A Three-Dimensional Data-Based Pelvic Floor Support Structure Model and Modeling Method for Surgical Planning of Pelvic Organ Prolapse

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Abstract: Female pelvic organ prolapse (POP) is a prevalent pelvic floor dysfunction that severely affects the quality of life of middle-aged and elderly women. The main cause of high recurrence is the lack of direct and reliable preoperative visualization of pelvic floor ligament morphology and mechanical state. Traditional evaluation methods rely on two-dimensional imaging and clinical experience, leading to inconsistencies between preoperative planning and intraoperative conditions. This study aimed to develop and validate a patient-specific three-dimensional (3D) physical model of the pelvic floor support structure based on personalized MRI data, together with a standardized modeling procedure. The model consists of a pelvic bony framework, visceral organ modules, and elastic ligament units with biomechanical simulation functions. A total of 10 participants underwent standardized multi-planar MRI scanning, and 1:1 physical models were constructed and verified. The results showed that the mean error of uterosacral ligament length was 1.2±0.4 mm, the maximum stress of the uterosacral ligament was 1.510±0.086 MPa, and the maximum displacement was 19.46±2.37 mm. The 3D model accurately reproduces the in vivo anatomical structure and mechanical properties of the pelvic floor, enables intuitive preoperative simulation, helps identify defect locations, and supports personalized surgical design. This technology provides a novel and effective tool for precise diagnosis and treatment of POP, and has significant value in reducing surgical recurrence and improving clinical outcomes.
***Keywords*:** pelvic floor support; 3D model; pelvic organ prolapse; uterosacral ligament; biomechanical simulation; MRI-based modeling

1. Introduction

Female pelvic organ prolapse (POP) is a common chronic condition affecting up to 50% of parous women, with a lifetime surgical risk of 11%–19%[1]. The condition arises from structural failure of the pelvic floor muscles, ligaments, and connective tissues,leading to descent of the uterus,bladder,vagina or rectum.Clinical manifestations include pelvic pressure,urinary and fecal incontinence,sexual dysfunction, and psychological distress, severely reducing quality of life[2]. Despite multiple surgical approaches-including native tissue repair, sacrospinous ligament fixation, uterosacral ligament suspension and transabdominal sacrocolpopexy-postoperative recurrence remains high, approaching 30% in some series[3].

A major limitation in POP management is the lack of patient-specific, visualizable preoperative assessment of pelvic floor anatomy. Surgical planning currently relies on clinical examination, conventional MRI, and surgeon experience rather than direct 3D visualization of ligamentous defects[4]. The uterosacral ligaments (USL) are the primary supportive structures of the vaginal apex and uterus; their attenuation or avulsion is central to the pathophysiology of POP[5]. Accurate 3D representation of USL morphology, length, angulation, and tensile behavior is critical for surgical planning[6].

Conventional anatomical models are generic, not patient-matched, and cannot simulate biomechanical properties or dynamic deformation[7]. Recent advances in medical imaging and 3D printing have enabled patient-specific anatomical modeling, but few systems integrate realistic elastic ligament mechanics, modular assembly, and intraoperative simulation capabilities[8]. This study presents a novel 3D data-driven pelvic floor support model and a reproducible MRI-based modeling pipeline designed to address these gaps. The model integrates bony structures, visceral organs, and functional ligament subunits with tunable elasticity to mimic in vivo biomechanics[9].

2. Materials and Methods

2.1 Study Participants

Ten female participants aged 35-65 years were enrolled, including 5 patients with POP and 5 healthy volunteers. All participants provided written informed consent. Exclusion criteria included metal implants, severe pelvic deformity, and inability to cooperate with examination. This study was approved by the institutional ethics committee(Ethical approval number: ZXYY2024222).

2.2 MRI Data Acquisition

Before scanning, participants emptied their bladders 1 hour in advance and removed all metal objects. During scanning, participants lay supine with lower limbs slightly abducted and were instructed to maintain quiet breathing and perform the Valsalva maneuver[10-11].

2.3 3D Model Construction

The 3D pelvic floor model consists of three modules:Bony structure: hip bones and coccyx.Visceral structure: uterus, bladder, vagina, and rectum.Ligament structure: cardinal ligament, uterosacral ligament, and round ligament.Ligaments were designed with multi-layer elastic components, including separating plates, elastic tubes, telescopic rods, and elastic fillers to simulate tensile deformation. A honeycomb connection layer was applied on bone surfaces to enhance fixation stability. The model uses a T-shaped plug-in and anti-return locking structure for convenient assembly, disassembly, and anatomical display[12-14].

2.4 Modeling Procedure

Pre-scan preparation and participant training. Multi-planar MRI scanning at rest and during Valsalva. Image segmentation and 1:1 3D reconstruction.Physical model fabrication and assembly. Anatomical alignment and mechanical verification.

2.5 Outcome Measures

Anatomical accuracy: errors in length, angle, and position.Biomechanical parameters: maximum stress and maximum displacement.Clinical utility: 5-point Likert scores by ten senior surgeons[15].Assembly efficiency: time and connection stability.

3. Results

3.1 MRI Parameters

All sequences clearly delineated pelvic floor ligaments, organs, and bones with high resolution and no significant artifacts.

Table 1. Optimized MRI Acquisition Parameters for Pelvic Floor Imaging

Sequence	TR (ms)	TE (ms)	Slice Thickness (mm)	FOV (mm)	Matrix	NEX
Sagittal HASTE	1000	92	2	269×269	128×256	1
Coronal TSE T2WI	3100	33	1	349×349	384×84	2
Axial T1WI	500	11	1	320×320	320×320	2
Axial TSE T2WI	3100	33	1	279×380	376×512	2

3.2 Anatomical Accuracy

The model replicated real pelvic anatomy with clinically acceptable errors.

Table 2. Anatomical Accuracy of the 3D Pelvic Floor Model

Structure	In Vivo MRI Mean	3D Model Mean	Mean Error	Accuracy Rate
Uterosacral Ligament Length	140.2 ± 5.6 mm	139.0 ± 5.1 mm	1.2 ± 0.4 mm	99.14%
Uterosacral Ligament Angulation	28.6 ± 3.2°	26.5 ± 2.9°	2.1 ± 0.7°	92.66%
Cardinal Ligament Length	126.8 ± 4.9 mm	125.3 ± 4.5 mm	1.5 ± 0.4 mm	98.82%
Uterine Position Deviation	2.1 ± 0.7 mm	1.8 ± 0.6 mm	0.3 ± 0.2 mm	85.71%

3.3 Biomechanical Performance

The elastic ligament design reproduced physiological stress and displacement.

Table 3. Biomechanical Parameters of Simulated Ligament Structures

Ligament	Max Stress (MPa)	Max Displacement (mm)	Strain Region	Insertion Strength
Cardinal Ligament	0.267 ± 0.032	17.86 ± 2.14	Middle & Upper	High
Uterosacral Ligament	1.510 ± 0.086	19.46 ± 2.37	Middle & Upper	Highest

3.4 Clinical Utility Evaluation

Surgeons strongly endorsed the model for clinical application.

Table 4. Surgeon-rated Clinical Utility of the 3D Model (n=10, 5-point scale)

Evaluation Item	Mean Score	SD	Recognition Rate
Anatomical Authenticity	4.7	0.21	100%
Preoperative Planning Utility	4.6	0.27	100%
Surgical Simulation Value	4.5	0.31	90%
Decision-making Confidence Improvement	4.8	0.18	100%
Overall Clinical Recommendation	4.7	0.23	100%

3.5 Assembly Efficiency

The model showed excellent operability and stability.

Table 5. Model Assembly and Disassembly Efficiency

Operation Item	Average Time	Success Rate
Overall Model Assembly	2 min 45 s	100%
Ligament Installation	1 min 12 s	100%
Modular Section Disassembly	35 s	100%
Repeated Assembly Stability	>50 cycles	100%

4. Discussion

This study developed a personalized 3D physical model of the pelvic floor support system based on standardized MRI data, achieving high-fidelity simulation of bones, organs, and elastic ligaments. Compared with traditional 2D imaging and virtual models, the present model has multiple advantages.

First, the model achieves high anatomical accuracy. The mean error of ligament length is less than 1.5 mm, and the accuracy rate exceeds 98%, reliably reflecting individual anatomical differences. Second, the model provides realistic biomechanical simulation. The elastic ligament structure can restore stress distribution and displacement characteristics under physiological conditions, which is highly consistent with in vivo states. Third, the model supports intuitive preoperative simulation. Its modular and detachable design allows multi-angle observation and simulated operation, improving surgical safety and efficiency. Fourth, the standardized modeling workflow ensures reproducibility and clinical applicability.

In clinical practice, this model helps surgeons accurately evaluate ligament injury and pelvic defect locations preoperatively, formulate personalized surgical plans, reduce inconsistencies between preoperative planning and intraoperative conditions, and ultimately lower POP recurrence rates. In addition, the model can be used for surgical training and patient education, improving doctor-patient communication.

This study has limitations, including a small sample size. Future studies will expand the sample size, combine finite element analysis, and further optimize ligament mechanical properties to enhance clinical value.

5. Conclusion

The 3D pelvic floor support model based on personalized MRI data accurately reproduces the anatomical structure and biomechanical characteristics of the pelvic floor with high accuracy and clinical utility. It provides visualized and simulated support for preoperative planning of POP, helps improve surgical precision, reduces recurrence, and has important clinical application prospects.

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