FEM modelling of membrane structure in human hernia repair

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Abstract

The paper deals with a Finite Element modelling of human fascia-implant system. The synthetics mesh implanted in the abdomen during the hernia repair surgery is modelled as a membrane structure. Two types of boundary conditions analysed here reflect the two situation in hernia repair and the reaction force in the tissue-mesh connection is calculated in both cases. The material parameters of the mesh are identified in laboratory tests. The system undergoes the internal abdominal pressure appearing within the postoperative cough, that is the most essential load causing the connection failure and the hernia recurrence.

Keywords: biomechanics, membrane, hernia, finite element modelling

1 Introduction

The human ventral hernia is a leak in the musculo-fascial system of the front abdominal wall caused by a fascia defect (Fig. 1). Even if the ventral hernia repair surgery is a well recognized matter, mechanical properties of the tissue-implant system are not known so the implantation of the repairing mesh is quite intuitive and, recurrences of the illness happen (see e.g., Ref. [1,7]).

Figure 1. Abdominal hernia

Neither the number of the tacks required for holding the implanted mesh correctly is known nor their optimal position on the mesh surface (Fig.2). It is obvious that the tacks can potentially damage human nerves and blood vessels, for that reason their number should be reduced to a minimum. The medical knowledge itself is not sufficient to solve this complex problem therefore it becomes interdisciplinary, bringing together surgeons and engineers. To study the behaviour of implant-tissue system, the authors considered a mechanical model. The simple cable model of implant has been studied already and the results are presented in Ref. [9].

In the study, the system of implanted mesh and human abdominal tissue is considered as presented in the Fig. 3.

Figure 2. Implanting of the mesh

In this type of modelling is assumed that the implant acts only in the hernia orifice and the area between the orifice and the ring of joints is modelled independently.

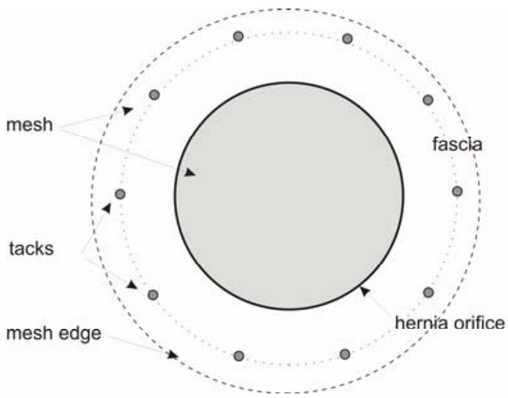

Figure 3. Hernia orifice with implanted mesh

In this contribution the authors propose two mechanical models of tissue-implant system that differ the issue if boundary conditions. First model with the stiff support in the points of joints refers to the case of the stiff hernia orifice while the second one with elastic supports allows one to take into consideration the cooperation of both system components, tissue and implant Ref. [4, 9].

In both cases the crucial result is the reaction force in the connection points that should not exceed the failure load identified in Ref. [11].

2 Material properties of the implant

The experimental tests were carried out on the Proceed® mesh samples (Fig. 4) undergoing tension in the testing machine Zwick Roel 020 as presented in Ref. [5, 9].

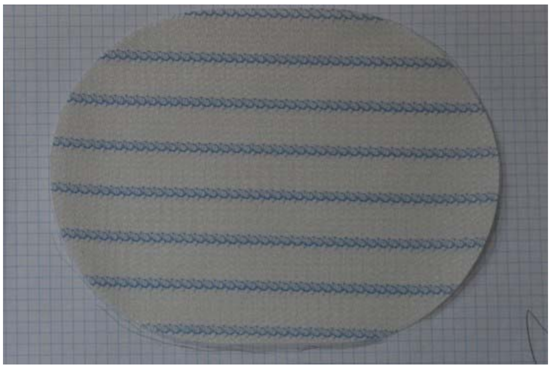

Figure 4. Proceed® sample

The mesh material were identified as orthotropic, Ref. [12] of the mass density = 256.55 kg/m3 with elastic moduli $E_1 = 83.98e6$ Pa and $E_2 = 12.367e6$ Pa. The Poisson's coefficient estimated as $\nu_{12} = 0.28$. The orthogonal direction 1 and 2 refers to the mesh structure. As presented in Ref. [3], the material parameters have to fulfil Eqn. (1) and Eqn. (2):

$$E_2 \nu_{12} = E_1 \nu_{21}\,, \tag{1}$$

$$\varepsilon_1 = \frac{1}{E_1}(\sigma_1 - \nu_{12}\sigma_2), \quad \varepsilon_2 = \frac{1}{E_2}(\sigma_2 - \nu_{21}\sigma_1), \quad \gamma_{12} = \tau_{12} / G_{12}\,. \tag{2}$$

The load applied to the structure refers to the abdominal pressure. The crucial value of the pressure, p = 35997 Pa, that can cause the recurrence of the illness, appears during the postoperative cough, Ref. [13].

3 Numerical models of hernia and the finite element analysis

The implant is modelled as an orthotropic membrane structure. In this approach the hernia is considered as a stiff, circular orifice in a human fascia, which refers to a practical clinical case. The implant is fixed to the fascia at 10 points by tacks in a semi-circular order. The assumed membrane radius is equal to r = 0.05 m and the thickness t = 0.6 mm. The geometry of the structure and the joints number and positions refer to the clinic case. Usually the joints are applied every 2-4cm. The most unfavourable situation appears with the lowest number of joints and so the largest gaps between 2 tacks. This is represented in the proposed model and determines the number of supports of the studied membrane.

The nonlinear static analysis has been performed by means of MSC.Marc system. A 4-node finite membrane elements of type 18 (MSC.Marc) containing 3 translational degrees of freedom in each node were applied, see e.g. Ref. [8].

3.2. *Model 1 with stiff supports*

First, the stiff support in the places of joints were assumed and taken to the analysis (Fig. 5).

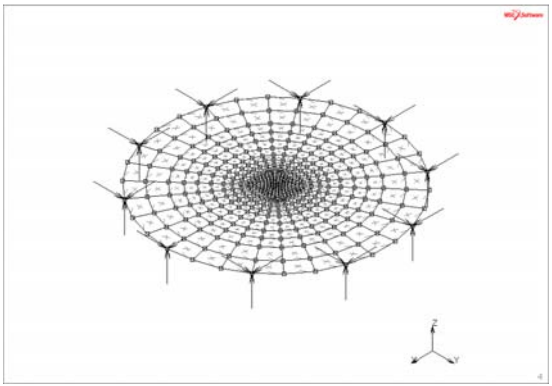

Figure 5. Model 1 with stiff supports

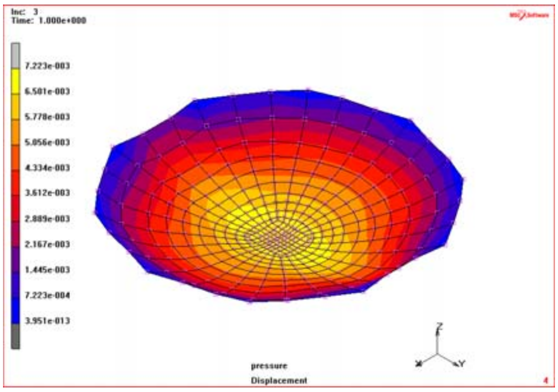

Figure 6. Model 1. Membrane deflection

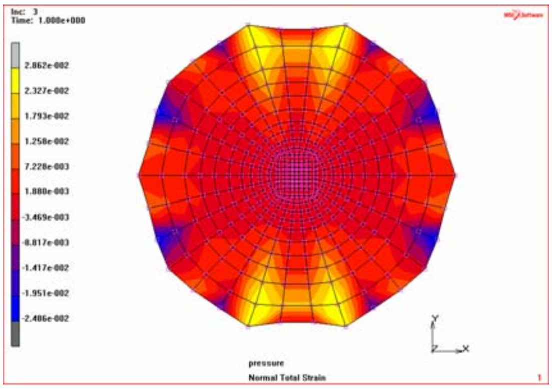

Figure 7. Model 1. Membrane deflection

These boundary conditions refer to a stiff hernia edge. In the model, the 3 orthogonal displacements are blocked in the points of joints with additional vertical support around the membrane not shown in the figure. In this case, the junction force R_1 = 5 N and the maximum deflection dz_1 = 7.2e-3m (Fig. 7) appear.

3.2. Model 2 with elastic supports

3.2.1 Approximate identification of the stiffness of the elastic supports

In the mechanical model of the implant-tissue system, the zone of interaction between mesh and fascia has been added. This zone is modeled using elastic springs connecting the point of tack with the edge of the hernia orifice (Fig. 8).

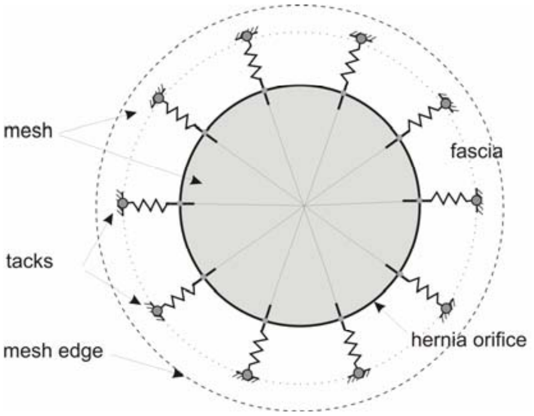

Figure 8. Hernia – implant system

The stiffness of the springs refers to the stiffness of the junction considering the interaction of abdominal elements of the human body like muscles, bones and implant. Only a few studies refer to the experiments on the stiffness of abdominal wall, like Ref. [2, 6, 14], so the authors decide to apply a approximate procedure of identification of the stiffness of the assumed elastic support of the model. To identify this value, the results of observations of the movement of human abdomen outside – based on the photos taken of moving people (Fig. 9) transformed to a Matlab script; and inside – based on the radiography of human abdomen with the implanted mesh (Fig. 10 and 11), Ref. [10].

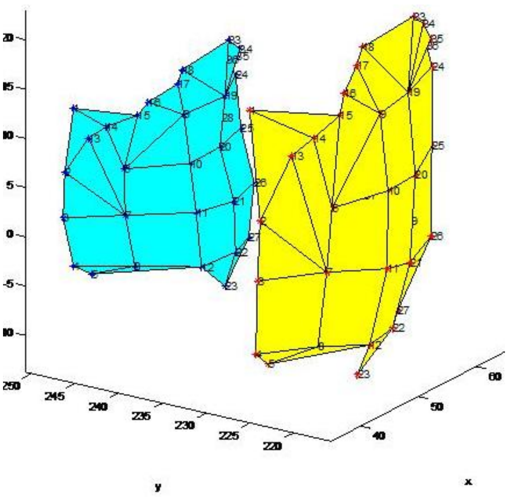

Figure 9. Human abdomen displacement in the process of respiration: blue – initial state; yellow – actual state

First, the authors observed the displacements of the outside of abdomen, based on photos taken when patients subjected to physiological movements. Then the photos were processed in a Matlab code to get the mesh of points of initial and deformed state. The range of the movement of joints of implants inside the patients abdomen were identified on the basis of radiography of people under the same physiological movements. The well visible metal tacks positions were analyzed in a Matlab code and then the inside and outside displacements were compared.

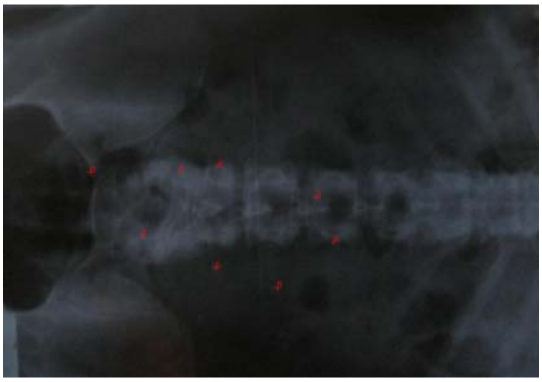

Figure 10. Human abdomen radiography with visible tacks – reference state

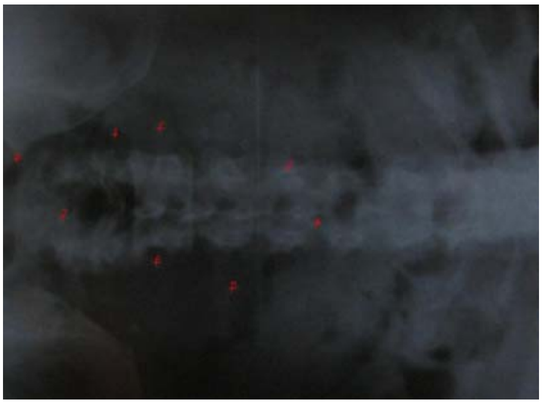

Figure 11. Human abdomen radiography with visible tacks – state of respiration

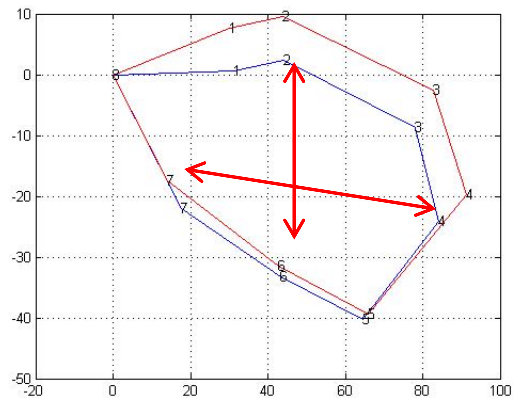

Figure 12. Displacement of tacks inside the abdomen

In the Fig. 11, the tacks indicated at the radiographies (Fig. 10 and 11) are represented by a number of points in the coordinate system. This allowed one to calculate the displacement of points as well as the strains range of the segments of abdomen during the respiration of the patient.

Considering the two kinds of tests, like radiography and photos, we can obtain the ranges of displacement of the human abdomen subjected to respiration. This also let us analyse the relative displacement taking to account the overall stiffness of the abdominal walls.

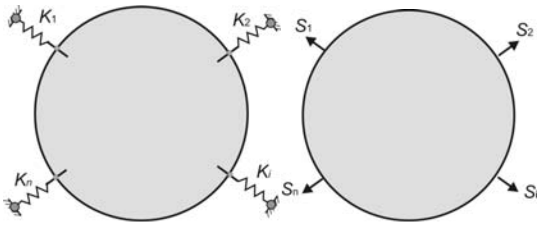

Figure 12. Identification of elastic supports

Let us assume the following data to identify the stiffness K_i of the springs – i.e. the elastic supports (Fig. 13):

U_i – displacement of the surface of the abdomen in the place of tack i;

u_i – displacement of the tack i.

The forces in the spring can be described by the formula (3)

$$S_i = K_i(U_i - u_i)\ . \tag{3}$$

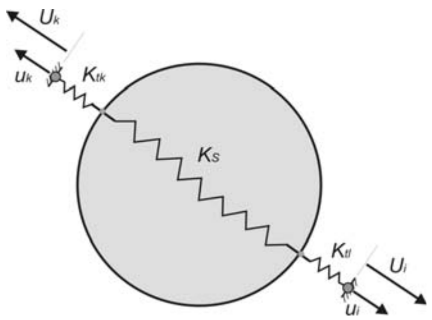

Figure 13. Approximate method of identification of linear springs system

We assume that the system is subjected only to tensile forces, so that $U_i \geq u_i$, while $U_i - u_i < 0$, the forces $S_i = 0$. Let us assume that δ_{ik} represents the displacement In the point and the direction i caused by the force $S_k = 1$. Then the displacement of the point i are described by the formula (4)

$$u_i = \sum_{k=1}^{k=n-3} \delta_{ik} S_k = \sum_{k=1}^{k=n-3} K_k \delta_{ik}(U_k - u_k) \tag{4}$$

where i, $k = 1,2,\ldots, n$.

In the approximate procedure we consider only a system of three collinear springs representing two elastic supports acting on opposite sides of the orifice (Fig. 14) and the strip of the implant. In this method, the force in the spring can be described by the formula (5)

$$S_S = K_S(u_i + u_k) \tag{5}$$

where K_s represents the stiffness of the implanted mesh. Thus the forces in springs placed in points i and k are described by the equations (6)

$$S_i = K_{ti}(U_i - u_i)\,,\ S_k = K_{tk}(U_k - u_k)\ . \tag{6}$$

Due to the equality of the forces $S_i = S_k = S_S$ we can obtain values of the stiffness K_{tk} and K_{ti} (7) and (8).

$$K_{ti}(U_i - u_i) = K_S(u_i + u_k) \ \Rightarrow\ K_{ti} = K_S \frac{(u_i + u_k)}{(U_i - u_i)}\,, \tag{7}$$

$$K_{tk}(U_k - u_k) = K_S(u_i + u_k) \ \Rightarrow\ K_{tk} = K_S \frac{(u_i + u_k)}{(U_k - u_k)}\ . \tag{8}$$

The calculations are based on the results of the laboratory tests of displacements observed on the outside and inside of the human abdomen.

As a result of the identification on the basis of equations (7) and (8) we obtained the values in different direction and points (Fig. 15):

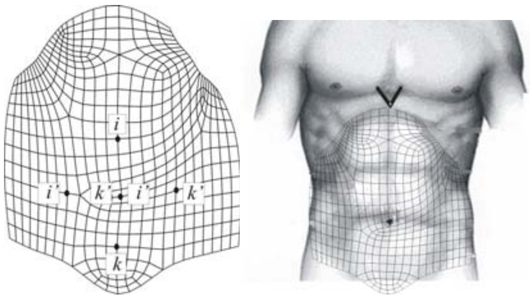

Figure 15. The location of the identified elastic support

The vertical direction (points 11-21, Fig.9 and 4-7, Fig. 12): K_{ti} = 6.15 N/mm; K_{tk} = 4.26 N/mm; in the horizontal direction (points 20-21, Fig. 9 and 2- 6, Fig. 12): K'_{ti} = 7.28 N/mm; K'_{tk} = 5.08 N/mm; in the horizontal direction (points 21-26, Fig. 9 and 2-6, Fig. 12): K'_{ti} = 7.28 N/mm; K'_{tk} = 5.96 N/mm.

3.2.2 *Finite element modelling of the Model 2*

Next, the model 2, containing the elastic supports was developed. This model is more appropriate in the case of hernia where it was assumed that the tissue has an influence to the membrane behaviour.

In this model (Fig. 16), the springs are provided in the plane of the membrane as well as perpendicular to its reference surface on the edge around the structure. In this case the springs support represents the zone of influence of the muscles and internal organs on the membrane behaviour.

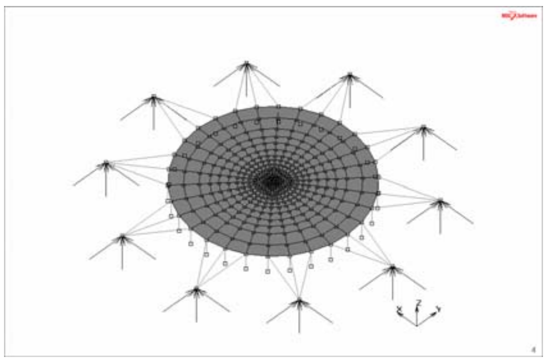

Figure 16. Model 2 with elastic supports

The stiffness of springs was assumed approximately as identified in the section 2.3.1. In this model, the junction force R_2 = 10 N and the maximum deflection dz_2 = 1.79e-2 m (Fig. 16). In this case, the junction force is close to the value of the failure load identified in Ref. [11].

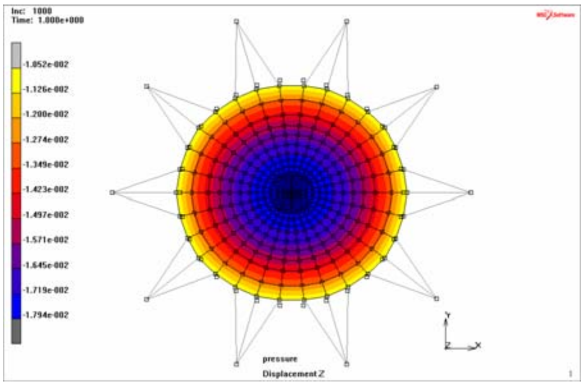

Figure 16. Model 2. Membrane deflection

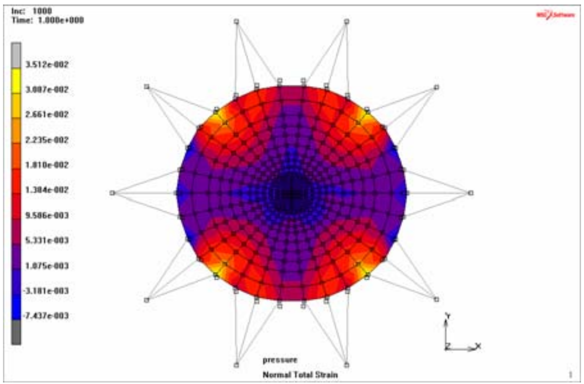

Figure 17. Model 2. Membrane deflection

The orthotropic behaviour of the implant is visible in the Fig. 17 representing the normal strains.

4 Conclusions

The authors developed a membrane finite element model of the mesh implanted in a human body to repair the ventral hernia with a stiff orifice.

The authors proposed two variants of finite element models with the stiff and elastic supports. Both models refer to rigid hernia orifice. Model 1 reveals lower junction force and also lower deflection in the centre of the membrane. In model 2, a higher value of the reaction force appears and the membrane deflects more. These models can be used to estimate the necessary joints number in different situation for laparoscopic surgery.

All the simulations will have to be compared with the laboratory tests to calibrate the finite element model.

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