Finite Element Analysis of a Female Pelvis to Model Pelvic Organ Prolapse

A Technical Report submitted to the Department of Biomedical Engineering

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia · Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Allison Douglas

Spring 2025

Word Count: 1948
Number of Figures and Tables: 3
Number of Equations: 0
Number of Supplements: 0
Number of References: 14

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

William Guilford, Department of Biomedical Engineering

Signed ________________ Date 5/9/2025

Signed ________________ Date 5/9/2025

Finite Element Analysis of a Female Pelvis to Model Pelvic Organ Prolapse

Allison Douglas[a]. Dr. William Guilford[a]

[a] Department of Biomedical Engineering, University of Virginia

Abstract

Pelvic organ prolapse (POP) occurs when the vagina, bladder, uterus, urethra, and or rectum drop from their position, causing a bulge in the vagina. This condition can affect all aspects of a person's life by limiting their bowel control, increasing pelvic pain and pressure, and causing harm to their mental or sexual health. Without helpful treatments, POP can affect all aspects of a person's life, including urinary and fecal incontinence, dyspareunia, vaginal spotting, and abdominal and back pain, affecting up to 50% of the population. Current treatments have up to a 43% failure rate and aren't a suitable option for most. This project looks to build a finite element model of a female pelvis to help understand the causes of prolapse. A proof of concept was created using a segmentation of a vagina from research images to evaluate the abilities of this computational approach.

Keywords: Women's health, pelvic organ prolapse, finite element analysis, computational modeling

Introduction

Pelvic organ prolapse (POP) occurs when the pelvic organs (vagina, bladder, uterus, urethra, and or rectum) bulge into the vaginal cavity[1]. By the age of 80, up to 50% of the female population will have experienced one or more occurrences of POP[2]. When prolapse occurs, symptoms such as urinary incontinence, fecal incontinence, dyspareunia, vaginal spotting, and abdominal and back pain can result[3]. In addition to the physical symptoms, individuals with POP may also experience a decline in their mental and sexual well-being.

POP is currently treated with physical therapy, surgery, or pessaries. However, these treatments do not actively work to fix the affected muscle or tissue strengths but are instead aimed at moving the protruding organs. On average, 200,000 POP surgeries are conducted annually in the United States alone[4]. These three surgeries are native tissue repair, sacrocolpopexy, and transvaginal mesh. However, in 2019, transvaginal mesh was banned by the FDA as a treatment for POP due to its negative effects and lack of long-term safety[5]. Despite new advances in treatments, there is still a recurrence rate of 28% for sacrocolpopexy, 29% for transvaginal mesh, 43% for native tissue repair, and 42% for pessaries[6]. New treatments need to be created to improve patient outcomes.

Pelvic organ prolapse is thought to be caused by the loss of strength in elasticity in 5 ligaments: uterosacral (USL), cardinal (CL), arcus tendineus fascia pelvis (ATFP), pubourethral (PUL), and perineal body (PB)[7]. Pelvic floor ligaments help hold up the bladder, vagina, bowel, and uterus. They control contractions of the pelvic organs, like the vagina, anal, and urethra, by lifting the organs and tightening them. They also control the release of bodily fluids. If these muscles loosen or are injured, by things such as older age, lifting heavy weights, having constant constipation, or having a vaginal birth as the baby can tear the ligaments, then prolapse symptoms are much more likely to occur[8]. Doctors can use MRIs, CTs, and pelvic ultrasounds to aid in the diagnosis and understanding of how these pelvic floor muscles and ligaments interact in normal and prolapsed conditions[9].

Finite Element Analysis

Others have developed computational models to simulate various pelvic and urinary disorders. A Finite Element model that included the anterior and posterior vaginal wall with supporting structures, created by Luo et al., helped identify that reproductive ligaments can help with vaginal wall descent predictions[10]. Another group, Chen et al., identified the support impairments that contribute to anterior vaginal prolapse conditions based on their 3D model created from MRIs[11]. Babayi et al. created a very simplified model, a beam and rod, to analyze soft tissue and ligament impairments[12]. Limitations to these studies included only looking at support-specific muscle areas, excluding parts of currently known muscle impairments, and not being able to scale up these studies to fit more patient data sets. Dias et al. developed a basic model with five components: fat, levator ani, bones, organs, and a body fill[13]. This body fill represented the intra-abdominal components and improved the bio fidelity of the model as it was used as a surface contact[13].

The current work was a continuation of last year's Capstone project conducted by Olivia Mergler[14]. Last year's project ran into problems with the cadaver's organ sizing, specifically the bowel being much bigger than the other organs due to feces left in the bowel, leading to unusable data as this couldn't be applied to larger groups of patients. Further, there were no sliding contacts between organs in that finite element model, and so the organs did not move as expected under load. This project was meant to rectify those issues[14].

The specific aims for this project were as follows:
Aim 1: Build a model of an anatomically correct female pelvic region.
Aim 2: Validate finite element simulations using normal anatomical properties (Ogden values as defined in prior literature).
Aim 3: Simulate modified muscle and tissue material properties that are thought to be associated with pelvic organ prolapse.

Results

The final model had 142, 438 facets made from a tetrahedral mesh with 10 structures added together (figure 1).

Meshing Errors

This model had lots of problems upon uploading and there were many debugging problems that were tried with different steps. First, I tried uploading each part individually, then reducing, refining, remeshing, then building the model. However, the mesh wouldn't load in correctly due to geometry issues. The next try was uploading the model as a whole and refining and remeshing. However, the model wouldn't load within the allowed time limit, so the simulation was moved from a desktop PC to UVA's Rivanna High-Performance Computer (HPC) system. However, the PC was used to conduct the proof of concept as described below due to the HPC having a different version of ANSYS and not allowing specific ANSYS module files to transfer over from one software version to the other. Next, the type of meshing, fixed holes, overlapping, and folds were changed, and shrink wrap was added to potentially fix meshing errors, but the geometry still had meshing issues.

Organ Validation

To have proof of concept, it was decided to fix one organ to be able to model muscle simulation. The vagina was chosen as the organ to fix the meshing errors on, as it is an important part of pelvic organ prolapse and had fewer geometrical facets compared to some of the other parts of the model (figure 2). The meshing errors were fixed in the geometric import and mesh workbenches in ANSYS by first using ANSYS SpaceClaim to fix all the geometric issues. This included fixing sharp edges in the mesh, deleting

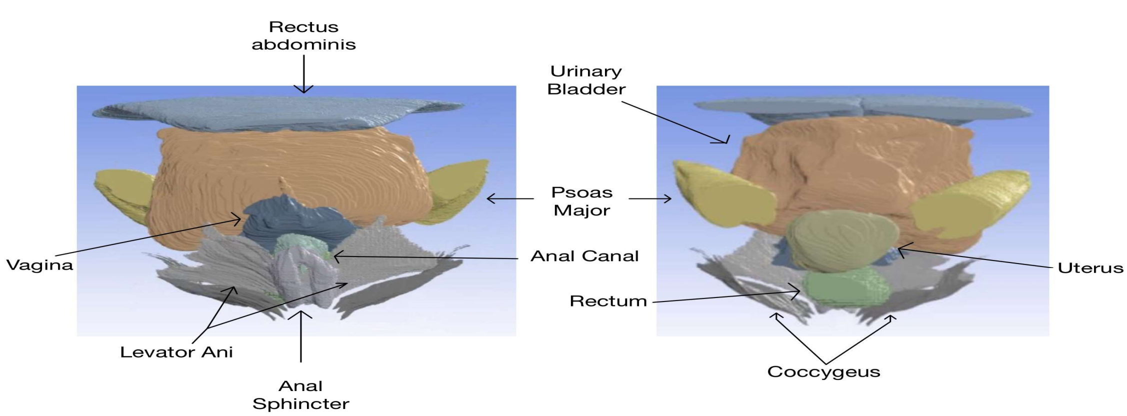

Fig. 1. Labeled diagram of model. This is a diagram of a female pelvis in the resting position with a posterior and anterior view and labeled parts.

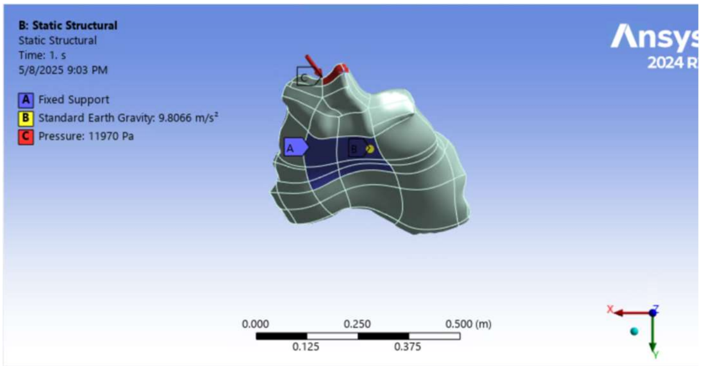

Fig. 2. Static Structural Simulation. This is the set up for the muscle elasticity simulation. Gravity was applied to the top, fixed support was applied to the posterior to simulate being fixed to the pelvic region, and pressure was applied to simulate the pressure from the Valsalva maneuver.

geometric faces, and filling the holes created from the previous step. Then it was turned into a solid geometric body by patchwork and shrink wrapping. It was then meshed in the meshing workbench and turned into a mechanical body. After that, in the main ANSYS Workbench, a static structural analysis system was created. To simulate the Valsalva maneuver, a pressure of 11.77 kPa was applied to the outside of the model at the top plane. To simulate the pelvic attachments in a real human, the posterior of the vagina was a fixed support. Lastly, gravity was applied to the top of the model to simulate organs existing in the natural human body. However, when the simulations were being conducted, it would crash about halfway through due to a modeling error that could not be fixed. So, the simulations were inconclusive as to whether the model would work fully or not with these meshing fixes.

Discussion

This project was a great indicator of the difficulties of computational models. Every fix caused a new issue, especially in the meshing design of ANSYS. It is a difficult software to utilize and is not efficiently fast for regular use. If this research is continued, the meshing errors would need to be the first thing fixed. Then, the simulations would need to be conducted to prove the use of the modeling system and obtain results that show it is beneficial for future research in understanding how ligaments and muscles are affected by POP. Then this model could be used in future research to look at how pessaries could be used to aid in the affected muscles. The model would also need to be more advanced, as this research only utilized the ten most needed parts for pelvic organ prolapse.

Materials and Methods

Model development

The Visible Korean Human, a research group that produced sectioned images from a cadaver, allowed us to access and use their images taken from a pelvic MRI. These 1,200 images were uploaded into 3DSlicer, a free-source imaging processing software. Within this software, 10 parts of a female pelvis, the uterus, vagina, anal sphincter, anal canal, levator ani muscles, coccygeus muscle, bladder, rectus abdominis, and the psoas major muscles, were identified and targeted during segmentations. These muscles and organs were chosen to best represent the muscles and organs affected by pelvic organ prolapse. These segmentations were taken image by image, allowing full encapsulation of each piece. These segmentations were then uploaded into ANSYS, an engineering software program that allows for finite element analysis. Using ANSYS SpaceClaim, these segmentations were smoothed and reduced, and the many facets were auto corrected to allow for easier meshing compatibility. These mesh facets were then combined into one full model with all ten parts together (figure 3).

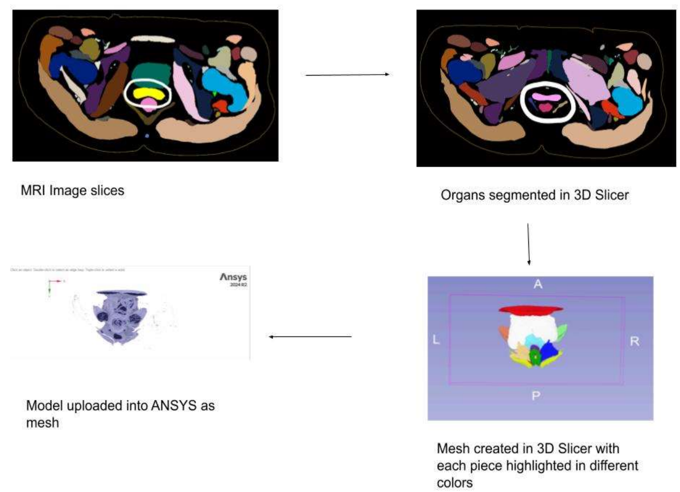

Fig. 3. Model Development Flowchart. This is the model outline for the development of the full pelvic model. The model started as images, were segmented in 3DSlicer, and were meshed in ANSYS.

This model was then further reduced and smoothed to try to get the file size easier to work with. Once this process was repeated a few times, the files were uploaded into ANSYS Workbench via UVA's Rivanna High-Performance Computing (HPC) operating systems. Workbench is the main operating system to set up the model before simulations, making sure that the geometry, mesh, and engineering properties are set up and loaded correctly. The geometry was checked using ANSYS DesignModeler, a different version of a geometry modeler (as compared to

ANSYS SpaceClaim), which was used due to switching to the HPC system. ANSYS Engineering data was set up with Ogden values set for each material and organ type.

Limitations

Meshing errors on ANSYS can occur for many reasons. These can occur from geometric issues in the mesh, the mesh not attaching to the solid model properly, the mesh having holes, or the mesh having sharp edges. If the geometry, mesh, and mechanical model aren't all loaded in fully, set up correctly, and fixed properly, simulations cannot be run. It can be difficult learning how to combat these errors, especially with files as big as the ones needed for this research. While the ANSYS forum is large and can help with many problems, there are just some meshing errors it does not have any solutions to.

While researching values for simulation testing, it was hard to find clear numbers for density and Ogden material equation variables. Some literature was contradicting with different measurements stated for the same organs or muscles, while others didn't have exact measurements for the specific pieces in this model. This stems from the issue of not having enough research and data for normal pelvic regions. Without these specific numbers, it is hard to tell if it is the mesh that is causing an error or if it is the assigned value for any of the variables.

End Matter

Author Contributions and Notes

A.R.D created the model, attempted to perform simulations, analyzed the model and lack of data, and drafted the report. W.H.G. provided advising throughout the project.

The authors declare no conflict of interest.

Acknowledgments

This research was a continuation of prior research supported by NIH R25 EB023841.

The authors would like to thank:
Dr. Timothy Allen for providing feedback and advising throughout the course.
Graduate Teaching Assistants Mario Garcia, Hayley Sussman, Tim Ho, and Shay Ladd for guidance and support throughout the course.
The Visible Korean Human Project for providing data.
Professor Matt Panzer and Graduate Student Peter Dow for ANSYS help and model debugging.

References

1. Pelvic organ prolapse - Symptoms and causes. *Mayo Clinic* https://www.mayoclinic.org/diseases-conditions/pelvic-organ-prolapse/symptoms-causes /syc-20360557.
2. Carroll, L., O' Sullivan, C., Doody, C., Perrotta, C. & Fullen, B. Pelvic organ prolapse: The lived experience. *PLoS One* **17**, e0276788 (2022).
3. Pelvic Organ Prolapse: Types, Causes, Symptoms & Treatment. *Cleveland Clinic* https://my.clevelandclinic.org/health/diseases/24046-pelvic-organ-prolapse.
4. Aboseif, C. & Liu, P. Pelvic Organ Prolapse. in *StatPearls* (StatPearls Publishing, Treasure Island (FL), 2024).
5. Surgical Mesh: Use and Complications in Women. *Cleveland Clinic* https://my.clevelandclinic.org/health/articles/16298-surgical-mesh-use-and-complications-in-women.
6. Science Update: Common surgeries for pelvic organ prolapse are comparable and safe, according to NIH-funded clinical trial | NICHD - Eunice Kennedy Shriver National Institute of Child Health and Human Development. https://www.nichd.nih.gov/newsroom/news/052224-pelvic-organ-prolapse-surgeries (2024).
7. DARREN M. GOLD, D. E. (n.d.). *A review of the Integral Theory of Pelvic Organ Prolapse and proposed concept of repair: Part 1 - Structural components and damage* [Text]. Pelviperineology A Multidisciplinary Pelvic Floor Journal. Retrieved May 8, 2025, from https://pelviperineology.org/articles/a-review-of-the-integral-theory-of-pelvic-organ-prolapse-and-proposed-concept-of-repair-part-1-structural-components-and-damage/doi/36912
8. *Pelvic Organ Prolapse*. (n.d.). Continence Health Australia (Formerly the Continence Foundation of Australia). Retrieved May 8, 2025, from https://www.continence.org.au/who-it-affects/women/prolapse
9. Pelvic Organ Prolapse (POP). (n.d.). *UCHealth*. Retrieved May 8, 2025, from https://www.uchealth.org/diseases-conditions/pelvic-organ-prolapse-pop/

10. Luo, J., Chen, L., Fenner, D. E., Ashton-Miller, J. A. & DeLancey, J. O. L. A multi-compartment 3-D finite element model of rectocele and its interaction with cystocele. *J Biomech* **48**, 1580–1586 (2015).
11. Chen, L., Ashton-Miller, J. A., Hsu, Y. & DeLancey, J. O. L. Interaction among apical support, levator ani impairment, and anterior vaginal wall prolapse. *Obstet Gynecol* **108**, 324–332 (2006).
12. Babayi, M., Azghani, M.-R., Hajebrahimi, S. & Berghmans, B. Three-dimensional finite element analysis of the pelvic organ prolapse: A parametric biomechanical modeling. *Neurourol Urodyn* **38**, 591–598 (2019).
13. Dias, N. *et al.* Pelvic floor dynamics during high-impact athletic activities: A computational modeling study. *Clin Biomech (Bristol)* **41**, 20–27 (2017).
14. Mergler. Exploring the Etiology of Pelvic Organ Prolapse with Finite Element Analysis. (2024)