilon_2^2 + 4\varepsilon_1\varepsilon_2^2 \right. \\ & \left. + 2\varepsilon_2^3\right) + n\left(\varepsilon_1\varepsilon_2^2\right).\end{aligned} \tag{8}$$

Finally, the stress components can be written in the following form

$$\begin{aligned}\sigma_{11} = {} & \frac{\partial\Phi}{\partial\varepsilon_1} = (\lambda + 2\mu)(2\varepsilon_1 + 4\varepsilon_2) - 2\mu 2\varepsilon_2 \\ & + (l + 2m)(\varepsilon_1 + 2\varepsilon_2)^2 - 2m\left(4\varepsilon_1\varepsilon_2 + 5\varepsilon_2^2\right) + n\varepsilon_2^2 \\ = {} & \varepsilon_1^2(l + 2m) + \varepsilon_1(4\varepsilon_2 l + \lambda + 2\mu) \\ & + \varepsilon_2(\varepsilon_2(4l - 2m + n) + 2\lambda),\end{aligned} \tag{9}$$

$$\begin{aligned}\sigma_{22} = \sigma_{33} = {} & \frac{\partial\Phi}{\partial\varepsilon_2} = (\lambda + 2\mu)(4\varepsilon_1 + 8\varepsilon_2) \\ & - 2\mu(2\varepsilon_1 + 2\varepsilon_2) + 2(l + 2m)(\varepsilon_1 + 2\varepsilon_2)^2 \\ & - 2m\left(2\varepsilon_1^2 + 2\varepsilon_1\varepsilon_2 + 8\varepsilon_1\varepsilon_2 + 6\varepsilon_2^2\right) + 2n\varepsilon_1\varepsilon_2 \\ = {} & 2\left(\varepsilon_1^2 l + \varepsilon_1(\varepsilon_2(4l - 2m + n) + \lambda) + 2\varepsilon_2^2(2l + m) \right. \\ & \left. + 2\varepsilon_2(\lambda + \mu)\right).\end{aligned} \tag{10}$$

It is necessary to solve the equation $\sigma_{22} = 0$ in order to determine the unknown component of ε_2 as in the Equation (11)

Then, the least squares regression is applied to determine the material parameters. The Marquardt–Levensberg algorithm is used to find the coefficients of the independent variables. On the basis of this numerical algorithm, the parameters λ, μ, l, m and n have been specified for each individual tensile test of the studied mosquito nets. For more detailed description of the Murnaghan model, see, for example, Ambroziak (2006).

3. Results

The results of identification are presented in the form $\bar{x} \pm \bar{s}_x$, where $\bar{x}$ is the arithmetic mean of certain stresses or strains and $\bar{s}_x$ is the standard error of the mean value of the specified range, presented by

$$\bar{x} = \sum_{i=1}^{N} \frac{x_i}{N}, \qquad \bar{s}_x = \frac{\sqrt{\frac{1}{N-1}\sum (x_i - \bar{x})^2}}{\sqrt{N}}, \tag{12}$$

where x_i is a value determined by i-test and N is the number of tests.

3.1 Mechanical properties

All tests were done until the specimens' failure. The value of the ultimate tensile strength (UTS) and rupture strain ε_R (see Table 1) has been specified for each experiment. Note that the stress–strain curves generally have repetitive characteristics and similar shapes. The rupture strain here coincides with strain at the UTS.

3.2 Identification of non-linear elastic constitutive law

The parameters for the piecewise linear model are given in the Table 2. In order to verify the results of the identification, a numerical simulations of the uniaxial tensile tests were performed for established mean values of the piecewise linear coefficients. The comparative results are shown in Figures 6–9, where a good accuracy of experiments and numerical simulations are observed.

Table 1. Values of UTS and rapture strain ε_R.

	UTS_{d1} (N/m)	ε_{Rd1} (–)	UTS_{d2} (N/m)	ε_{Rd2} (–)
MSQ1	2320 ± 180	0.38 ± 0.01	1020 ± 45	0.82 ± 0.04
MSQ2	1280 ± 35	0.48 ± 0.01	1140 ± 80	0.64 ± 0.02
MSQ3	1810 ± 25	0.13 ± 0.01	2070 ± 40	0.71 ± 0.02
MSQ4	2110 ± 40	0.46 ± 0.02	1695 ± 70	0.57 ± 0.01

3.3 Murnaghan model-based description of mosquito net behaviour

Identification of the non-linear elastic Murnaghan model has been successfully performed on the basis of the uniaxial tensile tests for the description of the mosquito net behaviour. Murnaghan coefficients are presented in Table 3. The calculation results are compared with the laboratory tests in Figures 10–13, where d1 and d2 represent the experimental outcomes and M d1 and M d2 the appropriate results of numerical simulation with application of the Murnaghan model.

4. Discussion

4.1 Mechanical properties of mosquito nets vs. implants used in hernia repair

In order to discuss usefulness of tested mosquito nets in hernia repair, their mechanical properties have been compared with commercial implants. In the study by Tomaszewska et al. (2013), the moduli of elasticity are given for the following surgical meshes: Proceed™ Surgical Mesh, Gore® Dualmesh® Biomaterial, Dyna-Mesh® and Parietex™ used in laparoscopic ventral hernia repair. The set of appropriate parameters is presented in Table 4. The longitudinal direction corresponds to direction d2 of mosquito nets and lateral direction corresponds to direction d1 of mosquito nets. Comparison of the mechanical performance of the surgical meshes material with the behaviour of tested fabrics is given in Figure 14, where an orthotropic performance of all discussed materials is noticeable.

Due to anisotropy of the human abdomen, defining of the stiffer direction of the mesh in range of strains in which it will be working is crucial to the proper choice of its orientation in the human body (Junge et al. 2001;

Table 2. Non-linear elastic properties of mosquito nets.

MQS	Thread direction	F_A (N/m)	F_B (N/m)	F_C (N/m)	ε_{P1} (–)	ε_{P2} (–)
MSQ1	d1	155 ± 17	14010 ± 160	–	0.21 ± 0.01	–
	d2	184 ± 24	125 ± 23	4000 ± 60	0.28 ± 0.04	0.58 ± 0.03
MSQ2	d1	100 ± 10	7840 ± 80	–	0.32 ± 0.01	–
	d2	254 ± 13	147 ± 7	3750 ± 90	0.14 ± 0.02	0.35 ± 0.01
MSQ3	d1	20,040 ± 420	12,900 ± 200	–	0.035 ± 0.002	–
	d2	1630 ± 110	140 ± 15	6900 ± 300	0.034 ± 0.004	0.43 ± 0.01
MSQ4	d1	180 ± 20	10,900 ± 700	–	0.28 ± 0.01	–
	d2	716 ± 39	350 ± 50	7000 ± 100	0.23 ± 0.08	0.36 ± 0.02

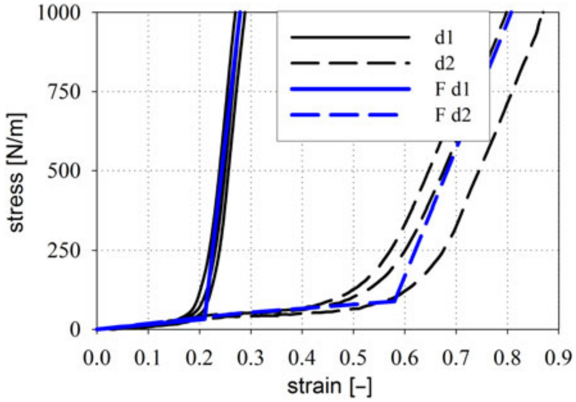

Figure 6. Piecewise linear material model vs. tensile tests for MSQ1.

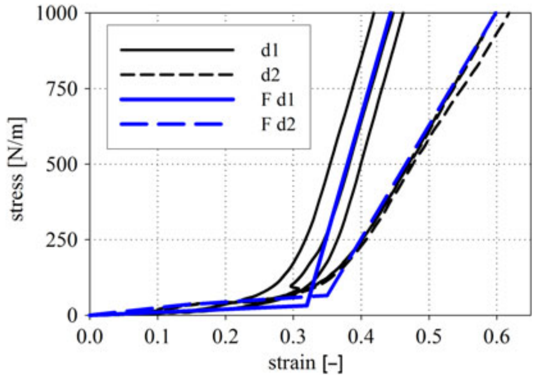

Figure 7. Piecewise linear material model vs. tensile tests for MSQ2.

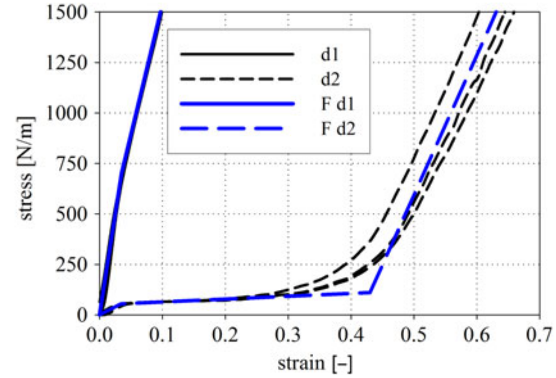

Figure 8. Piecewise linear material model vs. tensile tests for MSQ3.

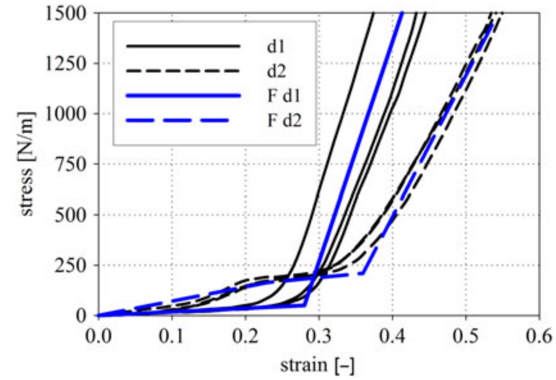

Figure 9. Piecewise linear material model vs. tensile tests for MSQ4.

Lubowiecka et al. 2014). The properties of polyester mosquito nets are not very consistent with the properties of considered surgical implants, especially in the direction of higher stiffness (Figure 14). Elasticity of MSQ3 in d1 is the closest to elasticity of commercial meshes (Dualmesh and Proceed). For strains up to 0.034, the stiffness of MSQ3 in d2 is consistent with value of more flexible direction of Parietex mesh. For larger strains, this mosquito net in direction d2 becomes much more flexible, and for strains higher than 0.43 it becomes stiffer again.

The orthotropy ratio E_1/E_2 of MSQ1 is close to the orthotropy ratio of Parietex implant. The stiffness of MSQ4 in direction d2 for strains greater than 0.45 is almost the same. In commercial meshes, Dualmesh, DynaMesh, Proceed and MSQ3, one direction of the implant material is stiffer than the other in whole range of strains. For Parietex, MSQ1, MSQ2 and MSQ4, direction d2 is initially stiffer and then direction d1 begins to be stiffer. The range where d1 reveals higher stiffness is

Table 3. Murnaghan coefficients for mosquito nets.

MSQ	Thread direction	$\bar{\lambda}$ (N/m)	$\bar{\mu}$ (N/m)	$\bar{m}$ (N/m)	$\bar{n}$ (N/m)	$\bar{l}$ (N/m)
MSQ1	d1	− 359	730	− 6945	− 29,326	3511
	d2	− 97	290	− 954	− 4140	481
MSQ2	d1	− 169	388	− 2562	− 10,921	1289
	d2	− 97	341	− 1939	− 8372	958
MSQ3	d1	3439	− 2406	− 40,769	− 049,733	33,490
	d2	− 204	697	− 2921	− 12,772	1459
MSQ4	d1	− 250	700	− 5000	− 21,450	2510
	d2	− 3	499	− 2930	− 12,920	1477

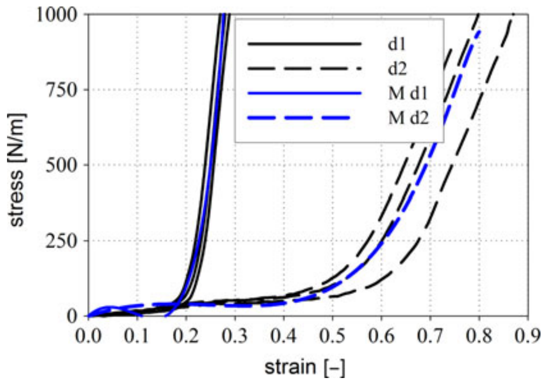

Figure 10. Experimental stress–strain relations vs. hyperelastic material model for MSQ1.

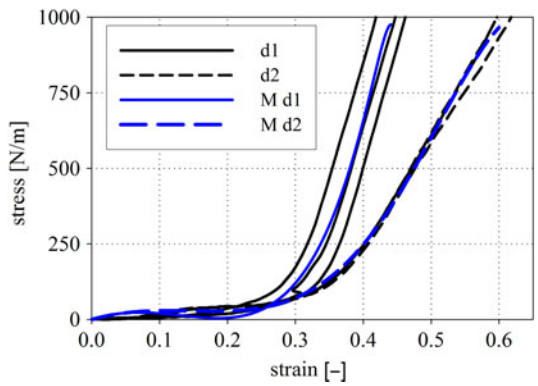

Figure 11. Experimental stress–strain relations vs. hyperelastic material model for MSQ2.

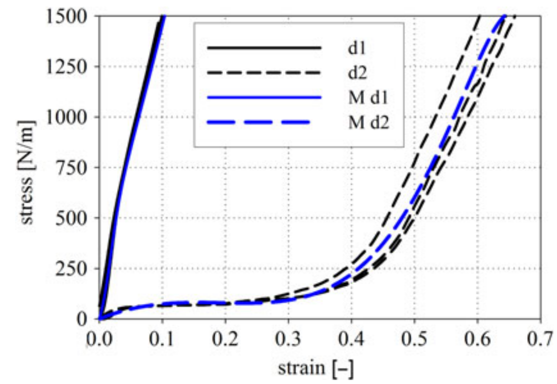

Figure 12. Experimental stress–strain relations vs. hyperelastic material model for MSQ3.

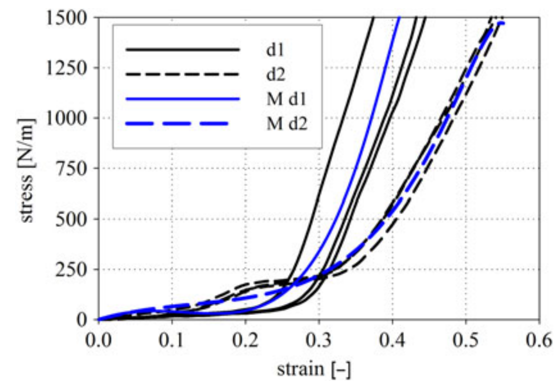

Figure 13. Experimental stress–strain relations vs. hyperelastic material model for MSQ4.

wider. However, in the scope in which mosquito net works after implementation, d2 should be specified as the stiffer direction.

4.1 Mosquito nets vs. human fascia

It is known that the properties of surgical meshes used in hernia repair should fit the properties of the abdominal wall (Junge et al. 2001). Transversalis fascia is a key tissue layer of abdominal wall in the context of herniation. Kirilova et al. (2012) proposed implant selection on the basis of comparison to properties of the fascia. In the present study, the mechanical properties of mosquito nets are compared to the properties of transveralis fascia in inguinal region investigated by Kureshi et al. (2008) and also to the properties of umbilical and transversalis fascia in inguinal region investigated by Kirilova et al. (2011).

The piecewise model for considered mosquito nets has been compared with piecewise model for transversalis fascia and shown in Figure 15. It refers to strains up to 10%, since according to Kirilova et al. (2011), the fascia physiological deformation is about 10%. Comparing the elasticity of mosquito nets with the transverse direction of transversalis fascia, one can notice that MSQ3 is much stiffer, MSQ4 comparable and MSQ1 and MSQ2 more flexible than fascia.

Table 4. Non-linear elastic properties of the surgical implants.

	Dualmesh		Dyna mesh		Parietex		Proceed	
	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral
F_A (N/m)	28,030	25,540	360	6410	2040	1580	7420	50,390
F_B (N/m)	4170	2840	3730	13,780	6700	21,440	–	–
ε_{P1} (–)	0.3	0.3	0.5	0.5	0.45	0.15	–	–
UTS (N/m)	8380	6110	1720	4470	2030	3720	4090	4210

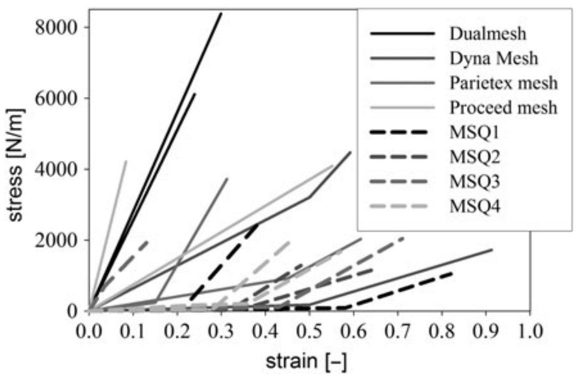

Figure 14. Comparison of the *F* parameters for commercial implants (continuous line) and mosquito nets (dashed line).

The values for direction d1 of mosquito nets and transverse direction of fascia are presented in Table 5. Toe strain and stress for mosquito nets are taken as a point of transition in piecewise model. The stress–strain curves of MSQ1, MSQ2 and MSQ4 have similar shape to curves of transversalis fascia presented by Kureshi et al. (2008). The MSQ3 has a different stress–strain curve shape and does not have toe zone in direction d1. The UTS of mosquito meshes is much higher than the UTS of fascia. However, the elastic modulus of mosquito meshes in range of strains after toe zone of stress–strain curve is much higher than the one of fascia. Kureshi et al. (2008) investigated fascia specimens which were cut in the transverse and longitudinal directions of human body, whereas Kirilova et al. (2011) cut samples in direction parallel and perpendicular to the direction of collagen fibres. Hence, extreme direction of mosquito nets should have similar characteristic to Kirilova et al.'s (2011) values. Unfortunately, the fascia thickness is not provided in that contribution, so the comparison of both studies is difficult.

Stress–strain relations obtained by Kirilova et al. (2011) for transversalis fascia are different and have no clearly visible toe region (like MSQ3). In order to compare results for mosquito meshes expressed in [N/m], the elastic modulus obtained by Kirilova et al. (2011) for 5% and 10% strain has been multiplied by average thickness of fascia given by Kureshi et al. (2008) (Table 6). According to these results (Figure 16), fascia is much stiffer than mosquito nets. Nevertheless, Parietex commercial implant also is more flexible in this range of strains. Among all tested mosquito nets, the MSQ3 has the elasticity closest to human fascia. In its direction d1 it is stiffer than stiffer direction of fascia and in d2 it is more flexible than more flexible direction of fascia.

Furthermore, the ultimate tensile strength of the analysed materials has been compared. The UTS of MSQ3 is greater in both types of fascia while UTS of MSQ2 is lower in comparison to UTS obtained by Kirilova et al.

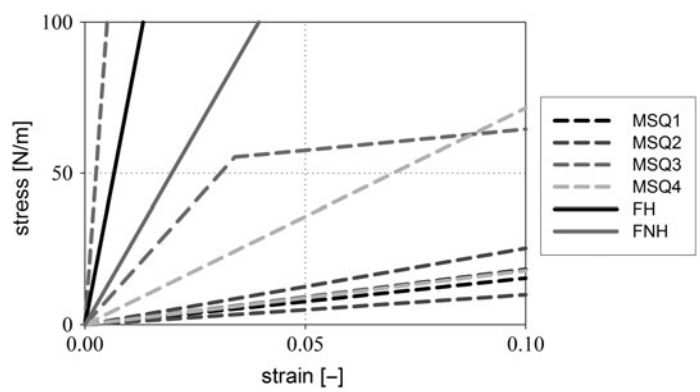

Figure 15. Stiffness of mosquito nets compared with data for transverse direction of transversalis fascia obtained by Kureshi et al. (2008) (FH – fascia of patient suffering hernia, FNH – fascia of donors with no hernia history) in physiological range of strains.

Table 5. Mosquito nets properties vs. transveralis fascia.

	Toe strain	Toe stress (N/m)	Strains at UTS	UTS (N/m)
Fascia of patients with no hernia history (transversal direction) (Kureshi et al. 2008)	0.13	108	0.62	720
Fascia of patients suffering hernia (transversal direction) (Kureshi et al. 2008)	0.17	90	0.66	522
MSQ1 d1	0.21	155	0.38	2320
MSQ2 d1	0.32	100	0.48	1280
MSQ3 d1	No toe region		0.13	1810
MSQ4 d1	0.28	180	0.46	2110

Table 6. Properties of transversalis and umbilical fascia obtained by Kirilova et al. (2011).

	$E_{(5)}$ (N/m)	$E_{(10)}$ (N/m)	Strains at UTS	UTS (N/m)
Transversalis fascia in direction 1	7578	8478	0.15	1791
Transversalis fascia in direction 2	2538	2934	0.24	567
Umbilical fascia in direction 1	7488	4734	0.15	1449
Umbilical fascia in direction 2	2268	2970	0.36	837

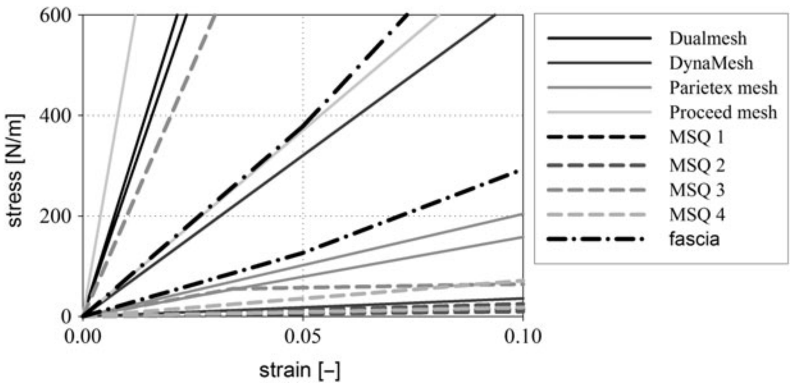

Figure 16. Stiffness of mosquito nets and commercial implants compared with properties of trasnversalis fascia obtained by Kirilova et al. (2011).

(2011). UTS of MSQ1 and MSQ4 in d1 is greater than UTS of fascia in its stronger direction. The strength of both nets in d2 is located between the stronger and the weaker direction of fascia. Hence, in future work, the optimal position of mosquito nets within implementation in abdominal wall should be investigated. Despite better coincidence of stiffness of d2 comparing the stiffer direction of fascia in physiological range of strains, maybe the direction d1 of mosquito nets should be positioned parallel to collagen fibres due to its behaviour under higher strains. Thus, the range of strains imposed to implanted mosquito nets should be evaluated. Human fascia in the direction of fibres is stiffer than in direction perpendicular to fibres in range of strains up to UTS. Hence, changing the proportions such as in MSQ1, MSQ2 and MSQ4 does not seem to be beneficial from the point of view of mechanical compatibility to human fascia.

The reference results of human tissues reveal big variability. However, the presented outcomes for mosquito nets have been compared to geometric mean (Kureshi et al. 2008) or median values (Kirilova et al. 2011) available in the literature. Summarising, it can be concluded that the investigated mosquito nets can be a good alternative for implants used in hernia surgery in poor countries.

5. Conclusions

The mechanical properties of four polyester mosquito meshes have been investigated. Experiments show the orthotropy of these materials similarly to some commercial implants and human fascia. The shapes of stress–strain curves obtained for MSQ1, MSQ2 and MSQ4 are comparable. These meshes have also a similar structure. Despite this match in general structure and material, the obtained values of properties differ noticeably. The shape of stress–strain relation of MSQ3, as well as its structure differs from the others.

The ultimate tensile stress of MSQ1, MSQ3 and MSQ4 is much higher than the ultimate tensile stress of transversalis fascia. However, stiffness of fascia in the direction parallel to collagen fibres does not coincide with mosquito net. Hence, mosquito nets do not fully reproduce the mean mechanics of abdominal wall. On the basis of comparison with results presented by Kureshi et al. (2008), the MSQ4 is a material, which in stiffer direction has the closest elasticity modulus to transveralis fascia compared to other mosquito nets and what is more also to commercial implants. However, considering the elastic modulus of fascia obtained in direction parallel to collagen fibres by Kirilova et al. (2011), the MSQ3 seems to be the best from mosquito nets, but worse compared to DynaMesh implant. Moreover, compared to the properties of fascia obtained by Kirilova et al. (2011) MSQ1, MSQ2 and MSQ4 have very small stiffnesses in the physiological range of strains.

On the other hand, the results for mosquito nets have been compared only to the geometric mean or median values. Due to high variability of properties of human tissue, the investigated mosquito nets can be very good alternative for commercial implants. On the basis of the numerical simulations of implanted surgical meshes (see e.g., Lubowiecka 2015a), one can observe that the lower stiffness of the implanted mesh leads to the lower forces in tissue–implant joints, so that it gives a greater chance of the repair persistence. In this context, the mosquito nets as more flexible than commercial implants should give good clinic results causing less hernia relapses. However, the higher flexibility results in higher strains under the same load conditions. Hence, mosquito nets may not be sufficient barrier against a bulge. The orthotropy ratio of surgical implants should reflect the anisotropy of human body in the area of implantation. Thus, the similarity of this ratio of tested mosquito nets and implants leads to a conclusion that mosquito nets can be a reasonable alternative for hernia repair. The use of these materials as prosthetic meshes needs a detailed follow-up in order to observe the efficacy of the repair reflected in the inguinal/abdominal wall deformation level. MSQ3 has the mechanical properties closest to commercial implant. This is the only mosquito net, which is stiffer than fascia in direction parallel to collagen fibres.

The identified parameters of piecewise linear elastic constitutive law and Murnaghan model of mosquito net will be used to further research on usefulness of mosquito nets in hernia repair, where mathematical modelling will be applied.

The piecewise elastic material model suits well the experimental data. However, due to the strongly non-linear transitions which are not always reflected by this model, the hyperelastic Murnaghan material law can be recommended in the modelling of mosquito net material. Identified parameters can be used in dense net material model. The finite element simulation of the mechanical behaviour of mosquito nets available on the market can provide more detailed information about their usefulness in human hernia repair. Various mosquito nets have very distinct mechanical properties, relatively comparable with human tissue. Hence, the numerical simulations will also help to evaluate which one is the best due to the compatibility with the abdominal wall mechanics.

Conflict of interest disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study is partially supported by the subsidy for young scientists given by the Faculty of Civil and Environmental Engineering, Gdansk University of Technology.

Notes

1. Email: ambrozan@pg.gda.pl
2. Email: katszepi@pg.gda.pl

References

Ambroziak A. 2006. Application of the Murnaghan model in analysis of non-linear elastic material properties of PVC-coated fabric. TASK Quart. 10:253–265.

Ambroziak A, Kłosowski P. 2011. Review of constitutive models for technical woven fabrics in finite element analysis. AATCC Rev. May/June: 58–67.

Ambroziak A, Kłosowski P. 2014a. Influence of thermal effects on mechanical properties of PVDF-coated fabric. J Reinf Plast Compos. 33(7):663–673. doi: 10.1177/0731684413512705.

Ambroziak A, Kłosowski P. 2014b. Mechanical properties for preliminary design of structures made from PVC coated fabric. Constr Build Mater. 50:74–81. doi: 10.1016/j.conbuildmat.2013.08.060.

Branicki C. 1969. Some Aspects of Cable nets static analysis [in Polish, Ph.D. thesis]. Gdansk University of Technology, Gdańsk.

Clarke MG, Oppong C, Simmermacher R, Park K, Kurzer M, Vanotoo L, Kingsnorth A N. 2009. The use of sterilised polyester mosquito net mesh for inguinal hernia repair in Ghana. Hernia. 13(2):155–159. doi: 10.1007/s10029-008-0460-3.

Freudenberg S, Sano D, Ouangré E, Weiss C, Wilhelm TJ. 2006. Commercial mesh versus nylon mosquito net for hernia repair. A randomized double-blind study in Burkina Faso. World J Surg. 30(10):1784–1789. doi: 10.1007/s00268-006-0108-3.

Frey DM, Wildisen A, Hamel CT, Zuber M, Oertli D, Metzger J. 2007. Randomized clinical trial of Lichtenstein's operation versus mesh plug for inguinal hernia repair. Br J Surg. 94(1):36–41. doi: 10.1002/bjs.5580.

Hernández-Gascón B, Peña E, Melero H, Pascual G, Doblaré M, Ginebra MP, Bellón JM, Calvo B. 2011. Mechanical behaviour of synthetic surgical meshes: finite element simulation of the herniated abdominal wall. Acta Biomater. 7:3905–3913.

Junge K, Klinge U, Prescher A, Giboni P, Niewiera M, Schumpelick V. 2001. Elasticity of the anterior abdominal wall and impact for reparation of incisional hernias using mesh implants. Hernia. 5(3):113–118. doi: 10.1007/s100290100019.

Kirilova M, Pashkouleva D, Kavardzhikov V. 2012. A selection of hernia meshes on the basis of experimental results for abdominal layers. Biotechnol Biotechnol Equip. 26(5):3292–3295. doi: 10.5504/BBEQ.2012.0068.

Kirilova M, Stoytchev S, Pashkouleva D, Kavardzhikov V. 2011. Experimental study of the mechanical properties of human abdominal fascia. Med Eng Phys. 33(1):1–6. doi: 10.1016/j.medengphy.2010.07.017.

Kureshi A, Vaiude P, Nazhat SN, Petrie A, Brown RA. 2008. Matrix mechanical properties of transversalis fascia in inguinal herniation as a model for tissue expansion. J Biomech. 41(16):3462–3468. doi: 10.1016/j.jbiomech.2008.08.018.

Lubowiecka I. 2015a. Mathematical modelling of implant in an operated hernia for estimation of the repair persistence. Comput Methods Biomech Biomed Eng. 18(4):438–445. doi: http://dx.doi.org/10.1080/10255842.2013.807506

Lubowiecka I. 2015b. Behaviour of orthotropic surgical implant in hernia repair due to the material orientation and abdomen surface deformation. Comput Methods Biomech Biomed Eng. 18(3):223–232. doi: 10.1080/10255842.2013.789102.

Lubowiecka I, Szepietowska K, Tomaszewska A, Szymczak C. 2014. Mechanical compatibility of implants used in hernia repair with abdominal wall. In: Pietraszkiewicz W, Górski J, editors. Shell structures, theory and applications. 3. London: Taylor & Francis Group; p. 351–354.

Lurie A. 1990. Nonlinear theory of elasticity. North-Holland: Elsevier.
Murnaghan FD. 1951. Finite deformation of an elastic solid. New York (NY): John Wiley.
Röhrnbauer B, Mazza E. 2013. Uniaxial and biaxial mechanical characterization of a prosthetic mesh at different length scales. J Mech Behav Biomed Mater. 29C:7–19.
Saberski ER, Orenstein SB, Novitsky YW. 2011. Anisotropic evaluation of synthetic surgical meshes. Hernia. 15(1):47–52. doi: 10.1007/s10029-010-0731-7.
Sanders DL, Kingsnorth AN, Stephenson BM. 2013. Mosquito net mesh for abdominal wall hernioplasty: a comparison of material characteristics with commercial prosthetics. World J Surg. 37(4):737–745. doi: 10.1007/s00268-012-1900-x.
Tomaszewska A, Lubowiecka I, Szymczak C, Śmietański M, Meronk B, Kłosowski P, Bury K. 2013. Physical and mathematical modelling of implant-fascia system in order to improve laparoscopic repair of ventral hernia. Clin Biomech (Bristol, Avon). 28(7):743–751. doi: 10.1016/j.clinbiomech.2013.06.009.