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Two-criteria optimisation problem for ventral hernia repair

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ABSTRACT
Two-criteria optimisation problem related to laparoscopic ventral hernia repair is formulated in this paper. An optimal implant from a given set and its orientation is sought. The implant is subjected to kinematic extortions due to a patient's body movement and intra-abdominal pressure. The first criterion of the optimisation problem deals with the reaction force in the implant fastener, while the deflection of the implant constitutes the second criterion. A two-stage optimization procedure is proposed and the optimal solution is determined with the aid of minimization of an additional objective function. Numerical examples for typical locations of hernia are provided.

KEYWORDS Optimisation; finite element modelling; laparoscopic ventral hernia repair; surgical mesh

1. Introduction

The problem of optimal choice of an implant for laparoscopic ventral hernia repair (LVHR) is undertaken in this study. There is a need for optimisation in LVHR since surgeons often deal with recurrences of the sickness, caused usually by the implant-tissue connection failure. Another problem is mesh bulging, which is a pseudo-recurrence often causing considerable discomfort to the patient as commented in, e.g. Tse et al. (2010). Carter et al. (2014) shows that recurrences and the bulging problem are related to the mesh type.

Junge et al. (2001) showed that the elasticity of surgical meshes should be compatible with the elasticity of the abdominal wall. Therefore, some studies on abdominal wall mechanics (Podwojewski et al. 2014; Tran et al. 2014) and its components (Cooney et al. 2015) have been conducted in the context of hernia repair. The anisotropy of the abdominal wall indicates that crucial issue in the mechanical context of hernia repair and its persistence is the orientation of the anisotropic implant in the abdominal wall. Its significance for proper hernia repair has been outlined by Anurov et al. (2012).

There exist different studies discussing the properties of meshes in relation to mechanical and medical issues. In the paper by Klinge and Klosterhalfen (2012), a classification of hernia meshes based on 1000 explanted implants is provided. Mechanical properties of surgical meshes are widely discussed in the literature (Deeken et al. 2014). Maurer et al. (2014) proposes a procedure for comparing meshes in the context of their biocompatibility. The mechanics of the implants used for hernia repair are also addressed in the literature based on some experimental and numerical studies of the mesh behaviour in the simulated abdominal wall. Some physical models of the implant-tissue system are presented in the work by, e.g. Tomaszewska et al. (2013) Guérin and Turquier (2013) and Lyons et al. (2013). Different material models of the implant are proposed, e.g. bilinear orthotropic (Tomaszewska et al. 2013) dense net model (Lubowiecka 2015), hyperelastic transverse isotropic (Hernández et al. 2011). Models of implant structures are developed and discussed in, e.g. Hernández-Gascón et al. 2014;. Numerical studies on the behaviour of the abdominal wall –implant system can be found in the work by, e.g. and Simón-Allué et al. (2016). In all these works implants are modelled as a membrane structure.

The effectiveness of mathematical modelling and numerical simulations in modern hernia surgery has been confirmed by surgeons (see Stetsko et al. 2016) who used medical recommendations based on the mechanical approach (Tomaszewska et al. 2013) in LVHR surgeries and obtained a low recurrence rate. However, the universal procedure to select the best solution for a given medical case remains undetermined. In Lubowiecka et al. (2016), single-criterion optimisation of implant choice and its orientation is proposed. The objective is to minimise forces in staples fixing the implant in the abdominal tissue to decrease a risk of the fixation failure. Such a single criterion investigation is aimed at helping surgeons to select the best solution for an individual case of ventral hernia. It is known that the more elastic the mesh is, the lower the forces appear in the fixation points. However, bigger bulging appears for more elastic implants and because of that reoperation is required in some cases (Schoenmaeckers et al. 2010). On the other hand, the application of stiffer meshes leads to smaller bulging, but the forces in fasteners are larger, which increases the risk of fixation damage. In order to balance these opposing effects, the two-criteria optimisation procedure (Pareto 1896–1897) is proposed.

The aim of this study is to determine the best mesh and its orientation in relation to the craniocaudal axis, from a set of commercial products, for five typical hernia locations. We focus on two mechanical issues related to recurrence (or pseudo-recurrence) types: the risk of connection failure and bulging of the mesh. The analysis is based on numerical simulations of selected types of surgical mesh responses to physiological human actions, such as abdominal wall displacements during human movement and intra-abdominal pressure.

2. Materials and methods

2.1. Formulation of the optimisation problem

Finding an optimal implant from a given set S of implants and its orientation determined for an assumed circular layout of fasteners is considered on account of two criteria. The decision variable vector $\boldsymbol{x}$ consists of an implant number s of the set of implants S and the angle α between the axis of the implant's largest stiffness and the craniocaudal axis. The first criterion deals with the maximum reaction force in the fasteners $F_1(\boldsymbol{x})$, while the second one $F_2(\boldsymbol{x})$ is related to the maximum deflection of the implant. The considered reaction forces arise due to the implant's boundary displacements corresponding with the patient's abdomen movement or to the impact of the abdominal pressure related to the Valsalva manoeuvre.

If the maximum reaction force exceeds its admissible value, failure of the implant-tissue juncture is possible. Therefore, to reduce the risk of this situation taking place, a minimum of the maximum reaction force obtained with different orientations of various implants in the abdominal wall is sought

$$\min_{\substack{\\ i \in I, 0 \leq \alpha \leq 2\pi}} \max \quad F_1(i, \alpha, s), \tag{1}$$

where i denotes the number of the fastener, indicating its position, while I stands for the fasteners' set.

A two-stage process of minimising the criterion (1) is proposed following Lubowiecka et al. (2016). In the first stage, for any chosen implant s and the assumed angle of the implant orientation the maximum force $F_{1\max}(i, \alpha, s)$ in the fasteners is sought in the second stage, the orientation angle α_0 corresponding to the minimum value of the maximum fastener force $F_{1\max}$ is sought.

The minimisation procedure for kinematic extortions is conducted in a discrete manner; the implant orientation angle α changes by an assumed increment $\Delta\alpha$. Thus, the orientation angle of the implant α_0, for which the minimal force in fastener i_0 occurs (which is selected in a first step), is identified. The final value of the first criterion F_1 is the maximum of two values: the maximum reaction obtained under the intra-abdominal pressure and minimum (in optimal orientation α_0) of the maximum fastener reaction force under kinematic extortions.

The second criterion $F_2(s)$ is established for each implant s as the maximum deflection of the implant subjected to the impact abdominal pressure. To reach the optimal solution of the problem, firstly a scaling procedure is proposed. In order to obtain dimensionless quantities, the value of each criterion is divided by its admissible limits; the first one by the assumed limit tearing force $F_{1\mathrm{ad}}$ depending on the fasteners considered, and the second one by the admissible deflection $F_{2\mathrm{ad}}$.

$$\bar{F}_1(s) = F_1(s)/F_{1\mathrm{ad}}, \quad \bar{F}_2(s) = F_2(s)/F_{2\mathrm{ad}} \tag{2}$$

The optimal implant and its corresponding orientation angle is established by means of minimization of the following objective function with respect to $s \subset S$

$$\min_{s \subset S} F(s) = \sqrt{\bar{F}_1^2(s) + \bar{F}_2^2(s)}. \tag{3}$$

The optimal solution should be chosen among the admissible solutions, therefore it ought to fulfil the relationships

$$0 < \bar{F}_1 \leq 1, \quad 0 < \bar{F}_2 \leq 1 \tag{4}$$

The optimisation procedure may lead to results dependent on the localization of the hernia orifice.

2.2. Numerical modelling and simulations

The finite element method (FEM) and commercial software MSC.Marc® are applied. The model refers to a case in which a hernia orifice has a diameter of 5 cm. As recommended by surgeons, the overlap of the mesh is equal to 4 cm. Thus, the total diameter of the implant equals 13 cm. There is a single crown of fasteners. Two cases are considered: 10 fasteners, which is the minimal number to keep the maximum admissible distance between fasteners (4 cm), and 15 fasteners.

Four types of popular commercial implants are considered in the analysis. The meshes, which are different in weight, substance, mechanical properties and orthotropy ratios, are selected in order to search for an optimal solution among different materials. They are: Proceed™ Surgical Mesh (Ethicon Endo-Surgery, Inc., USA), which is a lightweight mesh, Parietex™ Composite (Covidien, USA), DynaMesh®-IPOM (FEG Textiltechnik mbH, Germany), which are medium-weight meshes and Gore® Dualmesh® Biomaterial (W. L. Gore & Associates, Inc., USA), which is a heavyweight mesh according to a classification after Brown and Finch (2010).

2.2.1. Implant model subjected to kinematic extortions

FEM model considered in this part of the study is the model proposed in Lubowiecka et al. (2016) and presented in Figure 1. This is a membrane model of an implant with point supports, as it is realized in practice by trackers or point trans-abdominal sutures. Membrane quadrilateral 8 node finite elements with three translational degrees of freedom per node were used. The number of elements in the case of 10 fasteners is 960 and in the case of 15 tacks there are 2232 elements (Figure 2(a)). Material models for the implants considered are described in the paper mentioned above. The model is subjected to kinematic extortions of supports that simulate displacements of the mesh fixation points during human life activities. The kinematic extortions applied to the models are specified based on the research concerning abdominal wall strains (Szymczak et al. 2012) and reduced owing to the results of Podwojewski et al. (2013). Five ventral hernia placements located in areas with a different range of strains (Figure 3) are designated by surgeons as worthy of consideration. The values of kinematic extortions in each zone for 10 fixation points of the implant are discussed in Lubowiecka et al. (2016), and also presented in Table 1. Table 2 presents values for 15 fasteners distributed as shown in Figure 1(b).

Twelve mesh orientations from 0° to 180° with respect to the craniocaudal axis with a 15° step are considered in the study. A nonlinear static analysis is performed in each case and reaction forces in supports are calculated and introduced into the optimisation procedure.

2.2.2. Implant model subjected to the intra-abdominal pressure load

The FEM model used in the second step of the analysis is similar to the one discussed above, but is enriched by spring elements that refer to the abdominal wall tissue' stiffness (Figure 4). The abdominal wall elasticity in the direction perpendicular to the implant plane is represented by the elastic foundation surrounding the hernia orifice. In the implant's plane, the stiffness of the connective tissue is represented by elastic springs situated in the supporting points of the implant. The following four-node quadrilateral membrane finite elements were used: 900 elements in the case of 10 fasteners and 1094 elements in the case of 15 fasteners (Figure 2(b)). The difference between elements (8 or 4 nodes) is because of the greater difficulty of reaching convergence in case of model with kinematic extortions. The model is validated on the basis of experiments on physical hernia models built of a porcine tissue and various implants, and then loaded by impact air pressure, as described in Lubowiecka (2015).

A dynamic analysis was performed for models of each implant loaded by the impulse of pressure. Two pressure values were applied; 50 mm Hg as in the study by Podwojewski et al. (2014) which corresponds to the value of the intra-abdominal pressure during the Valsalva manoeuvre. The maximum deflections of the meshes and reaction forces were collected for the optimisation procedure.

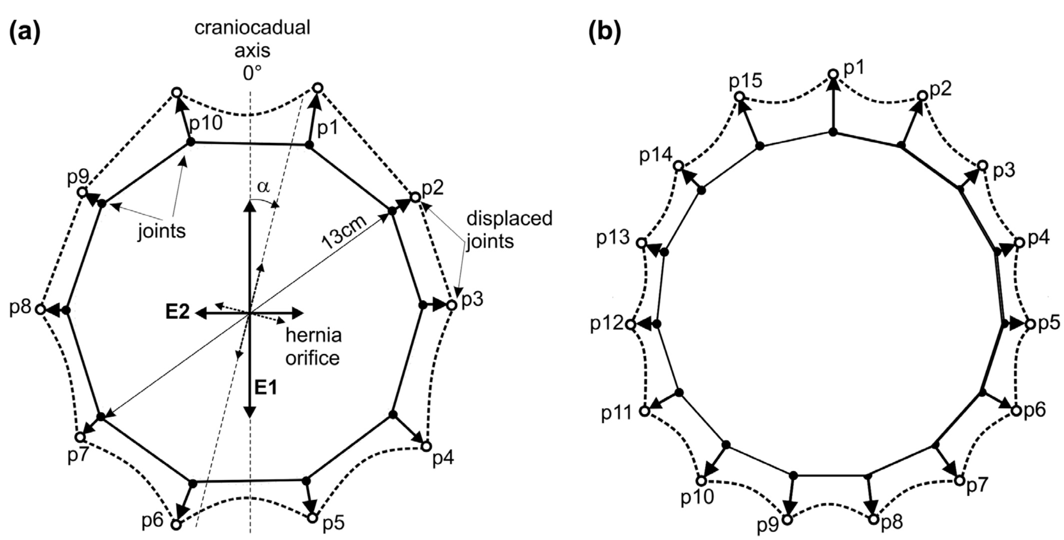

Figure 1. Scheme of the model subjected to kinematic extortions in the case of (a) 10 mesh fasteners, or (b) 15 fasteners.

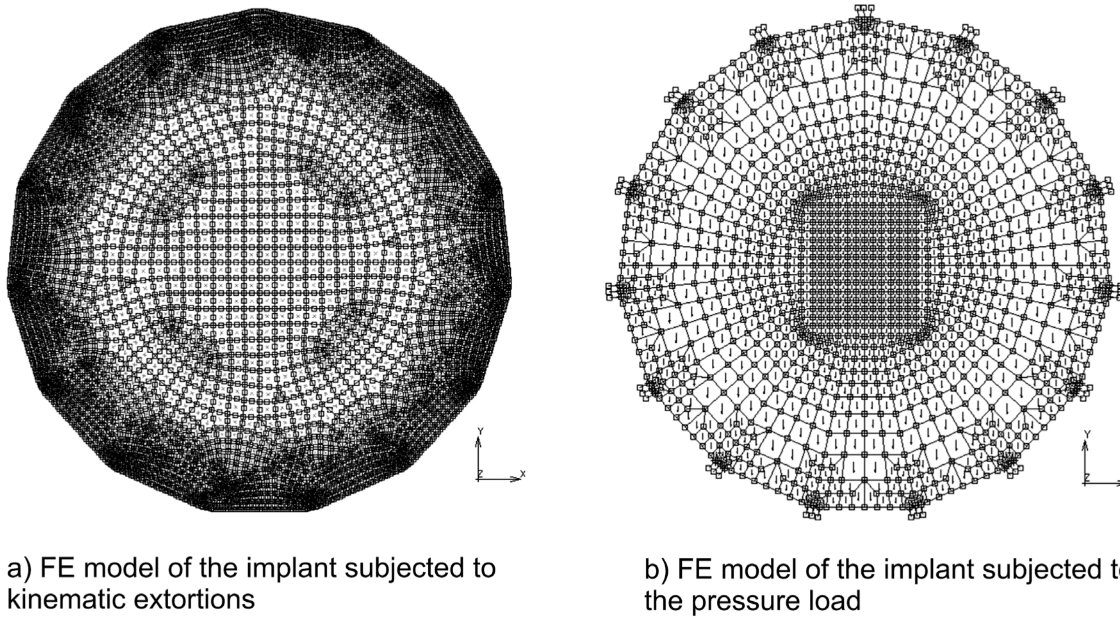

Figure 2. FE models.

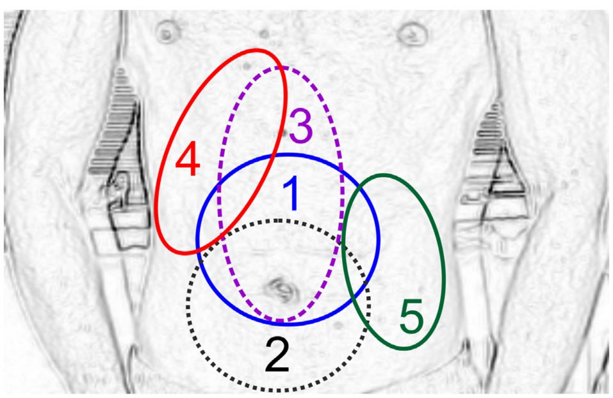

Figure 3. Considered hernia location zones.

2.3. Admissible values of reaction forces in fasteners and of abdominal wall deflection

The admissible reaction force in mesh fasteners is specified as load bearing capacity of a selected staple. It is determined based on the experimental results by Tomaszewska et al. (2013), concerning the strength of different types of mesh fixations made by staples or trans-abdominal sutures. Thus, the admissible force selected for the optimisation process equals 10 N, as the highest capacity of the staples. However, additional suture fixation is also taken into consideration, which renders more solutions admissible. The capacity of trans-abdominal sutures for the four kinds of meshes is discussed Tomaszewska et al. (2013). The acceptable level of implant bulging should guarantee subjective impression of comfort. As a result of the variability of abdominal wall properties, this study investigates different levels of admissible displacement starting from 0.005 to 0.05 m.

Table 1. Abdominal strains in radial direction imposed in the model supports in the case of 10 fasteners (%).

(%)	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10
Zone 1	9	3	3	6	7	7	6	3	3	9
Zone 2	9	3	2	6	7	7	6	2	3	9
Zone 3	12	4	3	7	9	9	7	3	4	12
Zone 4	9	6	3	5	13	13	5	3	0	0
Zone 5	9	5	3	7	13	13	7	3	5	9

3. Results

The deflections of different meshes under 50 mm Hg pressure in the model with 10 or 15 support points are in a range of 0.008–0.019 m. The reaction forces obtained

Table 2. Abdominal strains in radial direction imposed in the model supports in the case of 15 fasteners (%).

(%)	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	p12	p13	p14	p15
Zone 1	9	8	4	5	5	6	7	7	7	7	6	5	5	4	8
Zone 2	9	7	3	2	2	5	6	7	7	6	5	2	2	3	7
Zone 3	12	8	5	4	4	7	8	9	9	8	7	4	4	5	8
Zone 4	4	9	7	5	3	5	9	13	13	9	5	3	2	0	0
Zone 5	9	7	5	4	3	7	9	13	13	9	7	3	4	5	7

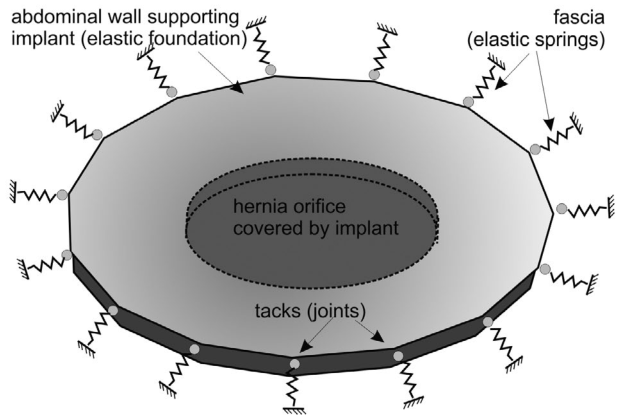

Figure 4. Scheme of the model subjected to intra-abdominal pressure.

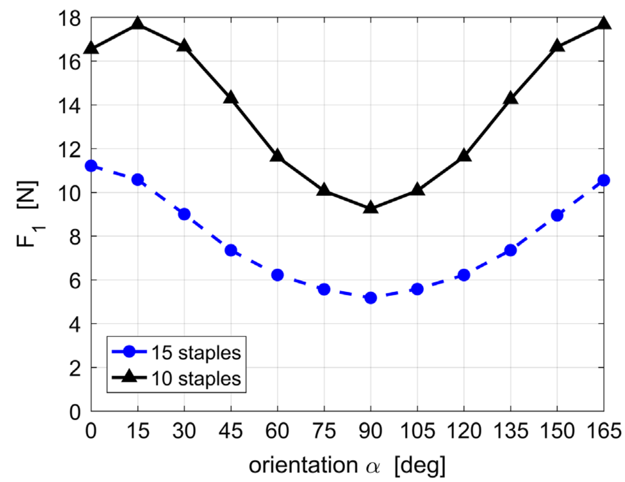

Figure 5. Maximum reactions vs. implant orientation in the case of 15 or 10 staples, DynaMesh implant, zone of hernia placement 5.

under kinematic extortions in the case of 10 fixation points of the implant are presented in Lubowiecka et al. (2016). The reactions calculated for 15 staples have similar values and are similarly distributed. Figure 5 presents an example of the comparison. The exact minimum and maximum of the reaction force may differ in some cases, but the general shape of the curve presenting maximum reactions in the function of implant orientation is quite similar.

The reactions obtained for the model under kinematic extortions are larger than the reaction forces in the model subjected to intra-abdominal pressure of 50 mm Hg. Hence, those values are taken into account in the optimisation procedure in all cases.

The values of reaction forces in the models of Proceed and Gore Dualmesh implants are much higher than the capacity of staples. Hence, these two implants are excluded from further analysis. Figure 6 shows an example of a solution in F_1/F_{1ad} and F_2/F_{2ad} coordinate systems. The optimal solution is the closest one to the origin, according to Equation (3). For each implant, two points are presented: for optimal orientation ($\alpha_{\min}$) and also for the worst orientation ($\alpha_{\max}$), to see if the correctness of orientation can change the optimisation outcome. For the value of F_{2ad} = 0.01 m, none of the values are in the admissible area. When increasing F_{2ad} to 0.02 m, which is more than implant deflections calculated in model 2 in this study, DynaMesh and Parietex are in the admissible area (Figure 7), but not

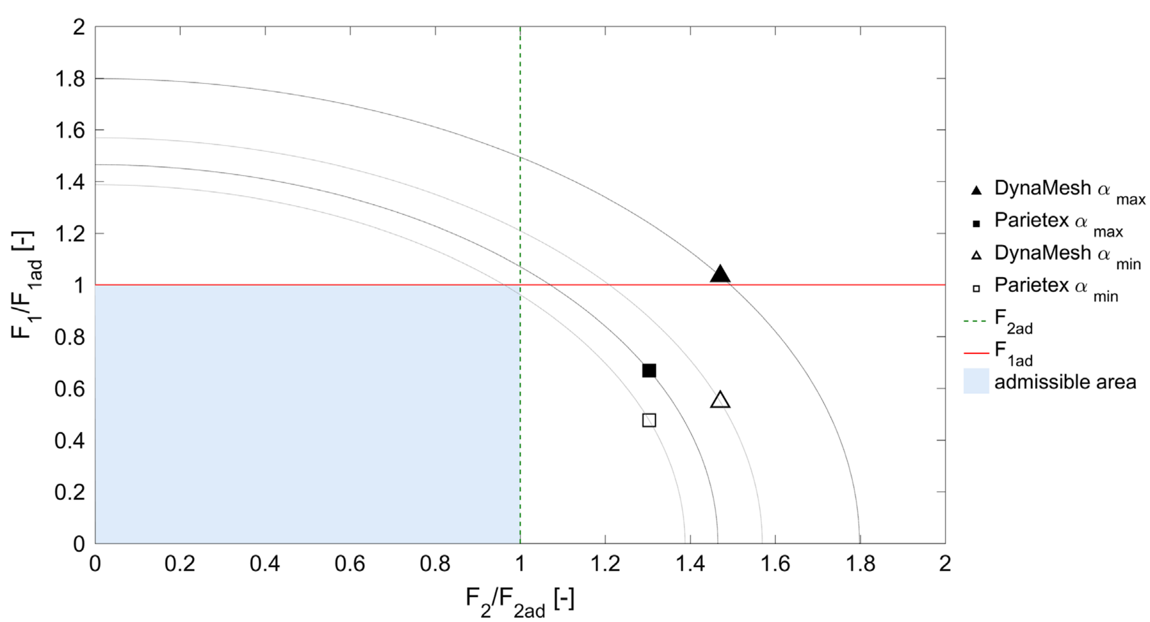

Figure 6. Solutions in zone 3, for F_{2ad} = 0.01 m, 10 staples.

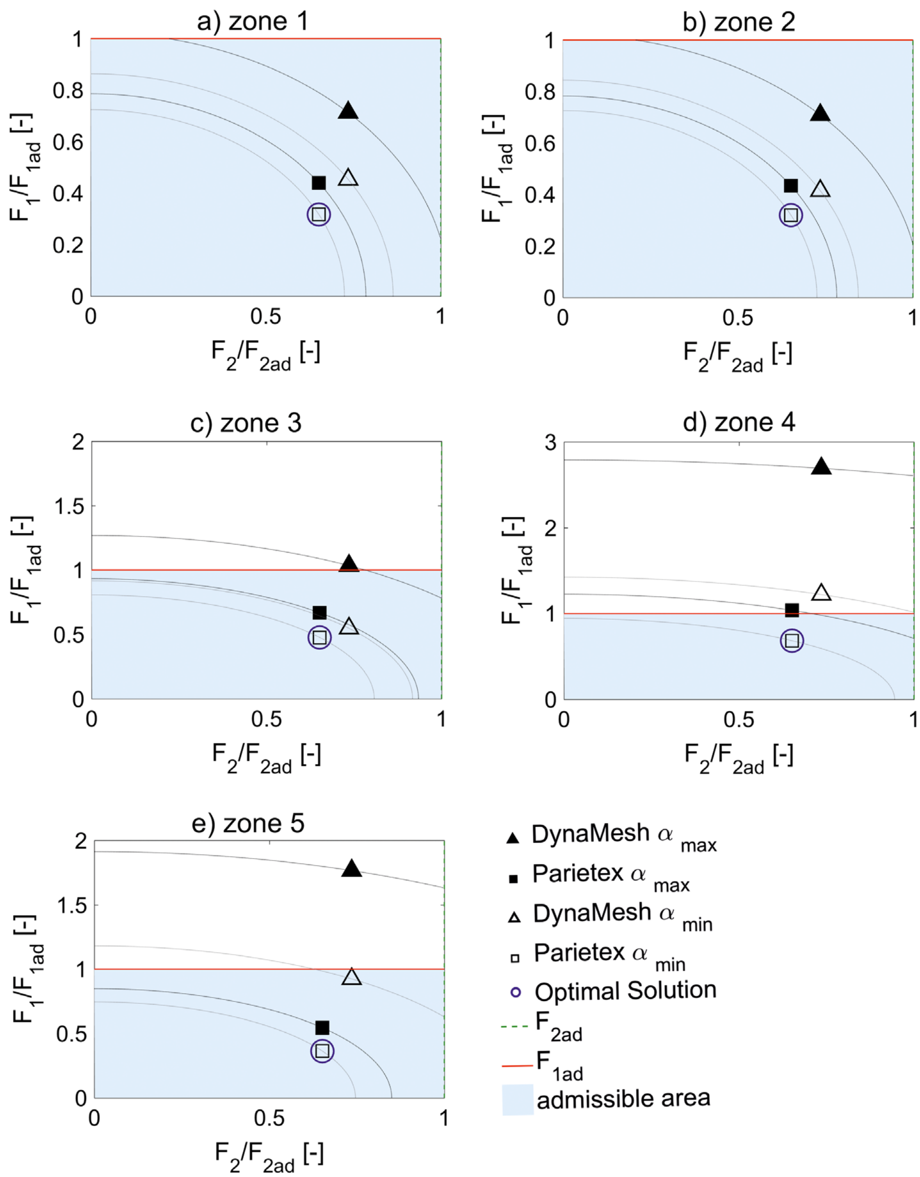

Figure 7. Optimisation results for $F_{2ad} = 0.02$ m, 10 staples, five hernia placements (a)–(e).

in all hernia locations, when considering the reaction force. Figure 8 shows how F_{2ad} influences the value of the objective function. The crossed points are the ones which do not fulfil the capacity condition $\frac{F_1}{F_{1ad}} \leq 1$ and the points with empty markers are the ones which do not fulfil the deflection condition $\frac{F_2}{F_{2ad}} \leq 1$. Figures 9 and 10 present these results for the mesh with 15 fixation points.

4. Discussion

This analysis is performed for the staple capacity $F_{1ad} = 10$ N. However, we can extend our admissible solutions span to a case when the load bearing capacity of not more than 4 fasteners is exceeded and forces reach not more than 20–35 N, according to the type of implant. Those 4 fixations are made by trans-abdominal sutures (see Tomaszewska et al. 2013). In such a case, Parietex is always admissible due to the force criterion. DynaMesh is not admissible only in zone 4 (see Figure 3), when unfavourably oriented. The appropriate results, which can be treated as admissible with additional sutures are marked in Figure 8.

In all considered cases with 10 staples, Parietex minimizes the objective function. However, in zone 3 of hernia placement for some values of F_{2ad} (Figure 8), DynaMesh in favourable orientation can be better than the unfavourably oriented Parietex implant. It should be noted that the differences in the outcomes in this case are very small. This is also the only case where level of F_{2ad} can change the sequence of the best implants if the orientation is not specified.

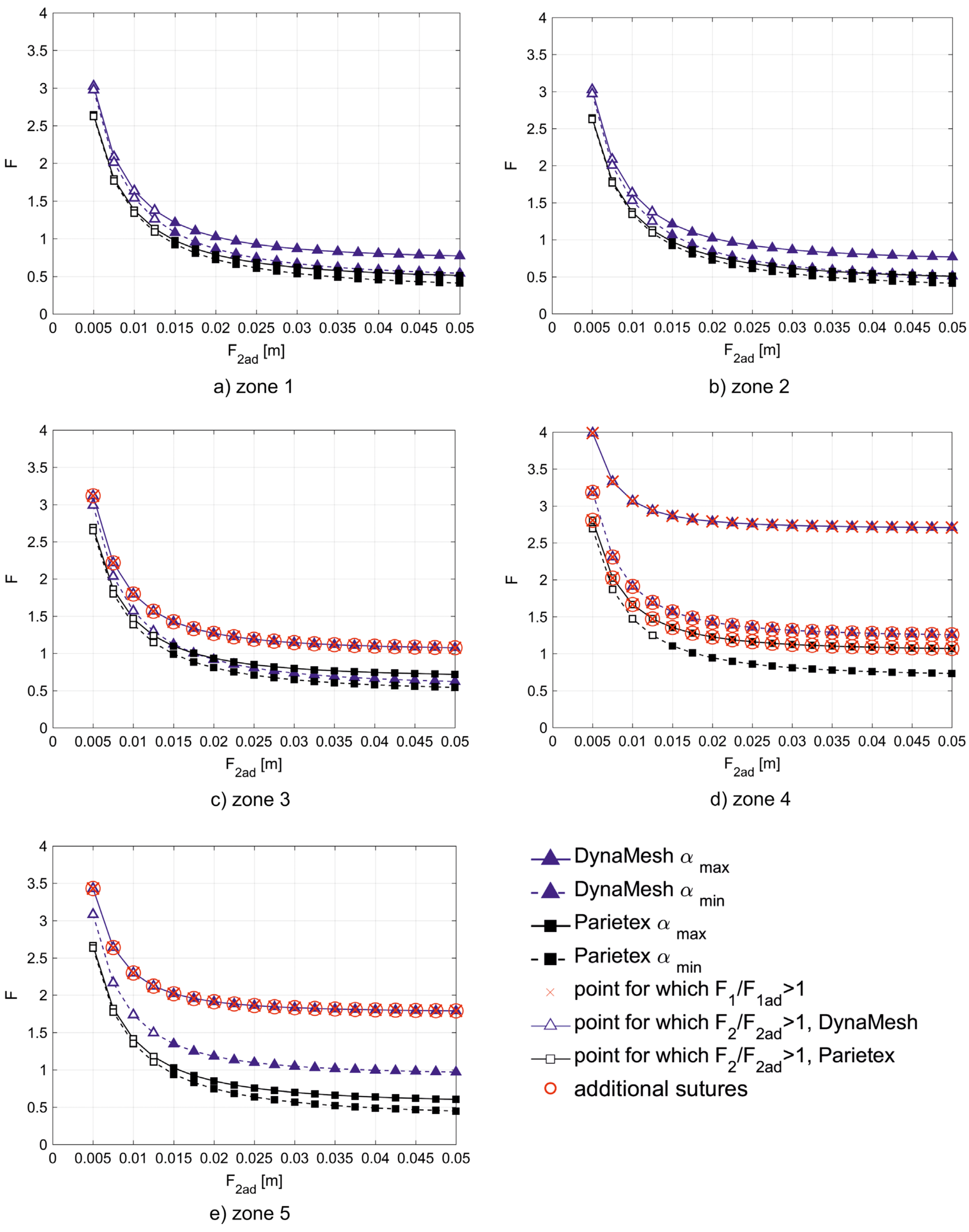

Figure 8. Objective function outcomes vs. F_{2ad}, in case of 10 staples, five hernia placements (a)–(e).

For the model with 15 staples, the optimisation solutions are similar to the model with 10 staples. A difference in the sequence of implants occurs only in zone 4 (Figures 9 and 10) of the abdominal wall, when DynaMesh optimises the objective function and the admissible deflection is larger or equal to 0.02 m. However, this difference is not significant. This is also the only case when non-optimal positioning of the implant changes the

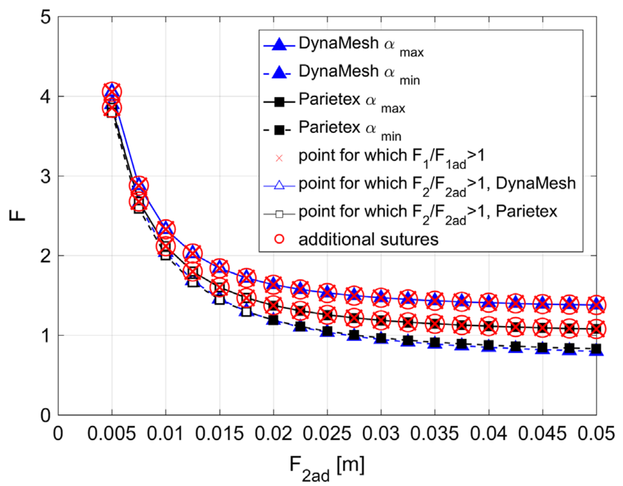

Figure 9. Objective function outcomes vs. F_{2ad}, in case of 15 staples, hernia in zone 4.

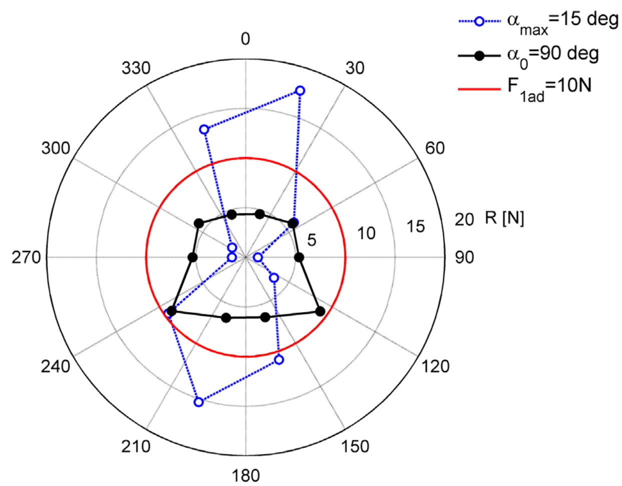

Figure 11. Distribution of reaction forces in 10 fixation points in zone 5, DynaMesh implant oriented in the least favourable orientation of 15° and in the optimal orientation of 90°.

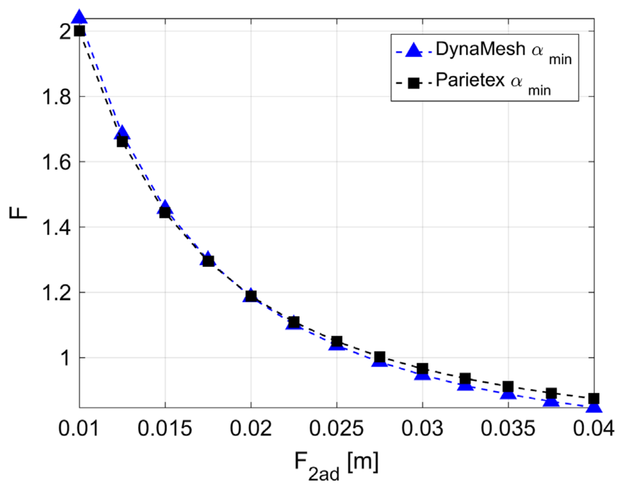

Figure 10. Objective function outcomes vs. F_{2ad}, in case of 15 staples, hernia in zone 4, range of F_{2ad} showing a change of an implant minimizing the objective function.

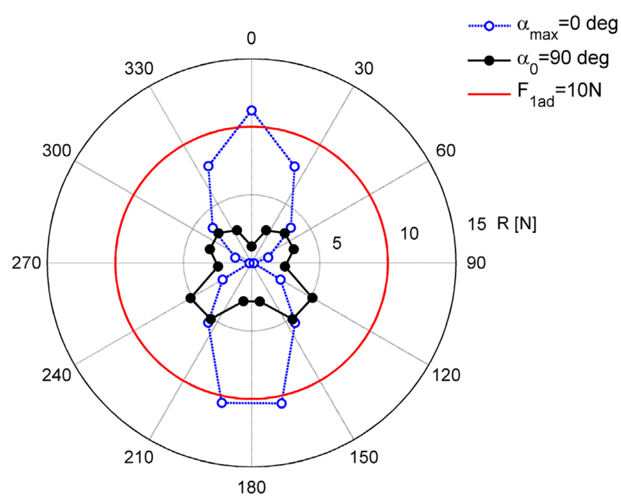

Figure 12. Distribution of reaction forces in 15 fixation points in zone 5, DynaMesh implant oriented in the least favourable orientation of 0° and in the optimal orientation of 90°.

optimisation results. The reaction forces in the model of the unfavourably oriented DynaMesh implant fixed by 10 staples in zone 4 of hernia placement can exceed the capacity of staples and also the suture capacity in one of the directions, which makes this solution unacceptable. However, when DynaMesh is fixed by 15 staples, the reaction forces do not exceed the capacity of sutures. Parietex is admissible from the point of view of the reaction force in the case of 10 and 15 fasteners in all zones, but in some of them additional trans-abdominal sutures are required. The sutures replacing the staples should be placed in points where the reaction forces are highest. For example, Figures 11 and 12 show that if the implant in zone 5 is unfavourably positioned the sutures are needed in the points near the craniocaudal axis.

The two-criteria optimisation process leads to the same sequence of favourable meshes in the considered set as the one-criterion optimisation discussed in Lubowiecka et al. (2016). The value of admissible implant deflection is quite important, as it can remove some solutions out of the admissible region. However, if the admissible level of deflection is bigger than the maximum deflection of implants (e.g. for 10 tacks, 50 mm Hg pressure, 0.015 m), it does not change the optimisation outcome, with one exception (15 tacks, zone 4 of hernia placement). Tran et al. (2014) studies the behaviour of the human abdominal wall under the static pressure *ex vivo*. The results described in that study allow assessing the mean deflection of the complete abdominal wall (containing all layers, including peritoneum and skin) under a pressure of 22.5 mm Hg at a level of 0.011 m (variability around 20%), for a tissue sample which is 0.160 m wide. This value can be the basis for the assumption of the admissible deflection range. The values of mesh deflection in our model under such pressure are in the range of 0.006–0.013 m, which is comparable to the experimental result for the abdominal wall tissue.

The approach can be validated by comparison with approach proposed by Kirilova et al. (2012). The elastic moduli of Proceed and Gore Dualmesh (Tomaszewska et al. 2013) are significantly higher than the modulus of fascia (Kirilova et al. 2011). According to Kirilova et al. (2012), the elasticity of the meshes should be close to the elasticity of fascia. In our study, junction forces in those meshes caused by kinematic extortions greatly exceed the admissible value, so the two meshes are excluded from the optimisation process. This is also in accordance with the approach of Kirilova et al.

Regarding the present study, some limitations can be mentioned. The abdominal wall is treated here as a flat structure and the friction effects between mesh and tissue are omitted. Moreover, the study relates to a time just after LVHR, which is critical for the repair persistence, so the mesh overgrowth by tissue or the mesh shrinkage are not included.

5. Conclusions

We propose an optimisation procedure of implant selection based on two criteria: the minimisation of maximal forces in the tissue-implant junction and the minimisation of implant deflection. The problem is illustrated by numerical examples. The results presented can have a direct impact on laparoscopic ventral hernia management since an optimal solution has been presented for particular medical cases. Four kinds of implants, five hernia placements and two fixation schemes are considered. Within implants with accepted forces and deflection, Parietex minimises the objective function in most cases, however, DynaMesh is competitive. The orientation of the orthotropic implant is important to minimise the risk of its fixation failure and decides on the admissibility of the solution due to the capacity of the fasteners. In the next step, the presented methodology can be extended to the design of an optimal implant.

Disclosure statement

No potential conflict of interest was reported by the authors.

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