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Biomechanical Analysis of Penile Erection Comparative Study Using LISA FEA

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Abstract— *With the objective to simulate mechanical reactions under radial compression stresses and blood pressure, this study uses finite element analysis (FEA) to investigate the biomechanics of penile erection. Diagnosing and treating erectile dysfunction (ED) requires an understanding of these mechanics, particularly when venous leakage or arterial insufficiency are involved. The study contrasts how radial compression and stress brought on by blood pressure affect the deformation of penile tissue. The findings point to radial compression as a possible non-invasive diagnostic method for determining penile stiffness because it results in less displacement than blood pressure loads. Blood pressure loads, on the other hand, caused higher displacements and concentrated stress at the penile tip, which could indicate buckling behavior at high loads. The study of stress distribution showed that while blood pressure-induced loading causes localized stress, especially at the penile tip, radial compression produces more uniform stress. The results demonstrate that the mechanical behavior of the penis under these two loading situations differs significantly, with radial compression showing potential for non-invasive ED diagnosis and blood pressure loads carrying a higher risk of structural failure in severe circumstances.*

Keywords: *Biomechanical, Erection, FEA, LISA, Simulate*

Abstrak— Dengan tujuan untuk mensimulasikan reaksi mekanis di bawah tekanan kompresi radial dan tekanan darah, penelitian ini menggunakan analisis elemen hingga (FEA) untuk menyelidiki biomekanik ereksi penis. Mendiagnosis dan mengobati disfungsi ereksi (DE) membutuhkan pemahaman tentang mekanika ini, terutama ketika kebocoran vena atau insufisiensi arteri terlibat. Penelitian ini membandingkan bagaimana kompresi radial dan stres yang disebabkan oleh tekanan darah mempengaruhi deformasi jaringan penis. Temuan ini menunjukkan bahwa kompresi radial merupakan metode diagnostik non-invasif yang memungkinkan untuk menentukan kekakuan penis karena menghasilkan perpindahan yang lebih sedikit dibandingkan dengan beban tekanan darah. Beban tekanan darah, di sisi lain, menyebabkan perpindahan yang lebih tinggi dan stres terkonsentrasi di ujung penis, yang dapat mengindikasikan perilaku tekuk pada beban tinggi. Studi tentang distribusi tegangan menunjukkan bahwa sementara pembebanan yang diinduksi oleh tekanan darah menyebabkan tegangan lokal, terutama pada ujung penis, kompresi radial menghasilkan tegangan yang lebih seragam. Hasil penelitian menunjukkan bahwa perilaku mekanis penis di bawah dua situasi pembebanan ini berbeda secara signifikan, dengan kompresi radial menunjukkan potensi untuk diagnosis DE non-invasif dan beban tekanan darah yang membawa risiko lebih tinggi dari kegagalan struktural dalam keadaan parah.

Kata kunci: *Biomekanik, Ereksi, FEA, LISA, Simulasi*

INTRODUCTION

Hemodynamic and biomechanical variables control the intricate physiological re-action known as penile erection. Blood flow, intracavernous pressure, and tissue me-chanics—particularly in the tunica albuginea and corpora cavernosa—all alter during the process. Treatment and diagnosis of erectile dysfunction (ED), which is frequently brought on by ailments such venous leakage and arterial insufficiency, can be diffi-cultBlood pressure loads on the penis are used to assess biomechanical responses under various loading circumstances, this study attempts to model the mechanism of penile erection using finite element analysis (FEA).

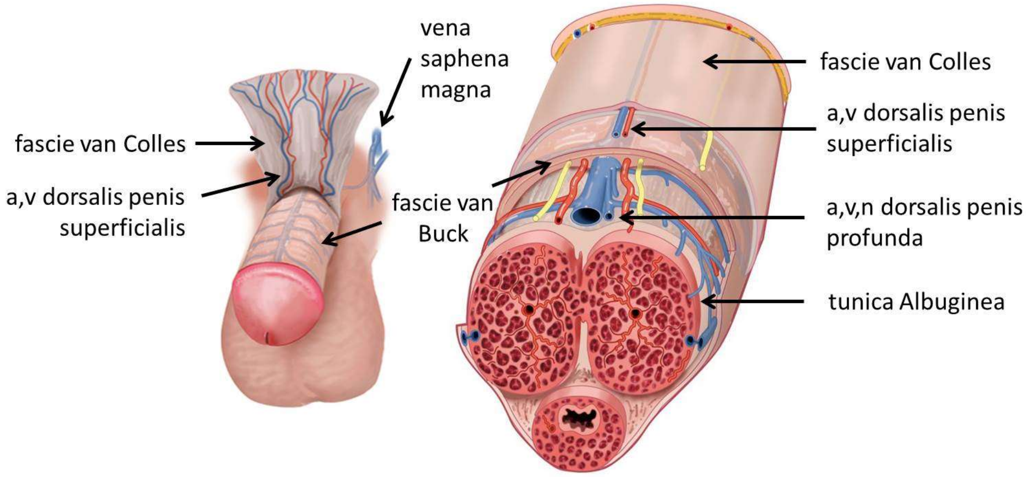


Figure 1. *Penis S*

The biomechanical phenomena of penile erection is impacted by mechanical load, tissue elasticity, and blood pressure. Diagnosing and treating erectile dysfunction (ED) requires an understanding of the erectile function, particularly in cases of dysfunction such as venous leakage and arterial insufficiency. The penis has traditionally been studied as an isotropic material or as a pressurized vessel with thin walls, this study uses the finite element technique (FEM) to model and compare the biomechanical response of the penis under blood pressure loading within the penis(1).

In circumstances where mechanical and tissue geometric factors are involved despite normal hemodynamic function, computational modeling presents exciting opportunities for the clinical assessment and treatment of erectile dysfunction. Even with adequate blood flow and erectile pressure, some people may experience erectile dysfunction as a result of structural anomalies in tissue geometry or mechanical qualities. For instance, these tissue variables may cause individuals following microvascular artery bypass surgery to still have insufficient penile stiffness. Clinicians would be better able to comprehend how these aberrant structural traits affect stress and deformation during the erectile process if they had access to a powerful computer model that could simulate the 3D mechanical behavior of the penis during an erection. This may result in more targeted therapies and interventions for those with complicated erectile dysfunction(2).

A unifying simulation of these mechanics under realistic hemodynamic settings is a critical missing piece in these research. Our goal is to close this gap by employing FEA to model axial and radial loading.

METHOD

The scientific understanding of penile mechanics has greatly benefited from earlier models, such as those put forth (3–5). In their hemodynamics-focused research, Gillon et al. studied the link between venous and arterial pressures during an erection by modeling the penis as a compliant chamber. Timm et al. investigated the behavior of penile buckling under axial stress, highlighting the need of comprehending tissue reactions to both axial and radial forces. The present FEA simulations, which use nonlinear finite element analysis to analyze both models in greater depth, are based on these research.

Penile tissue was modeled as a thin-walled pressure vessel and subjected to different mechanical loading conditions using the finite element method (FEM). Because of its stability when performing nonlinear analysis and bio-tissue modeling, the LISA v.8 FEA program was used.

Geometry modeling

The dimensions of the cylindrical penile shaft model were obtained using average physiological data. A material model of the tunica albuginea, a crucial structure in penile stiffness, was created using data from earlier research on the tunica's tensile characteristics. In order to simulate axial and radial compression scenarios, boundary conditions were implemented. To represent the intricate deformation of the penile tissue, nonlinear geometry was utilized (3,6).

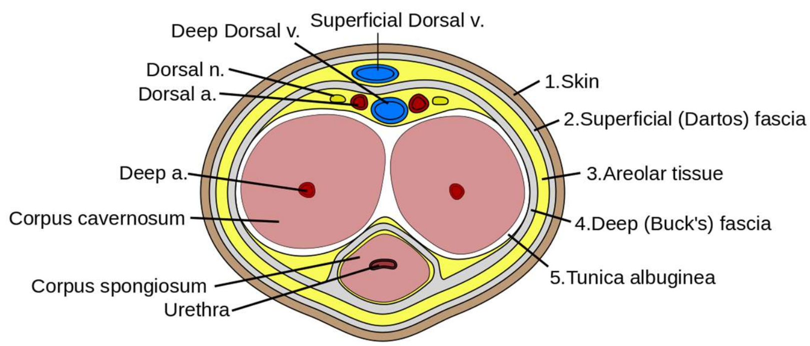


Figure 2*. The internal structure of the penis*

As seen in Figure 2, a model with a penis diameter of 4 cm and an erect length of 9 cm was built for this investigation. The dimensions of the model were carefully selected to represent a variety of physiological and clinical circumstances pertinent to the study goals. The 4 cm diameter and 9 cm length were chosen to reflect common measurements seen in the target demographic, guaranteeing the applicability and significance of the results in practical settings. These aspects are visually represented by the comprehensive illustration in Figure 3, which makes it easier to see how relevant the model is to the research. This method offers a thorough examination of all the variables influencing penile structure and function, which advances the discipline.

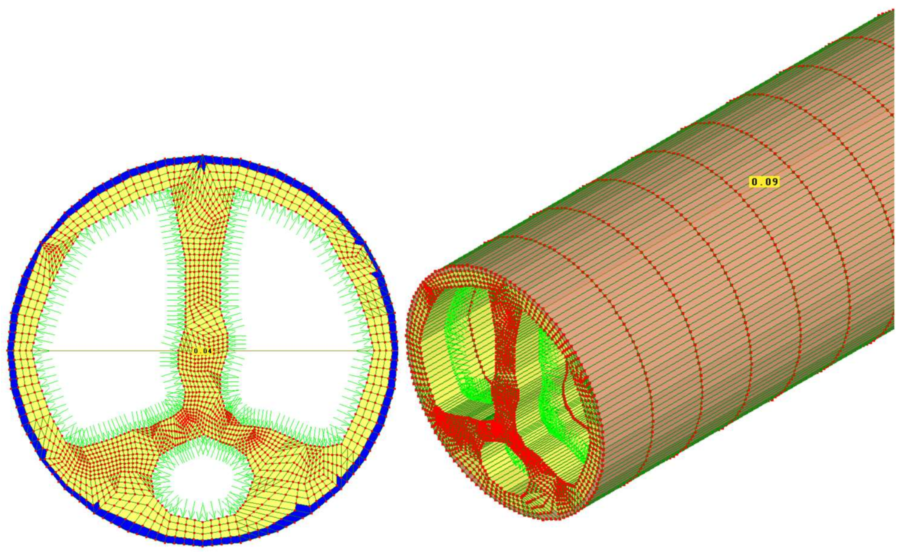


Figure 3. *Penis geometry modeling with lisa fea*

Mechanical properties

In the study, a three-dimensional orthotropic material model was employed, with values for the material coefficients derived from published elastic and shear moduli. The strains in the radial direction during erection were found to range between 1–4.5%. Poisson's ratio was consistently set at 0.4 across all material directions. Tensorial tissue stresses (σ) and strains (ϵ) were calculated using elastic moduli (E) and shear moduli (G), with Poisson's ratios incorporated according to Gefen et al. For the skin and tunica albuginea, Poisson's ratios were set at 0.4, and the glans was modeled as an incompressible, homogeneous, linear elastic material with an elastic modulus of 80 kPa and a Poisson's ratio of 0.4. The simulations included normal erection and erection with asymmetrical penile geometry, where one corpus cavernosa was larger by approximately 20% in cross-sectional area. Additionally, the mechanical conditions in Peyronie's disease were simulated by adjusting the elastic modulus and Poisson's ratio of a proximal dorsal segment of the tunica albuginea. Deformation, strain, and stress distributions were analyzed for each simulation. The detailed material constants for the skin and tunica are provided in Table 1, as shown in the study and shown in figure 4.

Table 1. Penile tissues' mechanical characteristics are assigned for finite element modeling

Tissue	Ex (kPa)	Ey (kPa)	Ez (kPa)	Gxy (kPa)	Gyz (kPa)	Gzx (kPa)	v
Tunica Albuginea	12000	12000	30	10	4000	4000	0.4
Skin	5000	5000	12.5	4.25	170	170	0.4

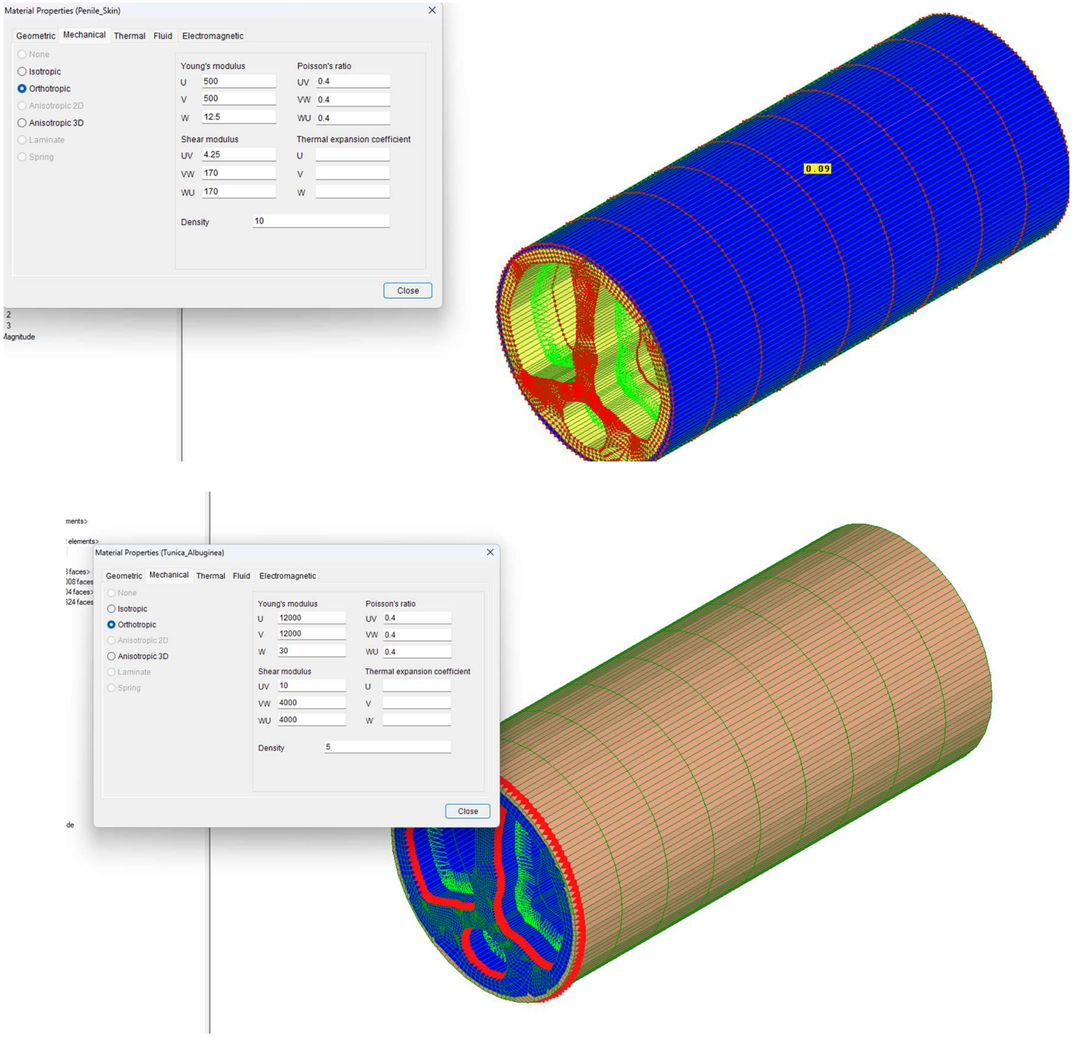


Figure 4*. Penis geometry modeling with LISA FEA*

Loading Conditions

The model includes key anatomical components such as the skin, tunica albuginea, corpus cavernosa, corpus spongiosum, and glans. The initial dimensions were set at 8 cm in length and 4 cm in diameter (3–9). The model was then transferred to a nonlinear finite element (FE) solver (MARC) for stress and strain analysis. This model was meshed into approximately 15,000 elements and 25,000 nodes, with an equivalent erectile pressure of 100 mmHg (~13.3 kPa) applied to simulate the internal conditions during erection. The skin and tunica albuginea were modeled as transverse-orthotropic materials with specific Poisson's ratios and elastic moduli based on previous studies (2).

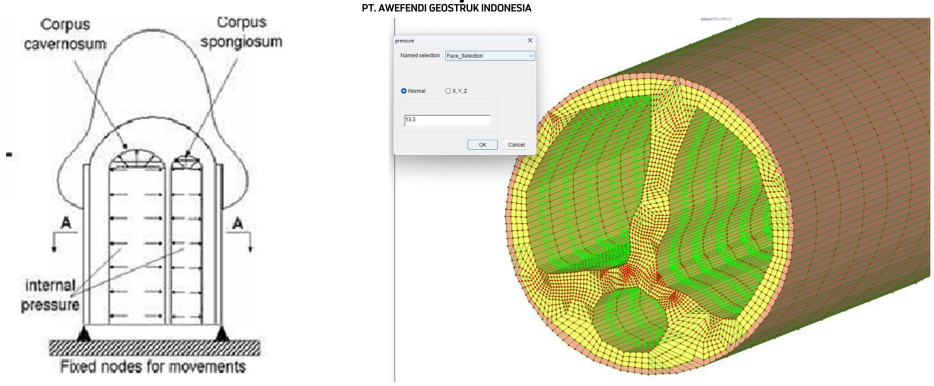


Figure 5. *Load applied*

Analysis

The simulation process involved analyzing normal erection and erections with altered penile geometry, specifically in cases of asymmetric corpus cavernosum and Peyronie's disease. One of the cavernosal bodies was increased by 20% in cross-sectional area to simulate asymmetry. For Peyronie's disease, changes were made to the mechanical properties of the tunica albuginea by increasing its elastic modulus and reducing the Poisson's ratio in a specific segment. Each simulation calculated deformation, strain, and stress distributions along the penile structure, enabling a detailed analysis of the mechanical behavior under different conditions. This approach provided insights into stress concentrations and structural deformations during erection.

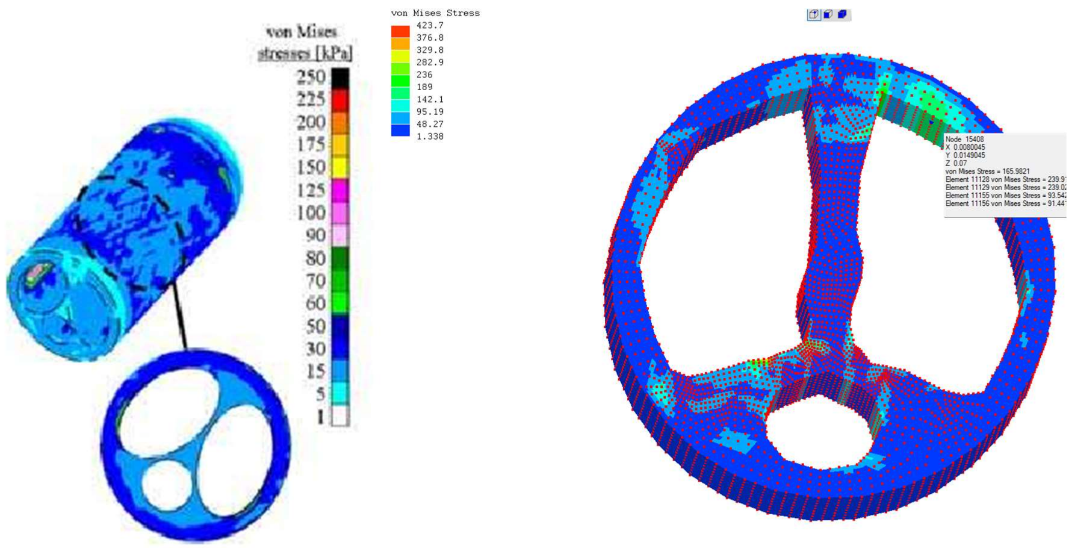
LISA V.8 Finite Element Analysis (FEA) software represents a sophisticated tool for performing detailed simulations and analyses of complex engineering problems. It offers advanced capabilities for modeling and solving problems involving structural mechanics, thermal analysis, and fluid dynamics. The software provides an intuitive interface for setting up simulations, defining material properties, and applying boundary conditions. Its robust solver algorithms enable accurate predictions of stress, strain, and deformation under various loading conditions. LISA V.8 also includes features for optimization and sensitivity analysis, allowing users to refine designs and improve performance. With its comprehensive set of tools and user-friendly environment, LISA V.8 FEA is widely used in industries such as aerospace, automotive, and civil engineering to enhance design reliability and efficiency (10–23).

RESULT

The FEA simulations showed that radial compression causes smaller total displacements than blood pressure load on the penis, which implies that non-invasive penile stiffness diagnostics using radial testing. Greater displacements at the tip of the penile produced by blood pressure load on the penis are suggestive of buckling behaviour under high loads.

Stress Distribution

The stress distribution revealed that the tunica albuginea underwent homogenous stresses under radial compression, but blood pressure load on the penis produced concentrated localized strains, especially at the penile tip. In Figure A, the von Mises stress is shown on a color scale ranging from 0 to 250 kPa. The highest stress regions are represented in red, while the lowest stress areas are in blue and purple. The object depicted has a cylindrical component connected to a circular ring, with stress concentrations localized at specific points, particularly around the connections and curved surfaces. The stress distribution appears more uniform on the circular part, with the stress magnitudes mostly lower than 100 kPa, except for some localized regions.



(a) **(b)**

Figure 6. *Stress Distribution(Von Mises) (a)Abaqus (b)LISA FEA*

Figure B shows a higher stress range by representing the von Mises stress on a considerably bigger scale, spanning from 1.338 kPa to 423.7 kPa. In this instance, the ring structure exhibits notable stress concentrations, especially in the vicinity of the internal spokes and connecting areas. This implies that there is more stress on the material in these areas. In comparison to Figure A, the red and orange areas—which depict stresses over 300 kPa—are more noticeable.

Figure A, which displays von Mises stress values surrounding the interior hole areas, indicates moderate stress concentrations with little variation. The stress levels in the hole areas are around 114 kPa, 32 kPa, and 122 kPa. As a schematic of a wider and greater stress range, Figure B displays stress values surrounding the internal holes that range from 48.27 kPa to 165.98 kPa.

According to the overall stress distribution, the hole regions of Figure 6B appear to be subjected to higher internal stresses. The highest stress in Figure B, which is 165.98 kPa, is approximately 1.36 times higher than the maximum stress in Figure A, which is 122 kPa. This indicates that the loading situation or structural integrity in Figure B causes more stress to build up around the holes. Additionally, compared to Figure A, which has a smaller range (from 32 kPa to 122 kPa), Figure B's range of stresses (from 48.27 kPa to 165.98 kPa) demonstrates a more pronounced variance in stress distribution.

As a result, compared to Figure A, Figure B exhibits generally increased stress levels, particularly in important regions like the interior holes where stress amplification is more than 1.36 times greater. Figure B likewise shows noticeably larger overall stresses, with the stress reaching a maximum of 423.7 kPa, or 1.69 times higher than Figure A.

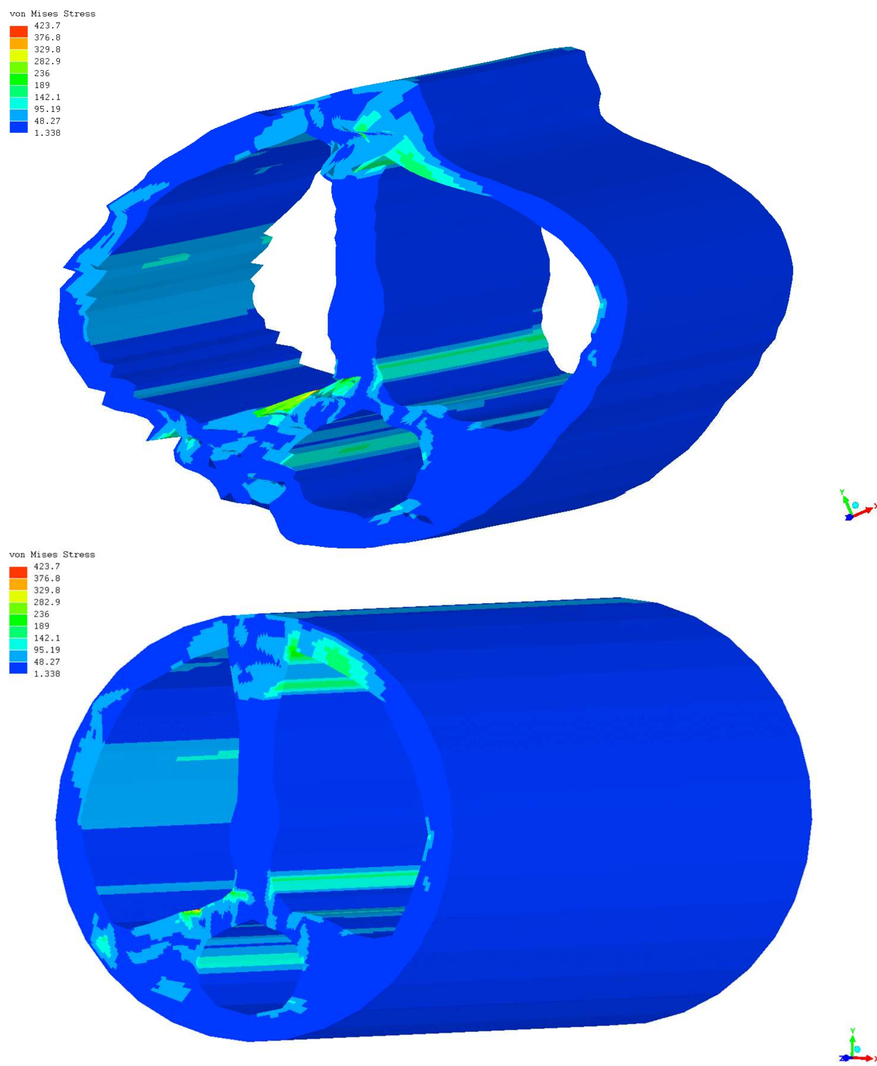


Figure 7. *Stress DistributionVon Mises with LISA FEA*

Deformation during penile erection

The stretching levels throughout the examined structure are represented by the displacement magnitude in the figure 8. The displacement values on the scale vary from 0.0006123 to 0.008846 m, with blue denoting the least displacement and red denoting the places with the largest deformation. Deflection or displacement is a crucial component in the typical penile erection mechanics context, as it pertains to the stiffness and curvature caused by elevated blood pressure and flow. In order to ensure homogeneous stiffness and structural support, a healthy erection is usually defined by a balanced deflection across the shaft with minimum localized displacement. The color gradient from blue to red in this figure 8, which represents the gradual increase in deflection, is similar to the soft-to-rigid transition that is seen during a typical erection process. During this transition, different parts of the erection experience varying degrees of expansion while maintaining overall functional rigidity.

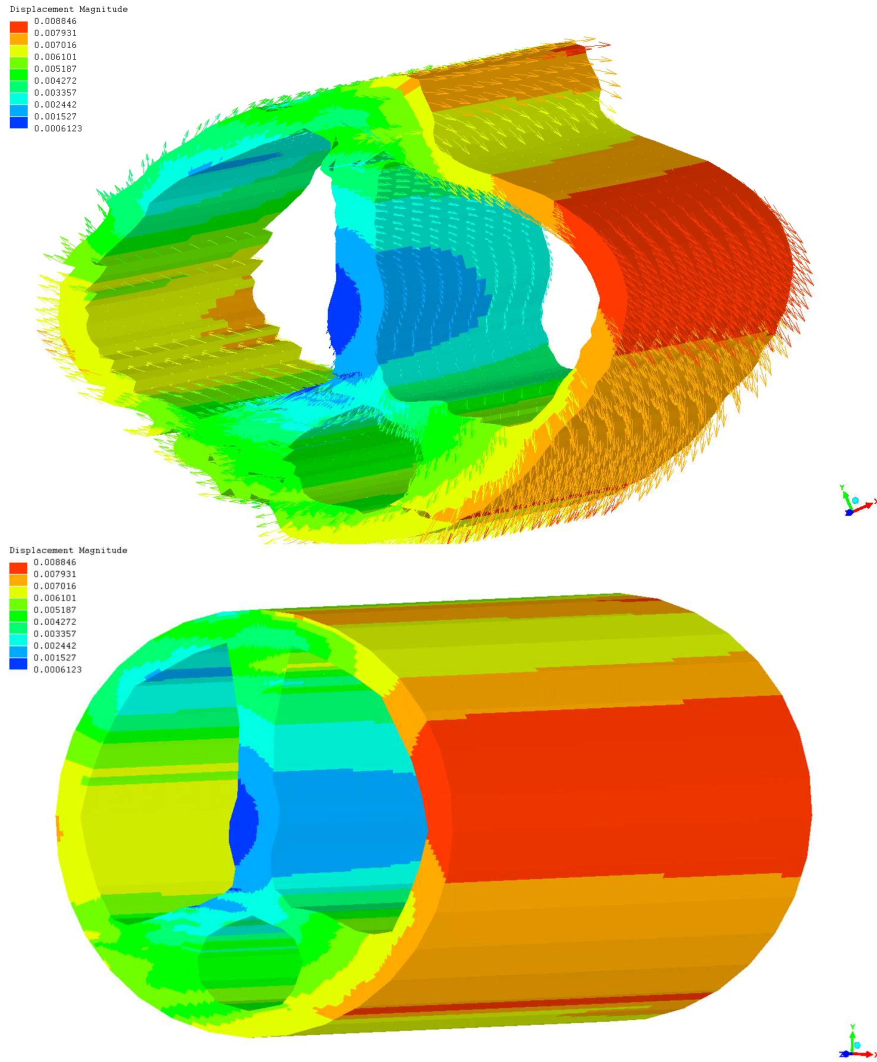


Figure 8. *The stretching behavior*

CONCLUSION

The study effectively used finite element analysis (FEA) to describe the mechanics of penile erections, providing valuable insights into mechanical reactions to blood pressure and radial compression loads. As radial compression causes less total displacement than blood pressure load, it is a useful non-invasive technique for evaluating penile stiffness, according to the data, which makes it useful for diagnostic purposes. Nonetheless, stresses created by blood pressure resulted in greater displacements at the penile tip, suggesting that under extreme stress, buckling behavior might occur. The stress analysis demonstrated that while radial compression provided a more uniform distribution of stress, blood pressure loading led to localized stress concentrations, especially near the penile peak.

In a particular model, the von Mises stress around internal holes was 122 kPa; in another, the greater stress concentrations (165.98 kPa) exceeded the stress levels by almost 1.36 times. Furthermore, 423.7 kPa maximum stress levels were recorded, 1.69 times higher than those in the lower-stress model. These results demonstrate the notable distinctions in stress distribution and deformation between the two loading scenarios: blood pressure loads raise the possibility of structural failure in severe circumstances, whereas radial compression shows potential for non-invasive diagnostics.

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