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Numerical Investigation of a Finite Element Model to Inform the Design of a Synthetic Abdominal Wall

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1. Introduction

Hernia meshes are used to reinforce the abdominal wall (AW) following surgical hernia repair, a pathology characterized by the protrusion of intestine through a weakness in the AW. Mesh design can influence key characteristics such as the mesh mechanical behavior, which in turn affect the mechanical properties of the repair (Le Ruyet et al., 2020).

The AW is a multilayered anatomical structure composed of muscular and fibrous tissues, which exhibit non-linear and anisotropic properties (Astruc et al., 2018). Subjected to intra-abdominal pressure (IAP), AW mechanical behavior exhibits predominant longitudinal strains with negative transverse strains at the midline, and larger circumferential deformations in the lateral muscles than in central muscles (Le Ruyet et al., 2020; Jourdan et al., 2020).

Characterizing how mesh design impacts the mechanical performance of the repair was performed so far using biological tissues from animals and human cadavers. However, such approaches raise ethical concerns and suffer from limited reproducibility due to high interindividual variability.

To overcome these limitations, our goal is to develop a synthetic AW, made of silicone matrix reinforced with fibers, that can reproduce the complex mechanical behavior to which a mesh is subjected immediately after surgery. In this study, we investigate through a numerical finite element model the influence of key design parameters (fiber density, fiber orientation and structural parameters) on the mechanical response of the synthetic AW, with the aim to reproduce the response of a biological AW subjected to an inflation test.

2. Methods

2.1 Geometry and mesh

The model geometry represents a triangular section of the anterior AW, extending from the rib cage to the pubic symphysis. The model includes the linea alba (LA), the rectus abdominis (RA) enclosed within the anterior and posterior rectus sheaths (ARS-PRS), as well as the lateral muscles (LM). Mechanical continuity between anatomical regions is ensured by the continuous mesh formulation (node-to-node).

2.2 Material properties and fibers directions

Fascias and muscles mechanical behavior was modeled as anisotropic hyperelastic tissues, as described in Jourdan et al. (2024), with an Ogden-type ground matrix with a Holzapfel-Gasser-Ogden (HGO) component to capture anisotropy, where fibers are represented within a continuum framework.

All muscles parameters were taken from Jourdan et al. (2024). Fascial parameters for the LA, ARS and

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PRS were identified by iterative fitting against *ex vivo* human uniaxial tensile test data in both longitudinal and transverse directions (Astruc et al., 2018), by minimizing stress-strain mismatch, with validation on biaxial tensile test responses. Two approaches were considered: the first used 2 fiber families at 0/90°, fitted to uniaxial data only and the resulting biaxial response in model was compared to experimental data. The second was similar but included a family at ±30° in transverse, to reflect anatomical structure and simultaneously fitting uniaxial and biaxial data from sheath experimental data.

2.3 Boundary condition and loading scenario

The entire boundary was constrained to represent the experimental boundary conditions. A uniform pressure from 0 to 50 mmHg was applied to the internal AW surface to simulate IAP increase during the test.

2.4 FEM and Sensitivity analysis

A full factorial Design of Experiments (DoE) was conducted to assess the influence of key structural and material parameters on the mechanical response of the AW model. Five factors were investigated: (i) the effect of fiber orientation in the fascias, comparing uniaxial-only versus simultaneous uniaxial and biaxial calibration; (ii) the mechanical contribution of the ARS and PRS, explored through lower and upper bound material parameters to cover their variability range; (iii) the structural heterogeneity of the model, assessed through the sheath thickness, varying from 0.5 to 3-mm, and the presence or absence of the lateral muscles. This DoE resulted in 32 simulation runs, all performed using LS-DYNA with an implicit solver.

Table 1. DoE factor summary - 2^5 design.

	Materials parameters			Structural parameters	
Factors	FB orient.	ARS prop.	PRS prop.	Sheath thick.	LM pres.
Levels	2	2	2	2	2
	0°	-1	-1	0.5	-1
	± 30°	+1	+1	3	+1

3. Results and discussion

The statistical analysis of the sensitivity study revealed that lateral muscles (LM), fiber orientation (FB), and sheath properties influence both transverse and longitudinal strains (Fig. 1-a).

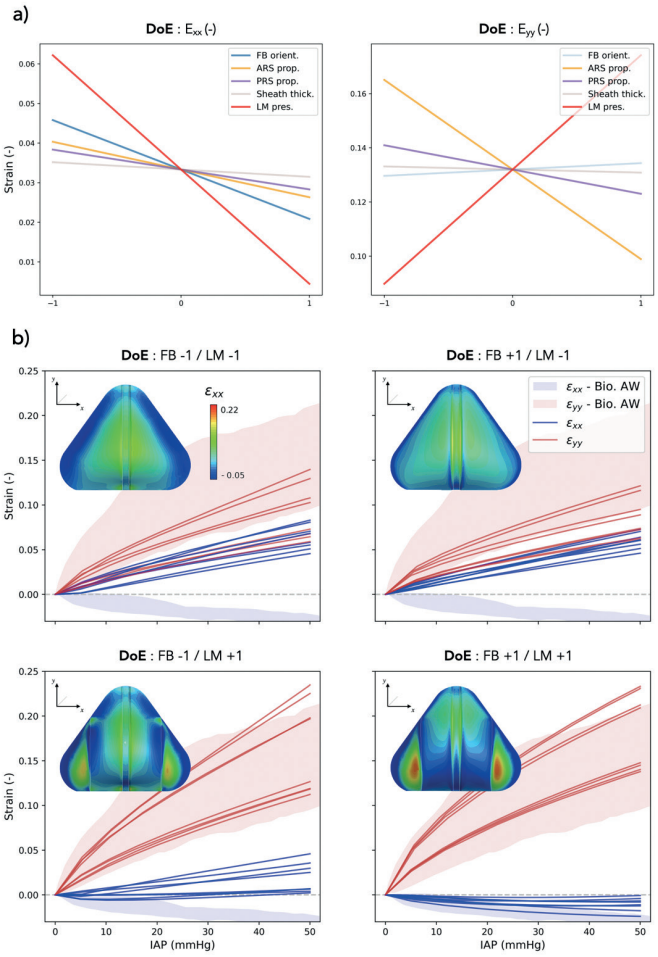

Figure 1. (a) DoE; factorial plots of the standardized effect over each output. (b) Transversal strain response to pressure for LM and FB factors, compared with experimental data from biological AW.

The LM had the strongest effect on E_{xx}, followed by FB and finally by sheath properties. Although sheath thickness did not significantly affect E_{xx} or E_{yy}, structural parameters associated with LM modified the overall curvature of the AW, thereby altering the distribution of transverse tensions. This structural effect enables simultaneous longitudinal elongation and transverse constriction. Furthermore, calibration based on both uniaxial and biaxial data, through adjustment of fiber orientations, showed a non-negligible impact by improving mechanical coupling (Fig. 1-b, curves include all conditions). Overall, the combined effects of material and structural parameters allow the model to reproduce E_{xx} and E_{yy} responses consistent with experimental observations obtained on biological AWs (Le Ruyet et al., 2025).

3. Conclusion

This numerical study demonstrated the importance of performing biaxial mechanical characterization in phenomena in AW mechanics. It also highlighted the important role of LM in shaping transverse and longitudinal strain distributions. Finally, these findings provide a framework to guide the development of synthetic AW models for future design.

Contributor Roles

ZF: Conceptualization, Methodology; Software; Analysis, Investigation, Writing original Draft; AL: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing; BP: Supervision, Validation, Writing – review & editing; GP: Supervision, Validation, Writing – review & editing; AB: Supervision, Validation, Writing – review & editing.

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