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Mechanical behaviour of the implant used in human hernia repair under physiological loads

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In laparoscopic operations of abdominal hernias some recurrences still take place, even when applying a surgical mesh. This is usually caused by a failure of the connection between the tissue and the implant. The study deals with the influence of an implant's orientation on forces in joints, which connect the mesh to human tissues. In the paper, the implant is modelled as a membrane structure within framework of the Finite Element Method. Two models are analysed: in the first one interaction between the mesh and a fascia is taken into account, in the second this interaction is not considered. Computations are conducted for two different material types of the implants: one with isotropic properties and second one with orthotropic properties. The models are validated by comparing dynamic numerical analysis with experimental outcomes, where load was simulating intraabdominal pressure during postoperative cough. Due to displacements of joints during activities like bending sideways or torsion of an abdomen, influence of kinematic extortions on forces in the joints is analysed. The outcome shows that position of the orthotropic implants is crucial and may strongly change the level of forces in the joints.

Key words: *finite element modelling, hernia repair, implants, membrane structure*

1. Introduction

The human ventral hernia is a leak in the musculo-fascial system of the front abdominal wall. One of the methods of hernia treatment is laparoscopic repair in which a synthetic implant is used. Unfortunately, recurrences still take place, which is usually caused by a connection failure. This often happens during a postoperative cough, when the implants are subjected to a high intraabdominal pressure.

Some properties of particular implants have already been described (see, e.g., [1], [2]). Also the value of extreme pressure which occurs in an abdominal cavity during coughing is identified [3]. However, the exact way of fixing the surgical mesh is not clearly defined and so a mathematical modelling can be beneficial in gaining information about the implant–tissue system behaviour. To investigate this problem, firstly a cable model has been considered [4]. Secondly, FEM two-dimensional models have been created [5]–[7] and also a membrane model under the dynamic load has been defined and analysed in [8]. In [9], two mechanical models for designing new meshes are proposed, a beam model to design weave and determine its stiffness and a membrane model, which can be used in more complex definitions, like whole abdomen modelling. However, these works do not present the influence of the orientation of implant on forces in the connection, the failure of which may cause a relapse.

In this paper, two models are proposed and analysed within the framework of Finite Element Method. The first one is built of membrane quad elements inside the hernia orifice and spring elements around, which includes the interaction of implant and fascia outside the orifice. The second one is just a polygonal mem-

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brane stretched between the elements joining the implant with tissue called tacks. This model is whole discretised by the membrane quad elements. The dynamic behaviour of both models is validated by comparing outcomes from experiment and numerical simulation and then applied to static analysis of the implant.

In the research about human abdominal hernia repair, also a mechanical behaviour of the abdomen is crucial. One of the issues refers to biomechanical modelling of muscles as presented, e.g., in [10]–[12]. Also mechanical properties of human linea alba, the place of the biggest stresses in abdominal wall [13] and so a common place of hernia, are discussed and presented in [14]. Furthermore, investigations of mechanical properties of animal and human abdomens in the context of hernia repair are done in [15]–[18]. The above papers, together with [13] and [19], where an animal and a human abdomen model have been created, emphasise anisotropy of the abdominal wall. However, the aforementioned human model [13] does not include skin [20], which may also affect mechanical behaviour of abdomen and hence of hernia and implant.

Because of the anisotropy of the abdominal wall, the direction of the anisotropic implant may affect junction forces in the tissue–implant joints. Extreme strain values and trajectories in abdominal wall during life excitations have been identified and presented in [21] and [22]. In these two articles as well as in [13], [15] and [19] the main conclusion shows that orientation of implant should fit to the abdomen elasticity. Also in [23] authors prove that anisotropy of the implant and its compatibility to the fascia can influence the long-term outcome of hernia repair. Displacements of tacks during human activities can cause additional forces, which can exceed the capacity of the joint. Due to the anisotropy of the human abdominal wall and the implants, the orientation of the mesh may affect the values of those forces. Hence, in the proposed study the authors consider the extortions with values based on the results published in [21].

In this contribution, the authors investigate how the orientation of an implant influences the junction forces acting on the tacks during activities like bending or breathing and how this affects the behaviour of the meshes with high and low orthotropy.

2. Materials and methods

The authors propose two mathematical models of the implanted mesh (Fig. 1). The assumed diameter of the analysed hernia orifice is 0.05 m. The implant is fixed to the fascia at 10 points by tacks placed every 0.04 m. Numerical models are built and simulated in MSC.Marc [24] – system based on Finite Element Method. The implant is modelled as a membrane structure. This type of the finite element has got three translational degrees of freedom in each node. A geometrically nonlinear analysis has been used in the range of large strains.

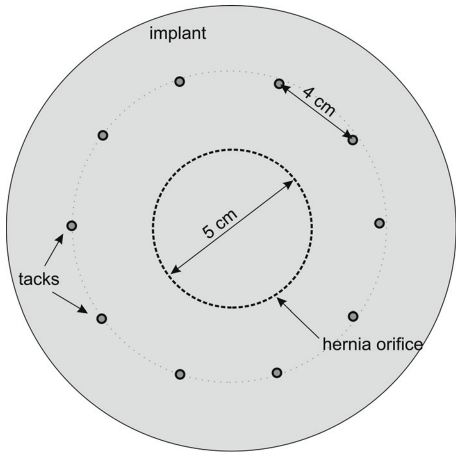

Fig. 1. Scheme of the hernia and implanted surgical mesh

2.1. Mathematical models

In the first model (Fig. 2), the interaction between the mesh and the human tissue is considered by the use of spring elements connecting membrane with tacks around hernia orifice. Element type QUAD4 with 4 nodes has been applied inside hernia. Tacks have been modelled as supports with blocked translations. The elasticity of radial springs is 600 N/m and of oblique springs is 400 N/m. These values result from the elasticity of fascia [25] and have been calibrated on the basis of experimental results.

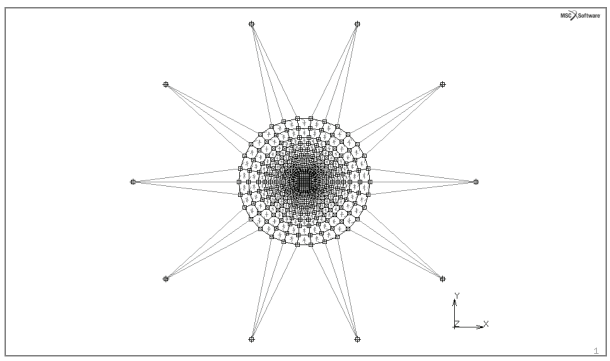

Fig. 2. FEM model M1

The second model (Fig. 3) does not take into consideration that the mesh lays on the human tissue between the hernia orifice and the tacks. This model is whole discretised by elements QUAD4. Nodes lying in the place of tacks (0.005 m span) have got blocked translations.

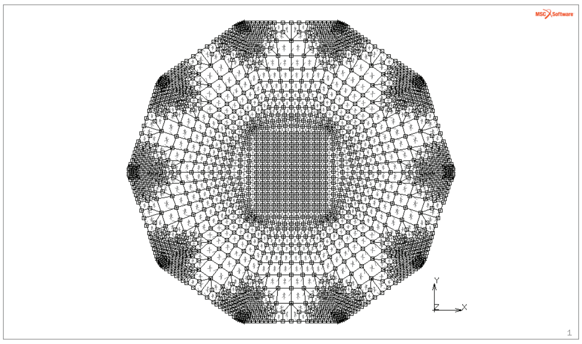

Fig. 3. FEM model M2

2.2. Materials

From a number of surgical mesh types, materials with the most distinct properties were chosen for the analysis. Dyna Mesh® implant is strongly orthotropic as reflected in the ratio of its elasticity in two orthogonal directions at a level of 18. Dualmesh Gore® implant behaves almost like isotropic material. The values of material properties given in Table 1 are taken from previous research [25]. The authors use elastic linear orthotropic constitutive law to model both materials. The relation between two elastic moduli is described by the formula: $E_1 \cdot \nu_{21} = E_2 \cdot \nu_{12}$ (see, e.g., [26]).

Table 1. Material properties of the implants

	Dyna Mesh®	Dualmesh Gore®
Thickness t [m]	0.00045	0.0007
Elastic modulus E_1 [Pa]	$1.42 * 10^7$	$4.00 * 10^7$
Elastic modulus E_2 [Pa]	$7.56 * 10^5$	$3.65 * 10^7$
Density ρ [kg/m^3]	368	568.64
Poisson ratio ν_{12}	0.3	0.35

2.3. Dynamic analysis. Intraabdominal pressure

To check the behaviour of numerical models, their simulation under dynamic load has been compared with experiment's outcomes taken from [25]. Within the experiment, the implants were fixed to a porcine tissue and put into a specially prepared pressure chamber. The experiment is described in detail in [25]. A similar comparative analysis for a different model is presented in [8] and [25].

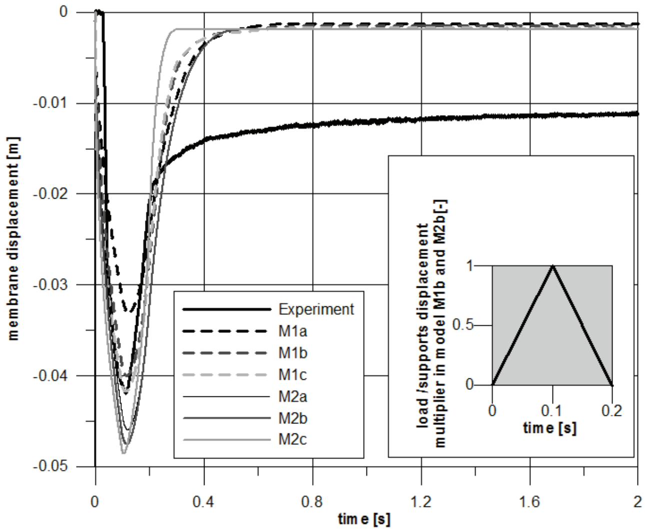

Fig. 4. Maximum displacement of the implant Dyna Mesh

An impulse of pressure p (Fig. 4) which was applied to model M1 and model M2 is the same as an impulse of a pressure which was applied during the experiment simulating the postoperative cough. The maximum value of triangular impulse pressure was 35 730 Pa [3]. One step Houbolt method and Rayleigh model of dumping were used to solve this dynamic problem. The analysis was conducted within time t = 2 s. Dead weight was taken into consideration and applied in direction perpendicular to the plane of the implant. During the experiment, displacements of the implant in the middle of the membrane and on the hernia edge were measured by laser sensors placed under the pressure chamber. The authors compared these values with numerical outcomes for Dyna Mesh® material and both models. Also the displacements of tacks were identified by the analysis of images from camera placed over the pressure chamber. Three different approaches were analysed. Firstly, the models without any changes were analysed (M1a and M2a), which assumed that the tacks did not move. In the

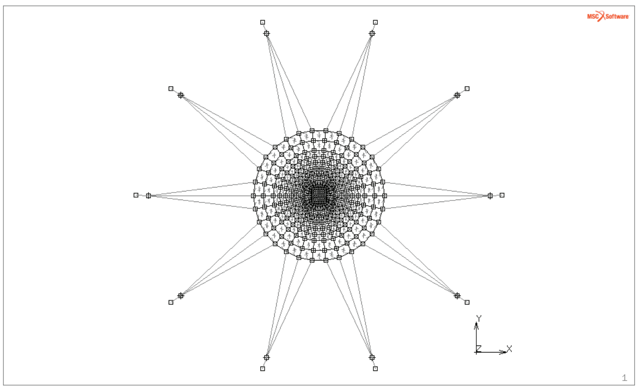

Fig. 5. FEM model M1c – model with additional spring elements in the places of the tacks

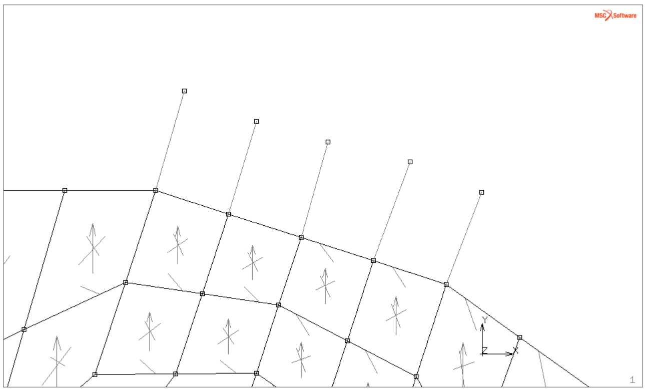

Fig. 6. FEM model M2c – spring supports representing the tack

second approach (M1b and M2b), the supports were displaced for the distance measured during the experiment ($2.74 \cdot 10^{-3}$ m) according to the pressure function plot (Fig. 4). In the last case (M1c and M2c), the springs in the place of the connections were added to the models (Fig. 5 and Fig. 6). This simulates elastic behaviour of the porcine in which the tacks were located.

2.4. Static analysis. Kinematic extortions

Reactions in the model supports (tacks) depend on boundary displacements of joints which can be caused by life excitations. Szymczak et al. 2012 [21] describe an experiment and computations which enable one to find values of strains of the abdominal wall during longitudinal stretching, bending sideways and torsion of the abdomen. These outcomes were used by the authors of this study to define kinematical extortions to be applied to the models. Figure 7 illustrates the range of strains in external surface of abdominal wall [21] considered by the authors with marked six typical areas of implantation of surgical meshes. For each of these cases computations have been conducted for 7 directions of the implant orientations (from 0° to 90°, where the angle 0° represents the direction with the elastic modulus E_1 parallel to the central vertical line). The kinematical extortions have been applied as displacement of the model supports (Table 2). Numeration of the joints is shown in Fig. 8.

Table 2. Applied kinematic extortion (displacement of supports [$\times 10^{-2}$ m])

Support:	a	b	c	d	e	f
1 and 10	1.346	1.495	2.223	1.404	1.872	1.404
2 and 9	0.468	0.52	0.936	0.468	1.404	0.468
3 and 8	1.17	1.04	0.351	0.936	0.936	0.585
4 and 7	0.936	0.52	0.936	0.468	0.468	0.936
5 and 6	1.053	1.496	2.223	1.404	1.346	2.223

3. Results

3.1. Dynamic analysis. Intraabdominal pressure

The simulation and experimental behaviour of the models are shown in Fig. 4 and Fig. 9. Relative differences between numerical analysis results and the experiment are shown in Table 3. In all the cases the outcomes for model M1 fit to the experimental data

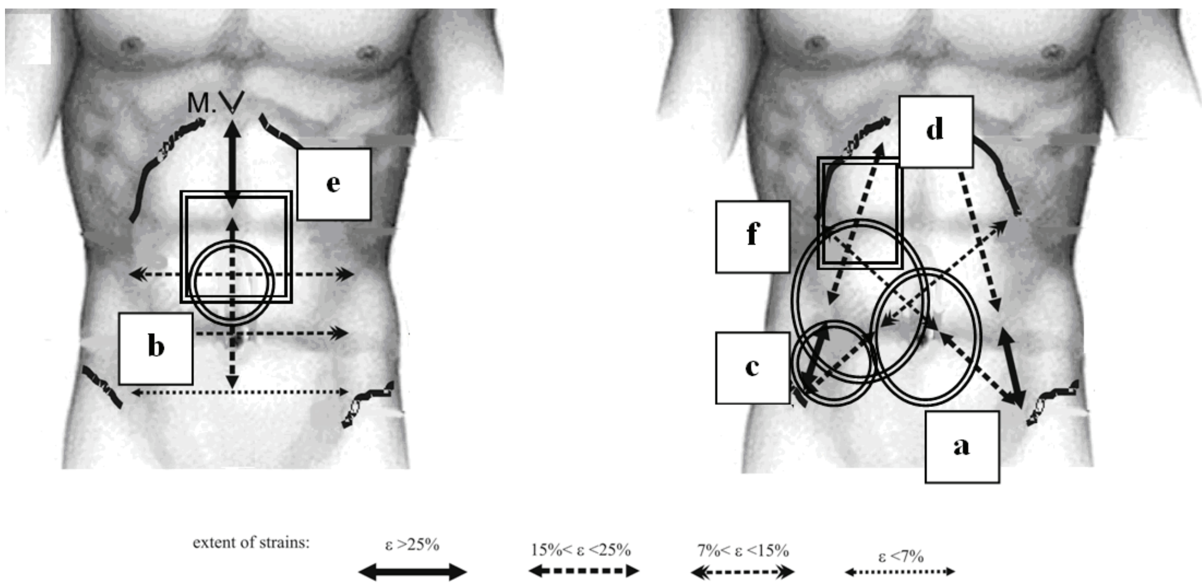

Fig. 7. Average strains of different parts of abdomen and zones of the implant placement

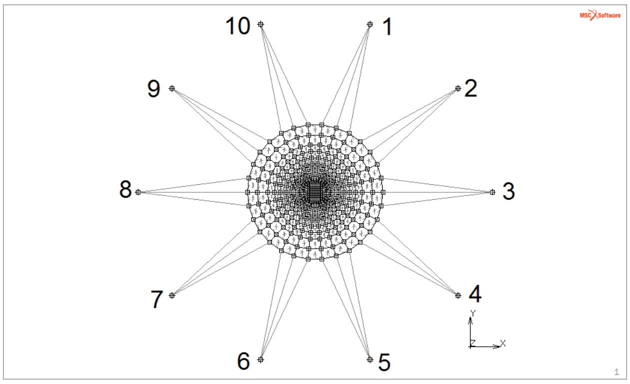

Fig. 8. Numeration of supports

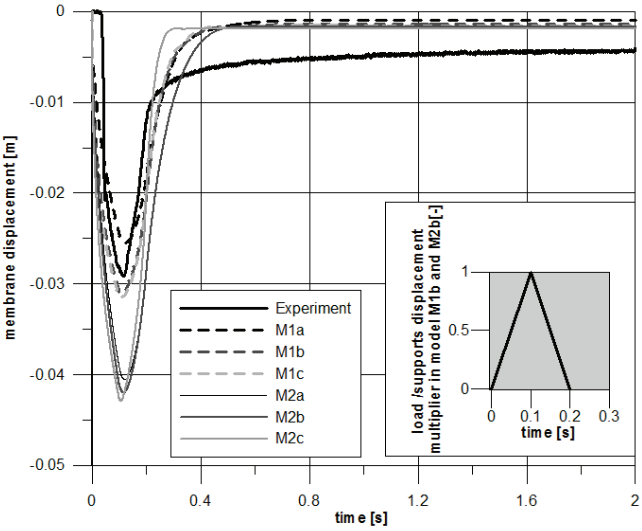

Fig. 9. Displacement of the implant Dyna Mesh on the hernia orifice edge

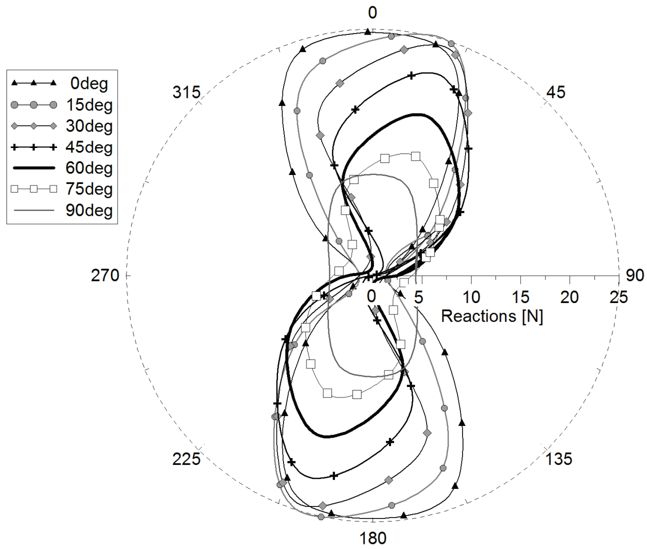

Fig. 10. Reaction forces in model M1, extortion "c", Dyna Mesh

Table 3. Relative difference between experimental and numerical displacements of implant (relative difference is expressed in percentage and calculated as a difference between experimental and numerical outcomes, divided by experimental one) calculated in the middle of implant and on the edge of hernia orifice for models M1a, b, c and M2a, b, c

Relative difference in the displacement of the implant	M1 [%]			M2 [%]		
	a	b	c	a	b	c
in the middle	21.42	4.81	0.68	–9.46	–13.23	–15.69
on the edge of hernia orifice	12.51	–6.30	–7.89	–39.14	–44.06	–47.26

better than the results for simulation of model M2. The results for model M1b with extortions and M1c with elastic supports give similar outcomes, which are very close to the experiment. Worse results are obtained for model M1a, which was the most simplified one and did not include displacements of the tacks. The most complex model M1c gives the best solutions. Model M2 behaves worse under dynamic load. For this model the displacements are bigger than in the experiment.

3.2. Static analysis. Kinematic extortions

Considering the tissue–implant connection failure as a typical reason of relapses, the analysis of results is focused on junction forces (in the tacks), which are represented by reaction forces in the model supports. The discrepancies between the results obtained for simulations of the two models are quite significant, especially for orthotropic Dualmesh Gore®, for which even the order of magnitude is higher than for model M2. However, what is essential, the shape of changes in the values of reactions as a function of the orientation of the implant is similar for both models and for all extortions (all outcomes can be found in [28] and [25]). Exemplary changes for each support are shown for more orthotropic material (Dyna Mesh) and extortion "c". For that extortion the biggest reactions and differences between outcomes for different orientations are found (model M1, Fig. 10). The results for extortion "f" with significant differences between orientations for model M2 are shown in Fig. 11. However, in some cases, the behaviour of reactions in the supports which have been displaced for the smallest distance is different in model M1 and M2.

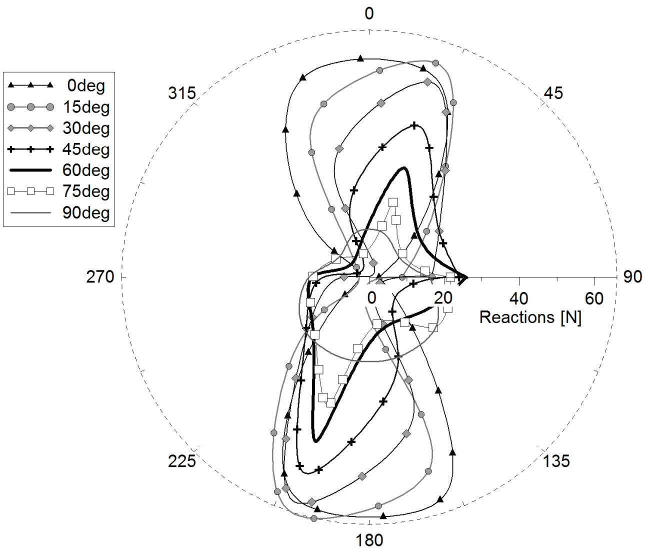

Fig. 11. Reaction forces in model M2, extortion "f", Dyna Mesh

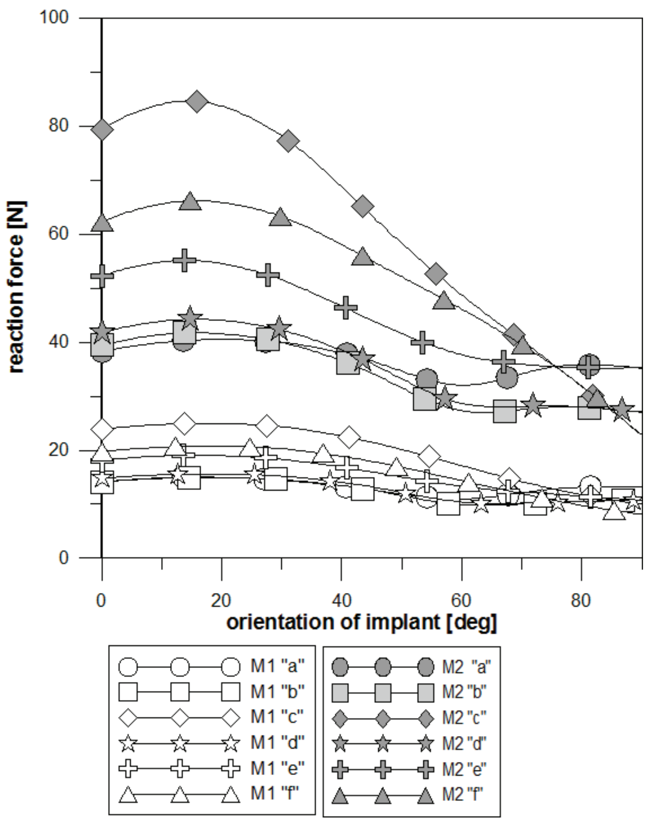

Fig. 12. Maximal reactions for all cases (a)–(f) of extortion and both models M1 and M2, material Dyna Mesh

The changes of maximal reactions are shown in Fig. 12 and Fig. 13, which illustrate the results for models M1 and M2 in cases (a)–(f) of all extortions (letter annotation to the name of model). These out-

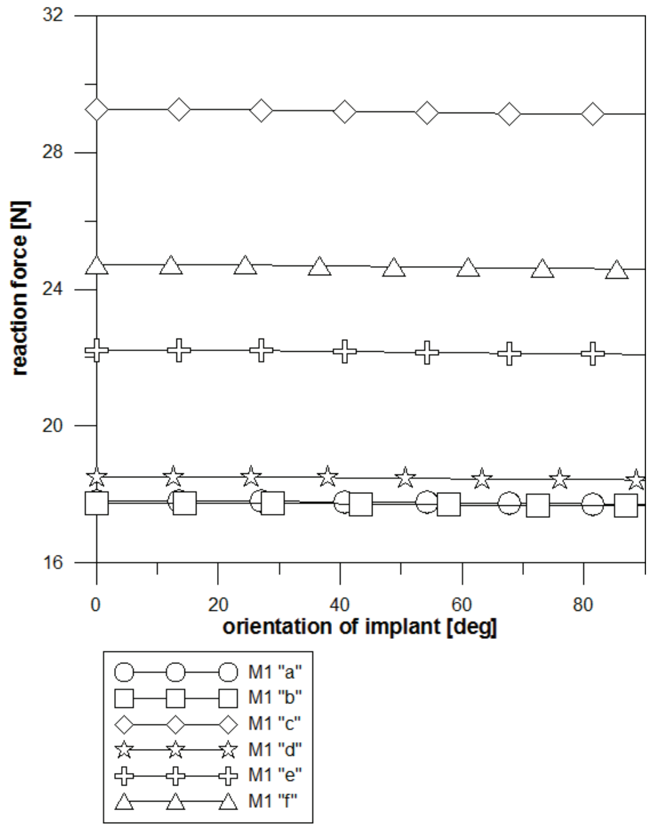

Fig. 13. Maximal reactions for all cases (a)–(f) of extortion, model M1, material Dual Mesh Gore

comes for Dualmesh Gore and model M2 have got similar shape. The maximal reaction force is noticed in all the cases when implant is oriented in the direction of 15 degrees, which is a direction close to the first support lays on. The lowest maximal reactions for the implant Dualmesh Gore are when implant is oriented in direction of 90 degrees for all the cases of the extortions considered. For extortion "a" of Dyna Mesh the lowest maximal force is when the implant is oriented at 60 degrees, for extortions "c", "e" and "f" when it is 90 degrees. The difference in models' behaviour is observed in cases b and d. For extortion "b" in model M1 the minimum is at 60 degrees but in model M2 at 90 degrees. For extortion "d" in model M1 the lowest maximal reaction is at 75 degrees but for model M2 at 90 degrees.

Table 4 shows the relative difference between the maximum and the minimum of maximal reactions. Material Dyna Mesh is strongly orthotropic and for that implant in all zones of abdomen the difference exceeds 20% for both models. In case "c" and "f" that difference can even exceed 60%. For extortion "c", in model M2 this relative difference is equal to 73.07%. Those outcomes prove that the wrong orientation of implant may decide whether or not the capacity of joint will be exceeded. Hence, the orien-

Table 4. Relative difference between the maximum and the minimum of maximal junction forces for each extortion obtained from numerical computations (%)

	a	b	c	d	e	f
M1 Dyna Mesh	27.11	33.61	60.11	33.48	43.58	60.86
M2 Dyna Mesh	20.68	35.31	73.07	38.75	35.89	65.67
M1 Dualmesh Gore	0.48	0.51	0.47	0.51	0.52	0.49
M2 Dualmesh Gore	4.68	5.13	5.46	5.14	5.14	4.47

tation has influence on the possibility of illness relapses.

Dual Mesh Gore implant is almost isotropic. Hence the relative differences for this implant are much smaller and for model M1 do not exceed 1%. However, if model M2 is taken into consideration, the relative differences in some cases start to exceed 5%, which can be established as a border of engineer's accuracy.

4. Discussion

Two mechanical models of implanted surgical mesh have been analysed. Model M1 includes interaction between fascia and implant between the orifice and the ring of tacks by using the spring elements. The second model M2 does not.

To check the behaviour of the numerical models described, a dynamic analysis was performed. The comparison between numerical and experimental outcomes shows that despite simplicity of the model which does not include the mechanics of muscles, bones and skin, the model can be used to analyse the fascia–surgical mesh system behaviour and can help in estimating the capacity of the joints. Under pressure load model M1 behaves better than model M2. However, under kinematic extortions model M2 is probably better. The models analysed can be used in assessing the persistence of the hernia repair subjected to the intraabdominal pressure and abdomen movements considering the forces in the joints of tissue and implants, here the models' supports.

The differences in the values of reactions between the models are big. Nevertheless, the nature of changes caused by the change of orientation is similar. The outcomes prove that the orientation of the implant has big influence on junction forces. Due to the fact that orientation of implant my cause the capacity of joints to exceed, surgeons should pay attention to the way they put the surgical mesh. Implant should be placed as the direction with a lower stiffness agrees with the direction of the central vertical line. With the exception of localization near a navel (zone "a" in Fig. 7), where the best direction is 60 degrees to the central vertical line. The outcomes presented show that orientation of the implant should fit to the mechanical behaviour of the abdominal wall. This confirms a conclusion suggested by [15], [21]–[23]. In [23], only longitudinal and transversal positions of the implant are investigated, while in the study proposed the authors present more detailed analysis of seven orientations of the mesh (from 0 to 90 degrees), considering more directions of extreme strains of human abdominal wall (Fig. 7). However, outcomes presented in [29] for slightly different extortions and for different material modelling of implant give in some areas different appropriate orientations of the mesh. This suggests that the proper orientation established with this precision may depend on the constitutive law considered. Due to the anisotropy and different microscopic structure of implants, a more appropriate constitutive law is to be investigated.

Conclusions about orientation of the implants are especially important for meshes with orthotropic properties like Dyna Mesh implant. The appropriate orientation is the most important in places where the biggest strains in the abdominal wall are observed. In the case of almost isotropic meshes like Dualmesh Gore it is not so crucial. However, because of the strongly anisotropic behaviour of abdominal wall it is better to use anisotropic implants oriented in the way compatible with the abdominal wall. Hence, in the future research a mathematical model of human abdominal wall will be defined and an analysis of its behaviour and compatibility with implanted mesh will be performed. This will assure more accurate results and more proper clinical recommendations.

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