
Impact of the surgical technique on the biomechanical response of the repaired abdominal wall evaluated on a physical model

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Abstract

1. Introduction

Ventral incisional hernia (VIH) occurs when abdominal content protrudes through a weakness in the abdominal wall. VIH repair is among the most commonly performed surgical procedures, with approximately 300,000 and 500,000 procedures carried out annually in Europe and in the United States respectively (Sauerland et al., 2011, Miller et Novitsky, 2019). This number continues to rise, with a 30 % increase over the past ten years, likely due to the growing prevalence of obesity (Gillion et al., 2019). Although the use of textile meshes has improved clinical outcomes, post-operative complication (e.g., recurrence) rates remain high and may reach a 25%-plateau of recurrence at 3 years post-operatively, from 2000 to 2024 (Luijendijk et al., 2000, Zolin et al., 2023, Bhardwaj *et al.*, 2024). These complications require additional surgery, exposing patients to further risks and imposing significant social costs, which are annually estimated at 3.2 billion dollars in the United States (Miller and Novitsky, 2019).

The abdominal wall is a complex anatomical structure that defines the boundary of the abdominal cavity. Its anterior and lateral periphery is defined by a flexible and complex mechanical multi-layered structure composed of muscular and fibrous tissues, which each exhibit non-linear and anisotropic properties (Astruc et al., 2018). The abdominal wall provides protection to viscera and plays a central role in regulating intra-abdominal pressure

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(IAP) during physiological activities. An increase in IAP is directly related to the formation and recurrence of hernia together with other factors such as pregnancy, weightlifting and chronic cough (Luijendijk et al., 2000). During a hernia repair procedure, hernia meshes can be placed on different planes of the abdominal wall, and it is recommended to secure them to the abdominal wall using surgical tacks or sutures. The primary goal of a mesh is to reinforce the abdominal wall, reducing the stress the wound is subjected to. This reduction in stress can create better conditions for the formation of high-quality neotissue, ensuring a safe repair over time post-operatively (Franz, 2008, Karrech et al., 2023). Hernia meshes are porous, warp-knitted structures that exhibit anisotropic, non-linear behavior with a strong coupling between directions (Pierrat et al., 2021) and load-profile dependent (Tomaszewska et Reznikov, 2024).

Ventral hernia repairs suffer from a lack of standardization (e.g., number of fixations, mesh type, mesh size, fixation method, mesh position) as well as a lack of personalization (e.g., based on the patient anatomy), which may explain the high variability observed in clinical outcomes. Little consensus on the surgical approach has yet been established leading to a successful repair (Cherla et al., 2018), so a high variability still exists in the adopted surgical approaches. According to Aquina and al., part of this variability is due to both the repair techniques and patient-specific factors (Aquina et al., 2017). Each of these factors impacts the initial state of the repair and, consequently, its healing behavior over time (Franz, 2008, Karkhaneh Yousefi et al., 2023).

One way to investigate the impact of different surgical techniques on the biomechanical response of the repaired abdominal wall is to use physical models. Most of them were developed based on *ex vivo* abdominal walls (Lyons et al., 2015, Végleur et Le Ruyet, 2023) subjected to a mechanical load which mimics daily activities. However, using biological tissues is challenging to handle, lacks control over their properties, and shows significant mechanical variability, reducing the repeatability of conditions. The use of synthetic materials can address this limitation, as it provides more control over the anatomy and mechanical properties of the different structures (Kroese et al., 2017).

In this study, we assessed the influence of key parameters of the surgical procedure for ventral hernia treatment on the overall behavior of repaired abdominal wall using a physical model. More specifically, the impact of the mesh type, mesh size, fixation configuration and abdominal wall stiffness on the mechanical response of the abdominal wall was investigated while subjected to pressure loading.

2. Materials & Methods

2.1. Physical model

A 5-mm thick synthetic silicone rubber wall was chosen as a substitute for the abdominal wall (Silex LTD, Silicone Rubber Sheet). A mesh was then fixed at 1-cm of the 4 mesh edges with a suture thread (Covidien PolysorbTM, SL-721, 0, 3.5 Metric) to 4 force sensors anchored in the synthetic wall. The sensors placed at the corners of the mesh allowed for the measurement of the forces applied at the textile's fixation points. A silicone membrane (0.250 mm, 22 ± 5 shore A, BISCO® HT-6220, Rogers Corporation) was placed under the synthetic wall to ensure that the mesh was loaded during the increase in intra-system pressure (Végleur et Le Ruyet, 2023). These synthetic layers were placed into a pressure chamber, which simulates the physiological conditions observed in the human abdomen (Campbell et al., 1953).

2.2. Experimental design

The forces at mesh fixation points were recorded at 100 Hz, characterizing the biomechanical interaction between the mesh and the wall constituents when subjected to an inflation test at 140 mmHg, simulating daily activities involving muscular contraction (Cobb et al., 2005). The forces were always measured at the same four points, regardless of the fixation

configuration. A pressure sensor (2 bar, XP5-M-2BG, Measurement Specialties™, 100 Hz) was used to measure the resulting pressure applied in the chamber. An acquisition system (Dewesoft SIRIUS®[®], V23-1) was used both to collect signals from the sensors and to send electric signal to precisely regulate the airflow (0–2 bar, QB2, Proportion Air). Additionally, two cameras (5MP, GS3-U3-41C6M, Point Grey®[®]) equipped with 3D-calibrated lenses (16 mm focal length, Schneider Kreuznach) were positioned above the setup to record the sample's response throughout the test Correlation (Correlated Solutions, VIC 3D, VIC Snap).

2.3. Parametric study

The effect of different surgical strategies on the biomechanical response of the abdominal wall was studied, along with the influence of the abdominal wall's elasticity.

- Two synthetic walls with mechanical characteristics similar to those of thawed biological abdominal walls, were used (Kriener et al., 2023), exhibiting 30-Shore A and 40 Shore A hardness properties respectively, with elastic moduli of 1.1-MPa and 1.7-MPa respectively (Silex LTD, Silicone Rubber Sheet, 30 ± 5 Shore A and 40 ± 5 Shore A). These moduli were obtained using a correlation formula between durometer values and elastic moduli (Larson, 2019).

- Three different meshes, among all the products in the Medtronic portfolio, were used in this study, with relatively low (type A, polyethylene terephthalate, monofilament, 45-g/m^2), semi-flexible (type B, polypropylene, monofilament, 70-g/m^2) and high (type C, polyethylene terephthalate, multifilament, 114-g/m^2) stiffness properties, with tangent moduli of 8-MPa, 19-MPa and 33-MPa respectively.

- Two mesh sizes 8x8-cm and 14x14-cm were considered in this use case.

- Three fixation configurations were included in this study, with 4, 8, and 12 fixation points: in the first configuration, 4 fixations were placed on the corners of the mesh (A). The 4 mesh fixations were maintained as in (A) but the mesh was also secured at 4 additional spots, symmetrically 1-cm from the mesh edge (B). In the last configuration, still based on the first configuration (A), 8 additional fixation points were added, forming a crown 1 cm from the mesh edge. Surgical tacks were used for these additional fixation points (Covidien ProTack™, REF-174006, 5 mm).

A sensitivity analysis based on a full factorial design was conducted, including in total 36 configurations. For each simulation, the model's response was analyzed in terms of the force at the mesh fixations and the principal strains on the external surface of the wall. Correlations between the model inputs and responses were examined through a multiple linear regression analysis.

2.4. Data Processing & Statistical analysis

The force values measured at the 4-sensors were averaged at maximum pressure. Following DIC analysis, the principal Green-Lagrange strains (e_1) were assessed by averaging the values over a 4-cm diameter at the center of the wall. Data analysis was subsequently performed using Minitab, a statistical software (Minitab, LLC. 2021). Regression analysis was employed to identify the most influential parameters on each biomechanical response.

3. Results & Discussion

All configurations were successfully tested. The statistical analysis associated with the sensitivity study revealed that all the factors significantly affected the forces at the mesh fixations and strain of the wall. Regarding the forces at the fixation points, the analysis showed that the factor with the greatest impact was the wall properties (standardized effect = 27.6, $p < 0.001$), followed by the mesh properties (standardized effect = 16.3, $p < 0.001$), then the mesh size (standardized effect = 8.07, $p < 0.001$), and finally the fixation configurations

(standardized effect = 2.4, $p < 0.05$). For the strains, the analysis indicated that the most influential factor was also the wall properties (standardized effect = 62.07, $p < 0.001$), then the mesh size (standardized effect = 16.6, $p < 0.001$), the fixation configurations (standardized effect = 12.06, $p < 0.001$) and lastly, the mesh properties (standardized effect = 6.4, $p < 0.001$).

These results suggest that the wall properties dominate the biomechanical response of the repair. Additionally, while a relatively stiff mesh (e.g., type C) tends to reduce deformations at the center of the wall, offering a better reinforcement, it also increases the forces at the mesh fixations, thereby raising the risk of mesh or fixation failure and post-operative pain. In contrast, a relatively elastic mesh (e.g., type A) tends to reduce the forces at the mesh fixations but leads to greater deformation of the wall. Studies have shown that mechanical mismatch between the implant and the host tissue is a contributing factor to surgical failure (He et al., 2023, Hernández-Gascón et al., 2011).

These results also demonstrated the significant impact of the mesh size used. It was observed that an increase in mesh size led to higher forces, while reducing strains at the center of the wall, due to a broader coverage of the mesh on the abdominal wall. Clinically, although larger meshes provide improved reinforcement of the abdominal wall, their use can also result in decreased mobility of the abdominal wall, as well as more invasive surgical procedures with a higher risk of post-operative complications.

Finally, this study was able to explore the impact of the fixation configurations. Indeed, increasing the number of fixations points significantly reduces both the forces and strains. This is likely explained by a more widespread distribution of forces across each fastening point, reducing the individual load supported by each fixation. Clinically, these results raise the question of the benefit of additional fixation, which, although it reduces the risk of mesh migration, seems to make the force at the mesh fixation decrease, while also increasing intra-operative time and leading to post-operative pain.

The experimental model developed has certain limitations due to its simplification. While it was designed to closely mimic real conditions, it should be noted that it does not fully represent the complexity of physiological conditions. Specifically, the synthetic wall used does not account for the natural anisotropy and nonlinearity of the human abdominal wall, or the active contribution of its various muscles (Deeken et al., 2017; Podwojewski et al., 2013).

4. Conclusion

This study helped deepen our understanding of the interactions between implant and the abdominal wall. By analyzing a wide range of model variables, it was possible to identify the key parameters influencing the biomechanical responses. The results show that surgical variables, whether related to the patient, the implant, or the operative choices, play a significant role in the forces at the fixations points and the deformation of the wall. This approach is a step toward patient-specific strategies for preoperative hernia planning. The focus on future work will be on enhancing and validating the realism of the mechanical response of the synthetic abdominal wall to assess the impact of various surgical techniques on the biomechanical properties of a hernia repair.

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