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Mechanical stability of new-generation meshes for M3 inguinal hernia repair: experimental pressure chamber testing of SWING-Mesh and 3DMax MID Anatomical Mesh

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KEY WORDS

hernia, inguinal surgery, laparoscopic methods, mechanics of biomaterials, surgical mesh

ABSTRACT

INTRODUCTION The necessity of mesh fixation in laparoendoscopic repair of large medial (classified by the European Hernia Society as M3) inguinal hernias (IHs) remains debated. Recent data, including the MEFISTO randomized controlled trial, suggest that rigid, anatomically contoured meshes may provide sufficient stability of hernia repair without mesh fixation, potentially reducing fixation-related complications. However, biomechanical performance of newly introduced anatomical meshes has not been thoroughly evaluated.

AIM This study aimed to assess the mechanical stability of 2 newly introduced anatomically shaped meshes—SWING-Mesh and 3DMax MID Anatomical Mesh—in a validated pressure chamber model simulating M3 IH defects.

MATERIALS AND METHODS A rigid 3-dimensionally (3D) printed groin model with a 4-cm medial defect was mounted in a sealed pressure chamber capable of generating intra-abdominal pressures of up to 70 kPa. Two meshes were tested: SWING-Mesh (lightweight polypropylene; 55 g/m^2; 16 cm × 12 cm) and 3DMax MID Anatomical Mesh (medium-weight polypropylene; 78 g/m^2; 17 cm × 12 cm). Both were positioned with an at least 3-cm overlap beyond the defect margins without fixation. Initial testing was performed at 36 kPa. If displacement occurred, lower pressures were applied; if stability was maintained, higher overload pressures were used. Each experiment was repeated 3 times, with outcomes documented on photo and video material. The primary end point was mesh displacement into the defect.

RESULTS SWING-Mesh consistently displaced into the defect at 36 kPa in all trials. Supplementary tests showed migration as early as at 10 kPa. In contrast, 3DMax MID Anatomical Mesh remained stable at 36 kPa in all repetitions. Overload testing confirmed its resistance at 53, 60, and 70 kPa—the maximum achievable pressure in the chamber—without measurable displacement.

CONCLUSIONS SWING-Mesh failed to provide stability even under moderate intra-abdominal pressures, which questions its suitability for nonfixed repair of M3 hernias. 3DMax MID Anatomical Mesh demonstrated complete stability under both physiologic and supraphysiologic conditions, confirming the mechanical advantage of medium-weight 3D meshes. Implant design, weight, and stiffness appear more decisive for stability than fixation, supporting the selective use of nonfixation techniques when rigid meshes are applied.

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INTRODUCTION The question of optimal implant type and the necessity of mesh fixation remain unresolved in minimally-invasive inguinal hernia (IH) repair (transabdominal preperitoneal

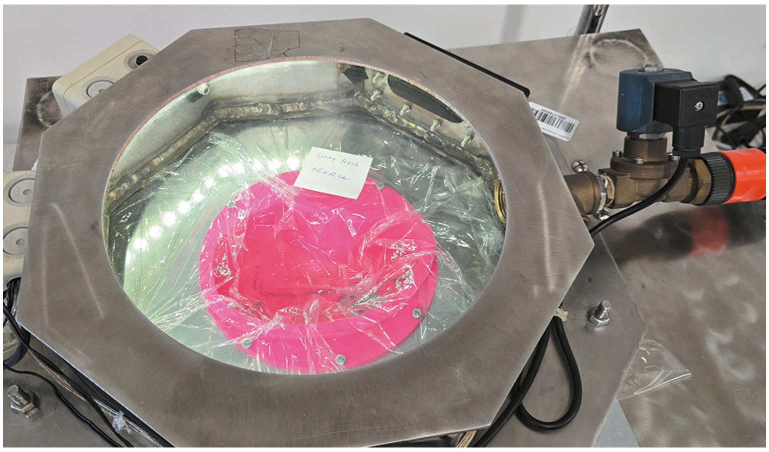

FIGURE 1 Three-dimensional groin model with the mesh placed in the measuring chamber

approach / totally extraperitoneal approach). Increasing evidence indicates that the choice of mesh—particularly its structure and stiffness—may be as critical as the use of fixation materials.[1-4] Recent data, including the updated European Hernia Society (EHS) guidelines[5] and the MEFISTO (Mesh Fixation Study in Laparoendoscopic Repair of M3 Inguinal Hernias) trial[6] have highlighted advantages of heavier meshes, which may achieve outcomes comparable to those of lightweight meshes, while eliminating the need for additional fixation materials.

This debate is particularly relevant in the setting of large direct (M3) IHs according to the EHS classification.[7] The 2018 HerniaSurge guidelines[1] strongly recommended mesh fixation in such cases, a position largely based on data from the Herniamed registry.[8] Since then, updated guidelines published in 2023 introduced only a weak recommendation favoring heavier meshes, without providing concrete directives regarding fixation strategies.[5]

In 2025, the MEFISTO trial compared fixation of flat lightweight meshes with nonfixation of rigid, anatomically shaped 3-dimensional (3D) meshes in M3 hernias.[6] The results demonstrated both approaches to be equally effective, with similar recurrence and complication rates. The key conclusion was that rigid, anatomically contoured meshes can obviate the need for fixation, which is significant from both the clinical standpoint—since fixation is associated with risks of chronic pain, discomfort, or meshoma—and a socioeconomic perspective, given the additional costs of fixation devices.[9,10]

Before the MEFISTO trial, Zamkowski et al[11] conducted an experimental study developed in collaboration with engineers from the Gdansk and Cracow Universities of Technology. In this study, various 3D meshes were tested in a validated pressure chamber model simulating an M3 defect. The chamber was capable of reproducing intra-abdominal pressure surges corresponding to extreme physiologic situations, such as coughing, sneezing, or vomiting. These experiments confirmed that mesh architecture and stiffness determine implant stability under pressure. Stability was understood as the implant remaining in place at the herniated area and not dislocating during the patient's normal life.

Since the publication of our experimental work[11] and the clinical results of the MEFISTO trial,[6] 2 new 3D meshes have been introduced to the Polish market: SWING-Mesh (SMH2, THT Bioscience, Montpellier, France) and 3DMax MID Anatomical Mesh (Becton Dickinson, New Jersey, United States). To evaluate their mechanical performance in the setting of M3 hernias, we conducted analogous pressure chamber experiments to assess their stability under simulated conditions of increased intra-abdominal pressure.

AIM The aim of this study was to evaluate the mechanical stability of 2 newly introduced anatomically shaped meshes—SWING-Mesh and 3DMax MID Anatomical Mesh—in a validated pressure chamber model simulating M3 IH defects, and to compare their performance under conditions of increased intra-abdominal pressure.[11]

MATERIALS AND METHODS A validated experimental setup was employed to evaluate the mechanical stability of newly introduced 3D meshes in conditions simulating large direct IHs (EHS classification M3). The model was based on previously published methodology, with appropriate modifications made for the current study.[11-13]

Groin model and pressure chamber A rigid 3D-printed model of the myopectineal orifice, incorporating a 4-cm medial defect, was created. The design was derived from averaged computed tomography data and postmortem casts, subsequently processed using computer-aided design software to smooth the surface and achieve reproducible anatomical contours. The model was manufactured from polylactide, chosen for its minimal elasticity, to reflect the stiff configuration of the inguinal region under physiologic load.

The model was mounted in a sealed cylindrical chamber capable of generating pressures of up to 70 kPa (approximately 525 mm Hg), higher than extreme intra-abdominal pressure surges occurring during coughing or vomiting. To reproduce physiologic friction conditions between the mesh and tissues, the model was coated with medical-grade vaseline. A thin plastic foil layer was placed over the model to mimic the parietal peritoneum and to enable pressure transmission on the porous mesh (**FIGURE 1**).

Meshes tested Two anatomically contoured implants currently available on the Polish market were investigated (**TABLE 1**). The first one was SWING-Mesh (SMH2 1216 MB; **FIGURE 2**), a bidirectional, lightweight, monofilament polypropylene mesh designed for use in both left- and right-sided IH repair. The tested size was 16 cm × 12 cm (largest

TABLE 1 Mesh characteristics

Mesh type	Size tested, cm	Weight, g/m²	Thickness, mm	Pore size, mm	Porosity, %	Notes
Swing-Mesh SMH2 1216 MB	16 × 12	55	0.48	1.53 × 1.30	up to 88	• Lightweight; • Bidirectional; • Semi-rigid; • Multidirectional elasticity; • Largest available size tested
3DMax MID Anatomical Mesh	17 × 12	78	0.68	0.12 × 0.19	–	• Medium-weight; • 3-dimensional, contoured anatomical shape; • Orientation markers; • Built-in recoil memory; • Trocar-compatible

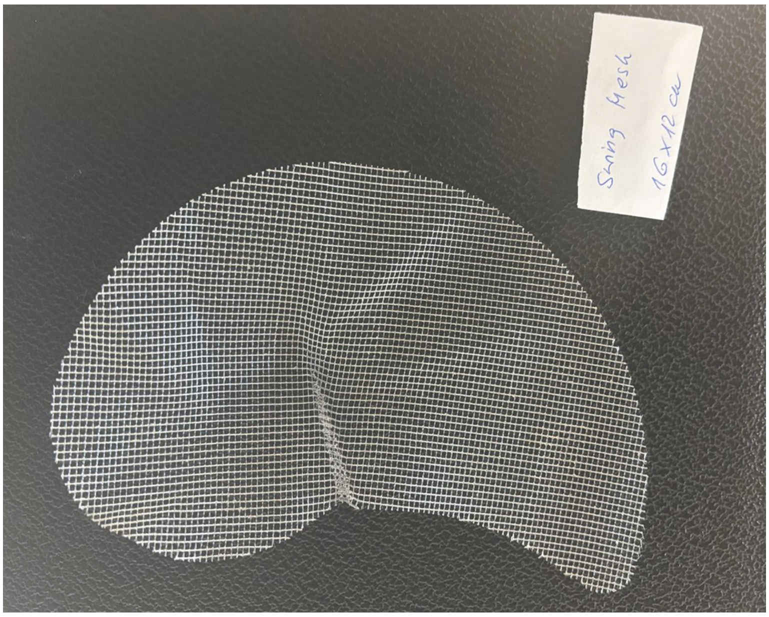

FIGURE 2 SWING-Mesh: lightweight bidirectional polypropylene mesh with multidirectional elasticity and semi-rigid curvature, designed for left- or right-side use

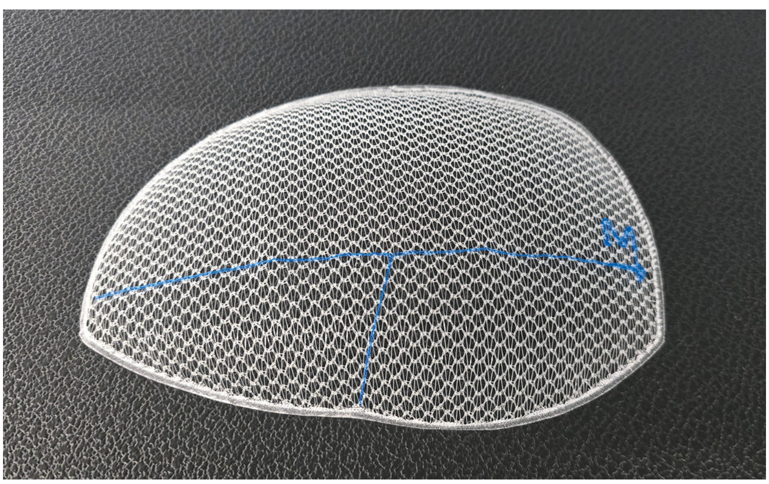

FIGURE 3 3DMax MID Mesh: medium-weight polypropylene implant with rigid 3-dimensional contouring and orientation marker, providing stable spatial architecture and built-in recoil memory

available). According to the manufacturer's specifications, the implant weighs 55 g/m², has a pore size of 1.53 mm × 1.3 mm, thickness of 0.48 mm, and porosity of up to 88%.

The second tested mesh was 3DMax MID Anatomical Mesh (**FIGURE 3**), which is a medium-weight, monofilament polypropylene mesh with a 3D-contoured anatomical design. The tested size was 17 cm × 12 cm (extra-large right). The data provided by the manufacturer indicate an approximate weight of 78 g/m², with an open-pore structure providing durable strength-to-weight performance. The mesh is equipped with an orientation marker.

Both meshes were positioned in accordance with international recommendations, providing at least 3 cm of overlap beyond the defect margins. No fixation was used in order to isolate the effect of implant design on its mechanical stability onsite.

Experimental procedure For both meshes, the initial test pressure was set at 36 kPa (approximately 270 mm Hg), corresponding to the upper limit of physiologic intra-abdominal surges, such as coughing or vomiting. Implant behavior was assessed under these conditions. SWING-Mesh consistently displaced into the defect at this level of pressure; therefore, supplementary trials were performed at lower pressures to determine the threshold at which migration occurred.

In contrast, 3DMax MID Anatomical Mesh remained stable at 36 kPa. To further explore its mechanical limits, additional overload tests were carried out by gradually increasing the chamber pressure above the physiologic range, reaching up to 70 kPa, which represented the maximum achievable pressure of the apparatus.

High-resolution photo and video documentation was obtained for all experiments, and each protocol was repeated 3 times for each mesh to confirm reproducibility.

End points The primary end point was mesh displacement, defined as any migration resulting in loss of the recommended overlap or protrusion into the hernia defect. Secondary end points included gross mesh deformation or failure to maintain the original position under pressure (**FIGURE 4**).

TABLE 2 Trial results

Mesh type	Trial 1	Trial 2	Trial 3	Supplementary tests, kPa	Result summary
Swing-Mesh SMH2 1216 MB	Displaced at 36 kPa	Displaced at 36 kPa	Displaced at 36 kPa	Displaced at 10 kPa	Early and reproducible migration at low (10 kPa) and maximum pressures (36 kPa)
3DMax MID Anatomical Mesh	Stable at 36 kPa	Stable at 36 kPa	Stable at 36 kPa	Stable at 53, 60, and 70 kPa	Maintained position under both physiologic (<37 kPa) and supraphysiologic pressures (up to 70 kPa)

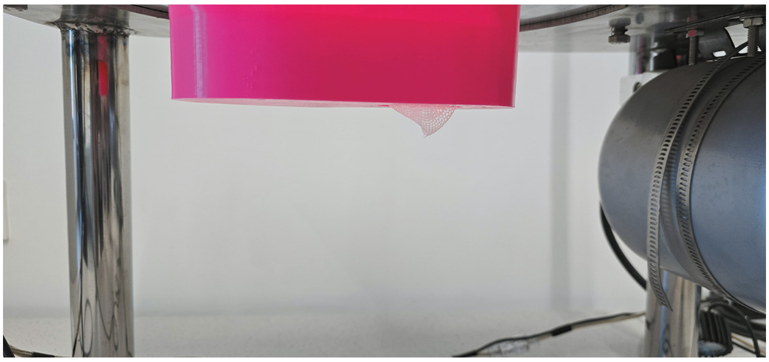

FIGURE 4 Representative image showing mesh displacement into the simulated defect under pressure. Displacement was defined as loss of overlap or protrusion through the defect, corresponding to early recurrence in the model.

Ethics As this was a purely experimental, in vitro study without patient involvement, no formal ethical approval or consent was required under national regulations.

Statistical analysis Due to the mechanical and qualitative nature of the experiment, no formal statistical testing was performed. The results were reported descriptively based on repeated trials to confirm reproducibility.

RESULTS The experimental evaluation demonstrated marked differences in performance between the 2 tested meshes (**TABLE 2**).

SWING-Mesh In all 3 trials performed at peak intra-abdominal pressures (36 kPa), the implant consistently displaced into the defect, corresponding to early recurrence in the model. Supplementary tests at lower pressures confirmed this tendency: migration was observed as early as at 10 kPa—well below the physiologic maximum. The behavior was reproducible in each repetition, with progressive protrusion of the mesh through the defect opening as the pressure increased.

3DMax MID Anatomical Mesh In contrast, the 3DMax MID Anatomical Mesh maintained its position during all 3 trials at 36 kPa, showing no evidence of dislocation or deformation. Extended overload testing further confirmed the high mechanical stability of this implant, proved by keeping its position in the groin model under pressure. The mesh kept its position with incremental pressures of 53, 60, and 70 kPa—the maximum achievable pressure in the apparatus—without any measurable displacement.

Summary Thus, while the lightweight Swing-Mesh failed to provide stability even under moderate intra-abdominal pressure levels, the medium-weight 3DMax MID Anatomical Mesh implant remained stable under both physiologic and supraphysiologic load conditions.

DISCUSSION Our experimental study highlights distinct differences in the biomechanical stability of 2 newly introduced anatomically contoured meshes—SWING-Mesh and 3DMax MID Anatomical Mesh—under simulated conditions of increased intra-abdominal pressure in the setting of large medial (M3) inguinal defects.

Our findings confirm that mesh architecture—determining its spatial stiffness—and overall weight remain the key determinants of implant stability. SWING-Mesh, despite its anatomical design, demonstrated early and reproducible dislocation not only at maximum simulated abdominal pressures (36 kPa) but also at levels as low as 10 kPa, which corresponds to mild physiologic surges during daily activities. This behavior resembles that of other lightweight meshes, which tend to dislocate under pressure load, as described in earlier experimental models, and suggests that such implants may be unsuitable for nonfixed use in M3 hernias. Conversely, 3DMax MID Anatomical Mesh maintained its position without measurable deformation under both physiologic and supraphysiologic conditions, withstanding pressures of up to 70 kPa—the highest achievable pressure generated in our chamber. These findings align with prior experimental observations for heavyweight 3D meshes, such as Dextile Anatomical Mesh (Medtronic, Dublin, Ireland) and 3DMax Heavy (Becton Dickinson), and provides further evidence that increased spatial stiffness of the mesh confers its superior mechanical stability when implanted in a herniated groin.[11,14]

These results once again demonstrate that lightweight meshes face significant challenges in maintaining stability under physiologic intra-abdominal pressure, when implanted without fixation, which raises a question regarding the appropriateness of their use in larger IHs. To date, the only lightweight mesh that showed adequate stability in the pressure chamber was one specifically tailored to the anatomical model, likely due to its excellent conformity and a greater number of contact points, providing higher frictional resistance.[15]

The clinical implications of these findings are relevant. Fixation in laparoendoscopic repair of M3 hernias has traditionally been recommended by international guidelines, largely based on registry data indicating higher recurrence rates in nonfixed cases.[1,8] However, both our earlier experimental work[11] and the multicenter MEFISTO randomized controlled trial[6] have shown that anatomically shaped, rigid 3D meshes may achieve noninferior outcomes without fixation. This approach eliminates potential fixation-related complications, such as chronic postoperative pain, meshoma, nerve injury, or increased procedural cost.[16-18] The poor performance of SWING-Mesh in the considered model raises concerns regarding its application in large direct defects without fixation. Although in vivo biological integration may provide additional stability, the early displacement observed at even modest pressure levels suggests a potential risk of recurrence. On the other hand, the demonstrated stability of 3DMax MID Anatomical Mesh under extreme loads reinforces its suitability for nonfixed use in high-risk M3 hernias.

Our experiments also raise questions about the continued relevance of the EHS IH classification. When introduced almost 20 years ago, the system was designed as a simple tool for categorizing hernias during open repair procedures, using the surgeon's fingertip as a practical gauge of defect size.[7] The cutoff points of 1.5 cm and 3 cm, which define the classification subtypes, may not adequately reflect the challenges posed by minimally-invasive repairs. The particularly poor performance of SWING-Mesh, which dislocated into the defect at just one-third of the maximum pressure, suggests that lightweight mesh stability cannot be guaranteed even in smaller defects (eg, M2). This issue warrants further investigation and reconsideration in future guideline updates.

This study has limitations inherent to its in vitro design. The rigid model cannot fully reproduce the complex dynamic interactions of tissues and implants in vivo, nor account for long-term biological fixation. Furthermore, only 2 meshes were tested, which limits generalizability across all available designs. Nevertheless, the pressure chamber has been validated in earlier studies and correlates well with clinical outcomes, strengthening the relevance of these findings. Although the experimental setup provides valuable insights into mechanical behavior, it does not account for biological processes that may significantly affect long-term outcomes. In vivo, progressive tissue ingrowth, collagen deposition, and fibrotic integration can substantially increase implant stability over time. These healing-related factors, absent in the present in vitro model, might mitigate early displacements observed in lightweight meshes or, conversely, affect the flexibility of heavier implants.

In summary, this study supports the concept that implant design—not fixation—determines stability in laparoendoscopic repair of M3 hernias. Lightweight meshes with insufficient stiffness may require fixation to ensure durability, whereas medium- or heavyweight, anatomically contoured meshes can provide secure repair without additional fixation materials.

CONCLUSIONS SWING-Mesh demonstrated early and consistent migration into the defect, even at low intra-abdominal pressures, which raises concerns regarding its use without fixation in large direct (M3) hernias. In contrast, 3DMax MID Anatomical Mesh maintained complete stability under both physiologic and supraphysiologic loads, confirming the mechanical advantage of stiffer and heavier anatomical meshes. These findings suggest that implant architecture and weight are more decisive for stability than fixation itself, supporting the selective use of nonfixation techniques when rigid medium- or heavyweight meshes are applied, while caution remains warranted for lightweight designs.

ARTICLE INFORMATION

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CONTRIBUTION STATEMENT MZ conceived and designed the study, coordinated the experimental work, performed the tests, analyzed the data, and drafted the initial version of the manuscript. AT, IL, and KK designed and constructed the mechanical test model, verified the reproducibility of the experiments, and participated in result interpretation. MŚ supervised the project, contributed to the study conception and interpretation of results, and critically revised the final manuscript for important intellectual content. MP assisted in the experimental setup, photographic documentation, and contributed to manuscript editing. All authors reviewed and approved the final version of the manuscript prior to submission.

AI STATEMENT Artificial intelligence was not used in the preparation of this manuscript.

CONFLICT OF INTEREST None declared.

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