



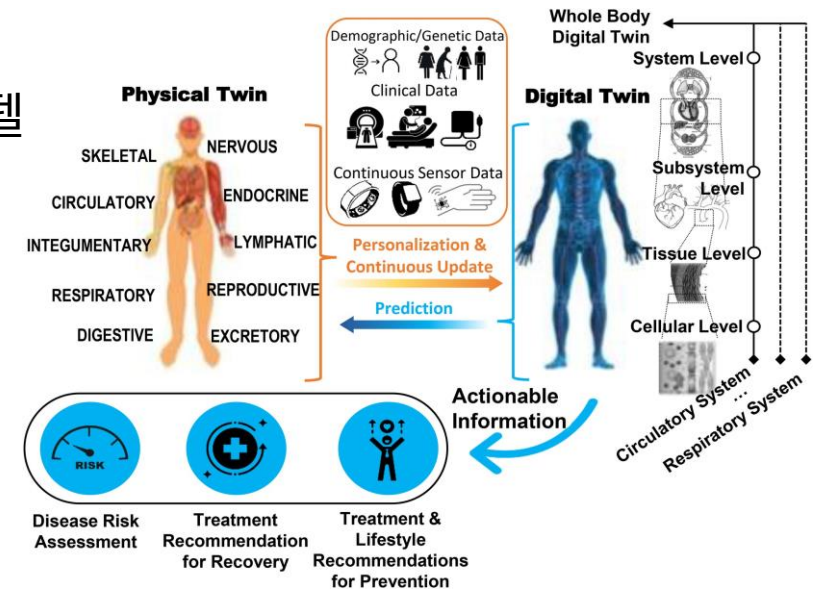
Patient-Specific Bladder Digital Twin Two-Way FSI-Simulation

Thar Htet Nyan

Key Concepts

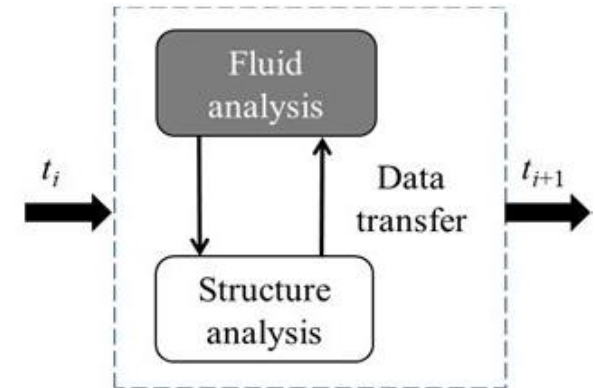
디지털 트윈 (Digital Twin)

- 환자 개인의 임상·분자·영상·환경 데이터를 실시간 통합한 동적 가상 모델
 - 건강 상태·치료 반응을 시뮬레이션·모니터링·예측
 - 3가지 핵심 요소:
 - 1) 물리적 환자
 - 2) 컴퓨팅(가상) 복제체
 - 3) 양방향 실시간 데이터 연결
- > 개인 맞춤형 예측 의료 구현



이중방향 유체-구조 연성 (Two-way FSI)

- 유체와 구조물이 서로 영향을 주고받는 시뮬레이션
- 유체의 압력·흐름이 구조물을 변형 → 변형이 다시 유체 흐름에 영향
- 상호 피드백을 통해 단방향 FSI보다 더 정확하고 현실적인 분석 가능



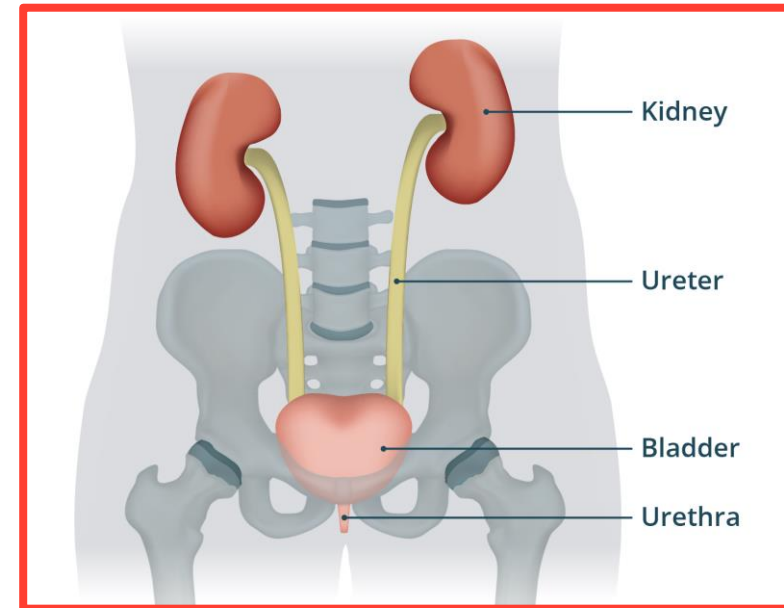
Background & Motivation

문제 상황

- 방광 충전 과정은 실제 환자에게 **침습적 검사 부담이 큼**
- 임상 실험은 **반복성 제한**, 벽 응력·변형 같은 **정량 분석 어려움**
- 큰 볼륨 변화(100 → 700 mL)에 대한 기계적 반응을 직접 측정하기 거의 불가능

필요성

- 안전한 **비침습적 평가 방법 필요**
- 다양한 조건에서 충전 과정을 **반복 시뮬레이션** 가능해야 함
- 실제 환자 데이터를 기반으로 하는 **정확한 가상 실험 환경 요구**



Objective

연구 목표

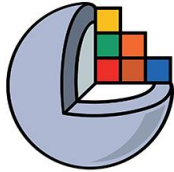
- 방광 100–700 mL 충만 시 유체 분포 변화와 벽 변형을 정량화
- 실제 충만 과정을 재현할 수 있는 FSI 기반 가상 모델 구축
- 향후 개인 맞춤형 시뮬레이션(디지털 트윈)으로 확장 가능한 기반 마련



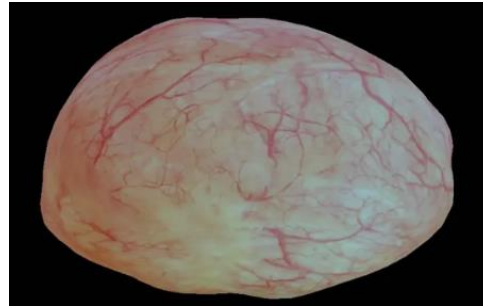
Workflow



MRI Image



3D Slicer

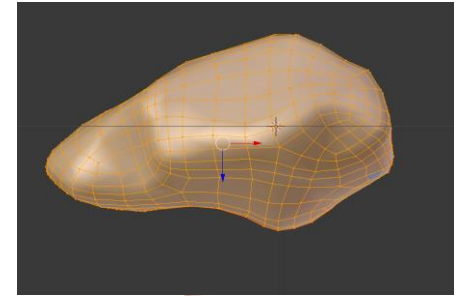


3D model



MeshLab

스무딩



3D model

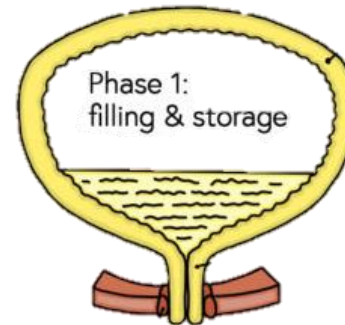
ANSYS Geometry → 요관(입구) 및 요도(출구) 추가

Two-Way FSI

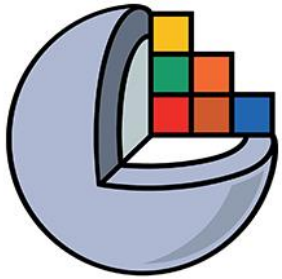
ANSYS Transient Structural → 방광 벽

ANSYS Fluent → 소변

Filling

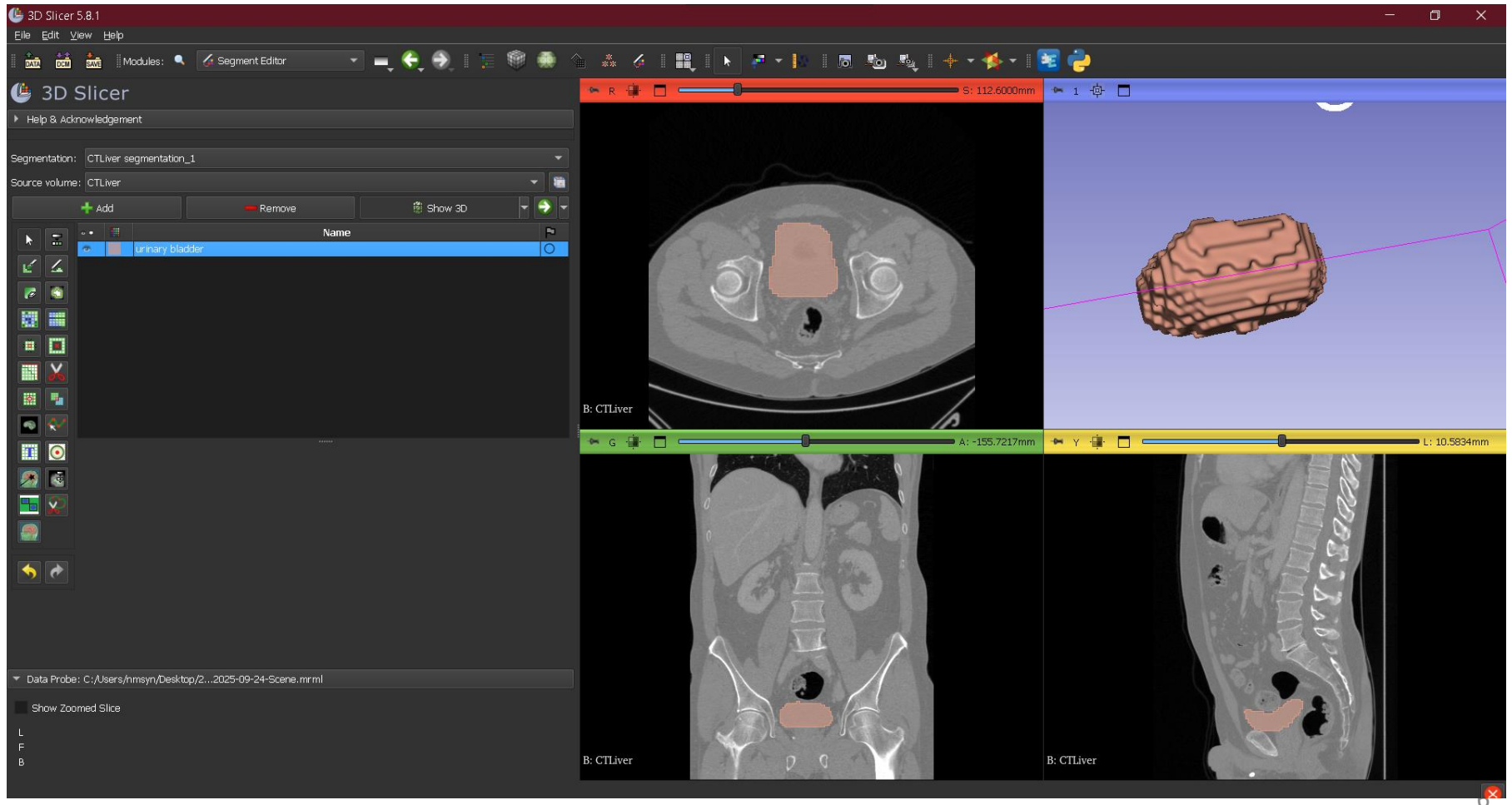


Workflow - Modeling



3D Slicer

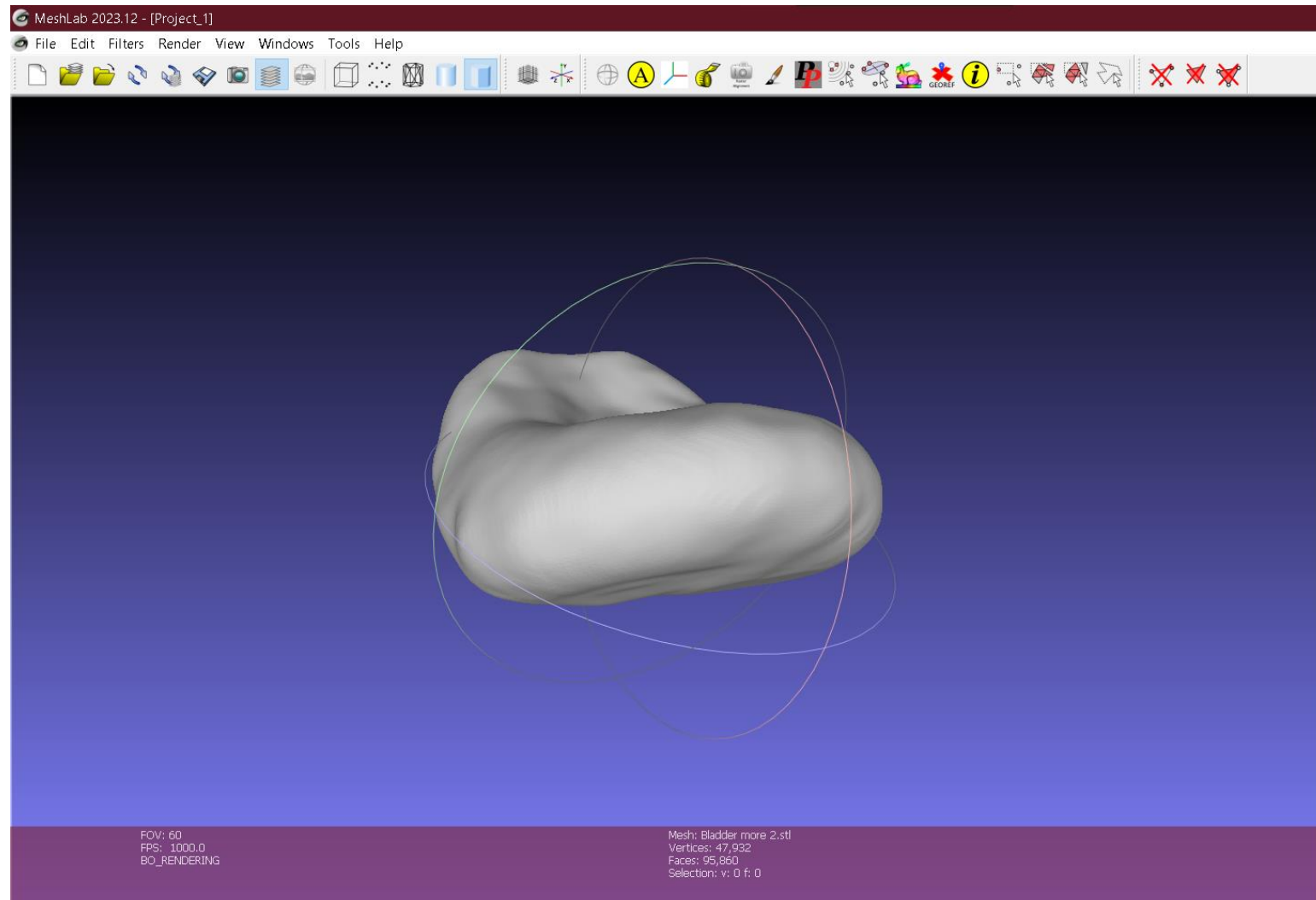
Segmentation



Workflow - Modeling



MeshLab
Smoothing



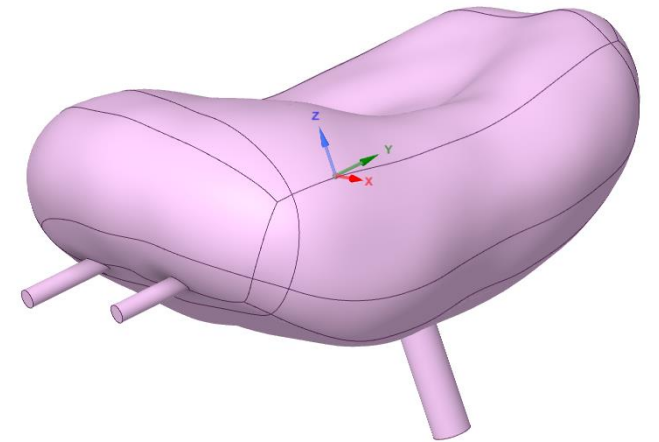
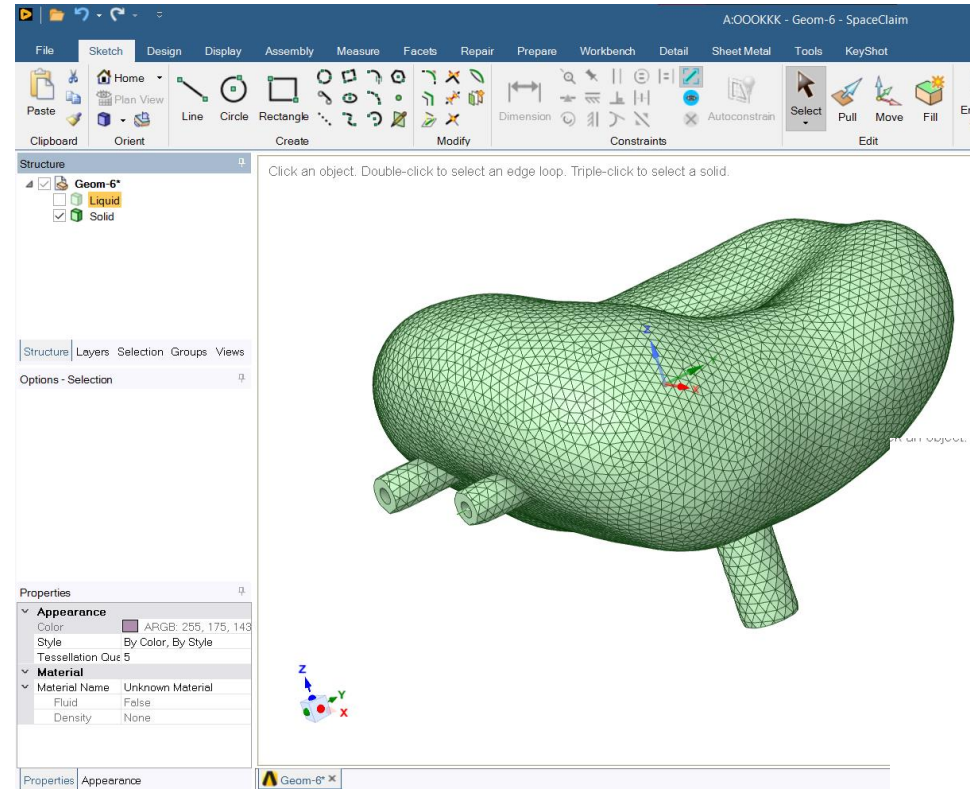
Workflow - Geometry

Ansys Geometry SpaceClaim

Inlet diameter – 3 mm [1]

Outlet diameter – 6 mm [2]

Bladder Wall Thickness – 3 mm [3]



Reference:

[1] Lescay HA, Jiang J, Leslie SW, et al. Anatomy, Abdomen and Pelvis Ureter. [Updated 2024 May 5]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 Jan-. Available from: <https://www.ncbi.nlm.nih.gov/books/NBK532980/>

[2] Su, Y., Fang, K., Mao, C., Xiang, S., Wang, J., & Li, Y. (2018). 640-slice DVCT multi-dimensionally and dynamically presents changes in bladder volume and urine flow rate. Experimental and Therapeutic Medicine, 15, 2557-2562. <https://doi.org/10.3892/etm.2017.5671>

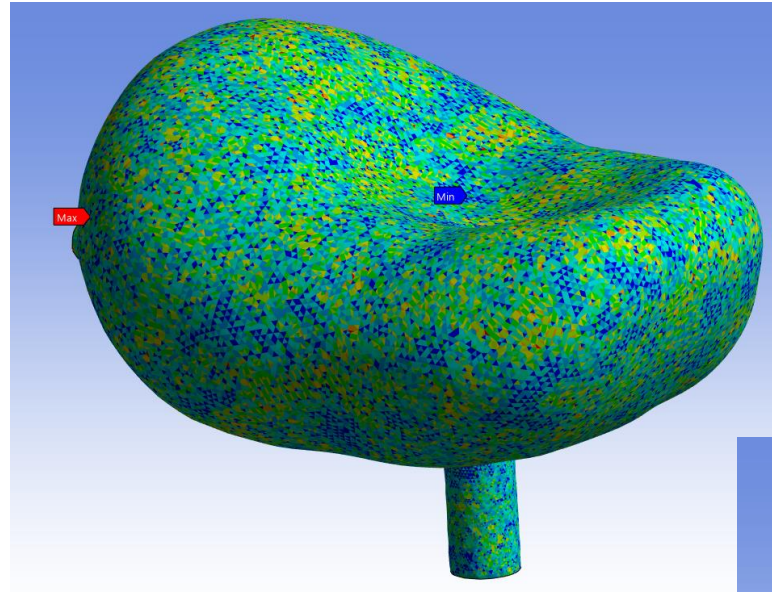
[3] Hakenberg, O. W., Linne, C., Manseck, A., & Wirth, M. P. (2000). Bladder wall thickness in normal adults and men with mild lower urinary tract symptoms and benign prostatic enlargement. Neurourology and urodynamics, 19(5), 585–593. [https://doi.org/10.1002/1520-6777\(2000\)19:5<585::aid-nau5>3.0.co;2-u](https://doi.org/10.1002/1520-6777(2000)19:5<585::aid-nau5>3.0.co;2-u)

Workflow - Mesh

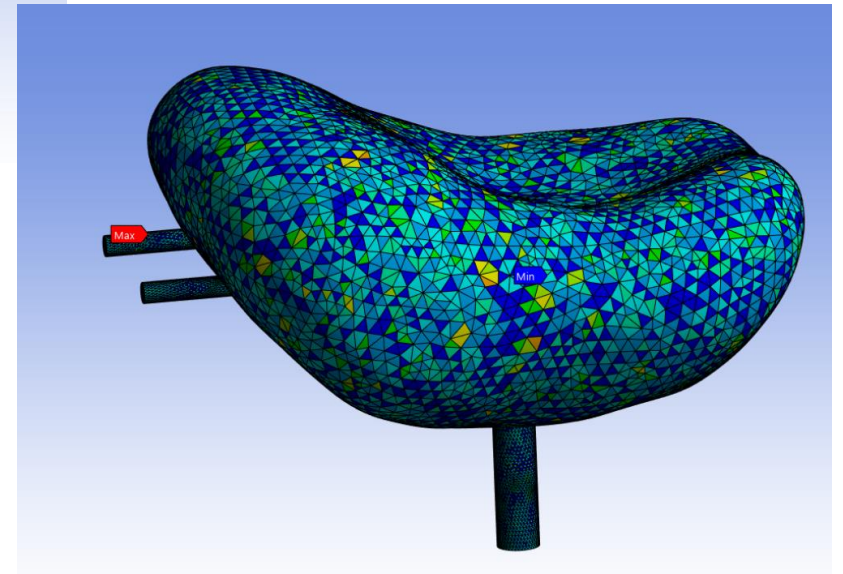
Ansys

MESH

Skewness

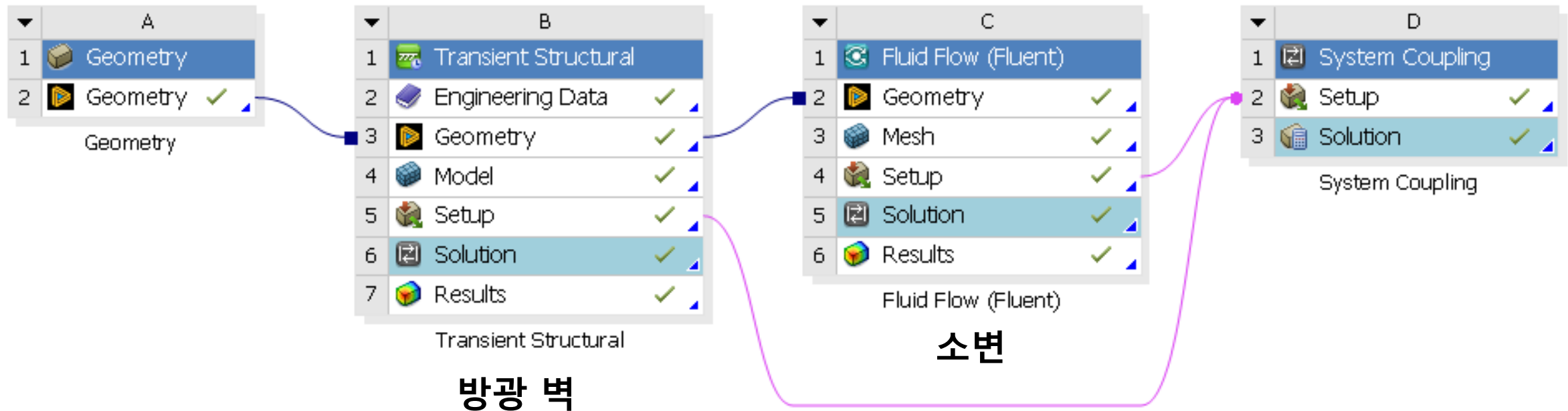


Method – Tetrahedrons
Resolution - 4
Body Sizing – 1 mm
Refinement - 3



Workflow

Project Schematic



Material Setup

Bladder Wall – Solid [4]

ANSYS Hyperelastic → Mooney–Rivlin (2-parameter).

Property	Value
C10 (A)	7500 Pa
C01 (B)	2500 Pa
Density	1060 kg/m ³
Poisson's Ratio	0.49 (nearly incompressible)
Bulk Modulus (K)	3,000 kPa (consistent with $\nu \approx 0.49$)
Shear Modulus ($\mu = 2 * C10$)	15,000 Pa

Urine – Liquid [5], [6]

Density = 1030 kg/m³

Viscosity = 0.000797 Pa·s

Reference:

[4] Barulina, M., Timkina, T., Ivanov, Y., Masliakov, V., Polidanov, M., & Volkov, K. (2024). Modeling the Stress–Strain State of a Filled Human Bladder. *Applied Sciences*, 14(17), 7562. <https://doi.org/10.3390/app14177562>

[5] Pradella, M., Dorizzi, R. M., & Rigolin, F. (1988). Relative density of urine: methods and clinical significance. *Critical reviews in clinical laboratory sciences*, 26(3), 195–242. <https://doi.org/10.3109/10408368809105890>

[6] Chai X, van Herk M, van de Kamer JB, Hulshof MC, Remeijer P, Lotz HT, Bel A. Finite element based bladder modeling for image-guided radiotherapy of bladder cancer. *Med Phys*. 2011 Jan;38(1):142-50. doi: 10.1118/1.3523624. PMID: 21361183.

Stimulation Setup

Solver: Pressure Based

Velocity Formation: Absolute

Time: Transient

Gravity: 9.81 m/s²

Models

Multiphase – Volume of Fluid

- Implicit Formulation
- Surface Tension Force Modeling
- Continuum Surface Force
- Surface Tension Coefficient [N/m] = 0.0587 [7]
- Phase 1: Air
- Phase 2: Urine

Viscous Model – SST k-omega

Boundary Condition

Inlet: 0.284 m/s [8]

Outlet: OFF (Filling Stimulation)

Method – SIMPLE

- Gradient: Least Squares Cell Based
- Pressure: PRESTO!
- Momentum: Second Order Upwind
- Volume Fraction: Compressive
- Turbulent Kinetic Energy: Second Order Upwind
- Specific Dissipation Rate: Second Order Upwind
- Transient Formulation: First Order Implicit

Reference:

[7] Mills, C. O., Elias, E., Martin, G. H., Woo, M. T., & Winder, A. F. (1988). Surface tension properties of human urine: relationship with bile salt concentration. Journal of clinical chemistry and clinical biochemistry. Zeitschrift für klinische Chemie und klinische Biochemie, 26(4), 187–194. <https://doi.org/10.1515/cclm.1988.26.4.187>

[8] Singla, N., Singla, A., & Lee, J. S. (2008). A Novel, Non-Invasive Approach to Diagnosing Urinary Tract Obstruction Using CFD. Journal of young investigators, 2008(6), <https://www.jyi.org/2008-may/2008/5/13/a-novel-non-invasive-approach-to-diagnosing-urinary-tract-obstruction-using-cfd>.

Stimulation Time Setup

Filling Time Calculation

- Ureter 1 Flow:

$$A = \pi(0.0015)^2 = 7.07 \times 10^{-6} \text{ m}^2$$

$$Q_1 = vA = 0.284 \times 7.07 \times 10^{-6} = 2.007 \times 10^{-6} \text{ m}^3/\text{s} (2.007 \text{ mL/s})$$

- Total Flow (2 ureters):

$$Q_{\text{tot}} = 2 \times Q_1 = 4.013 \text{ mL/s}$$

- Filling Time:

$$t = V / Q_{\text{tot}} = 700 / 4.013 \approx 174.5 \text{ s}$$

Time-Step Setup (based on calculation)

Total filling time: 174.5 s

No: of Time Step = 1745

Time Step Size = 0.1 s

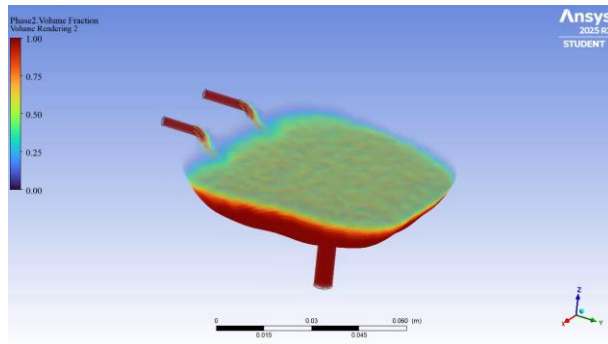
Max Iterations/step: 5

Reporting Interval: 1

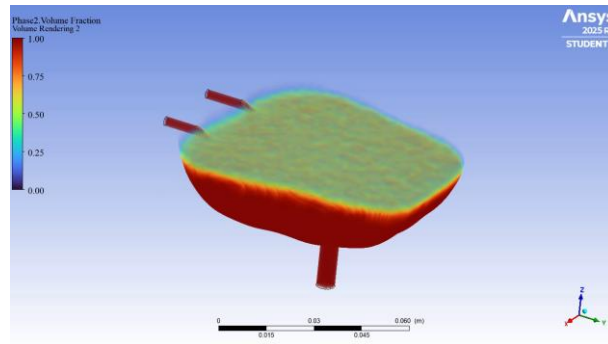
Profile Update: 1

Result

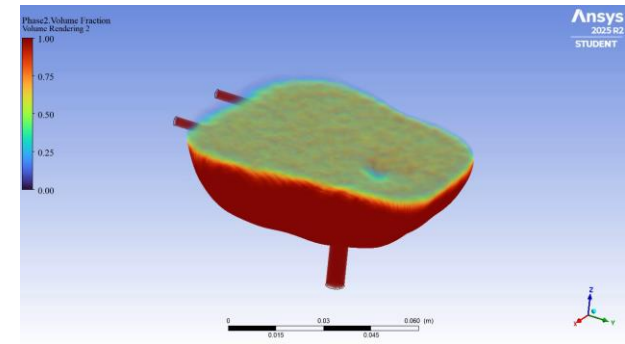
- Volume Fraction



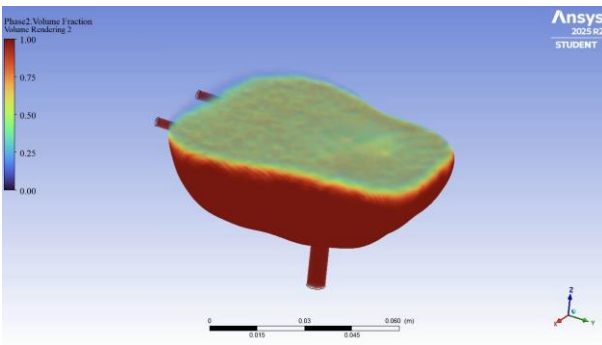
100 mL



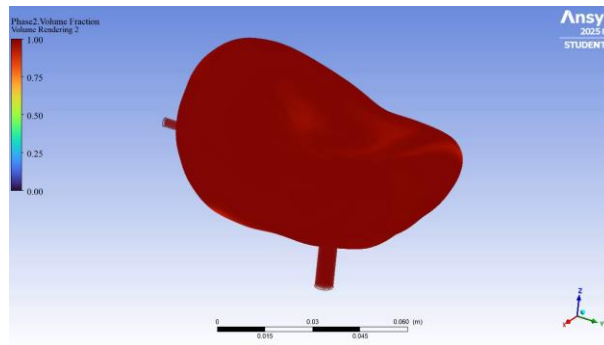
200 mL



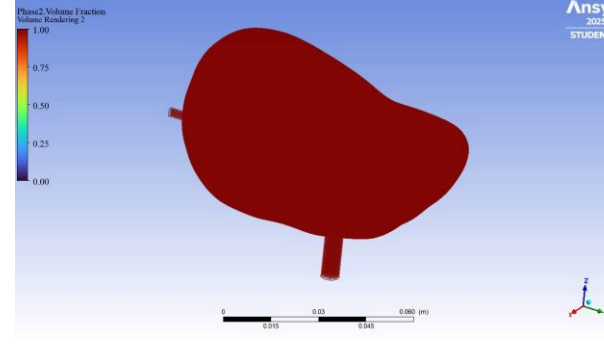
300 mL



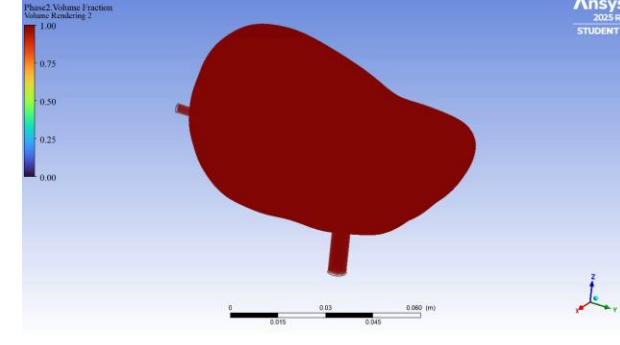
400 mL



500 mL



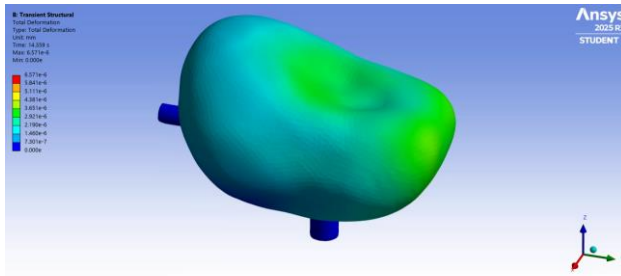
600 mL



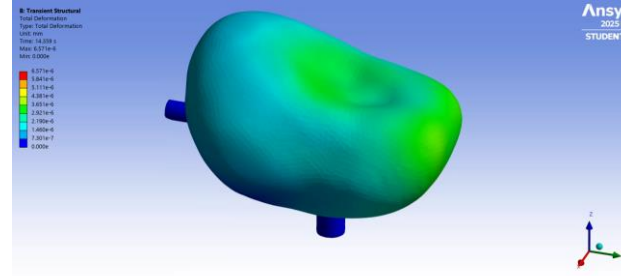
700 mL

Result

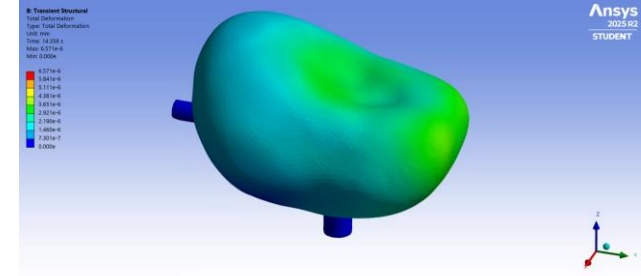
- Total Deformation



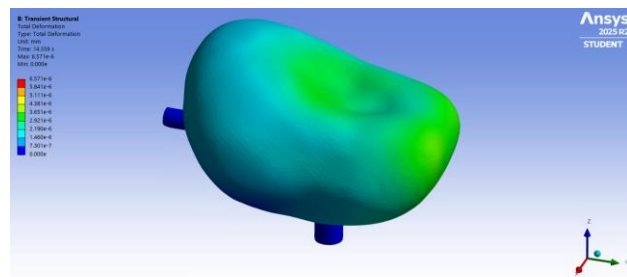
100 mL



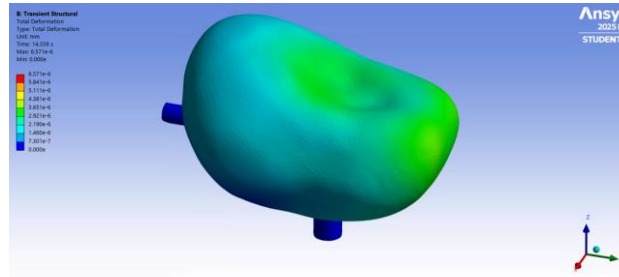
200 mL



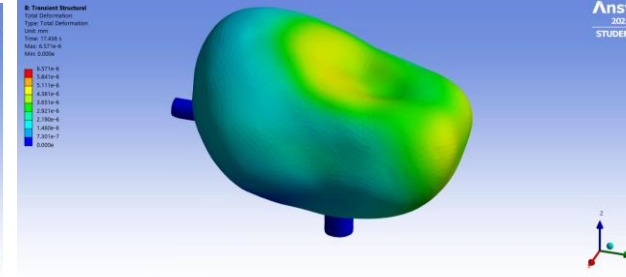
300 mL



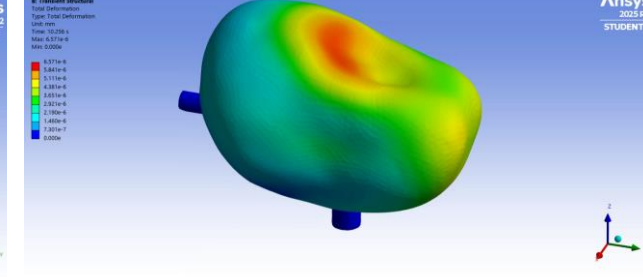
400 mL



500 mL



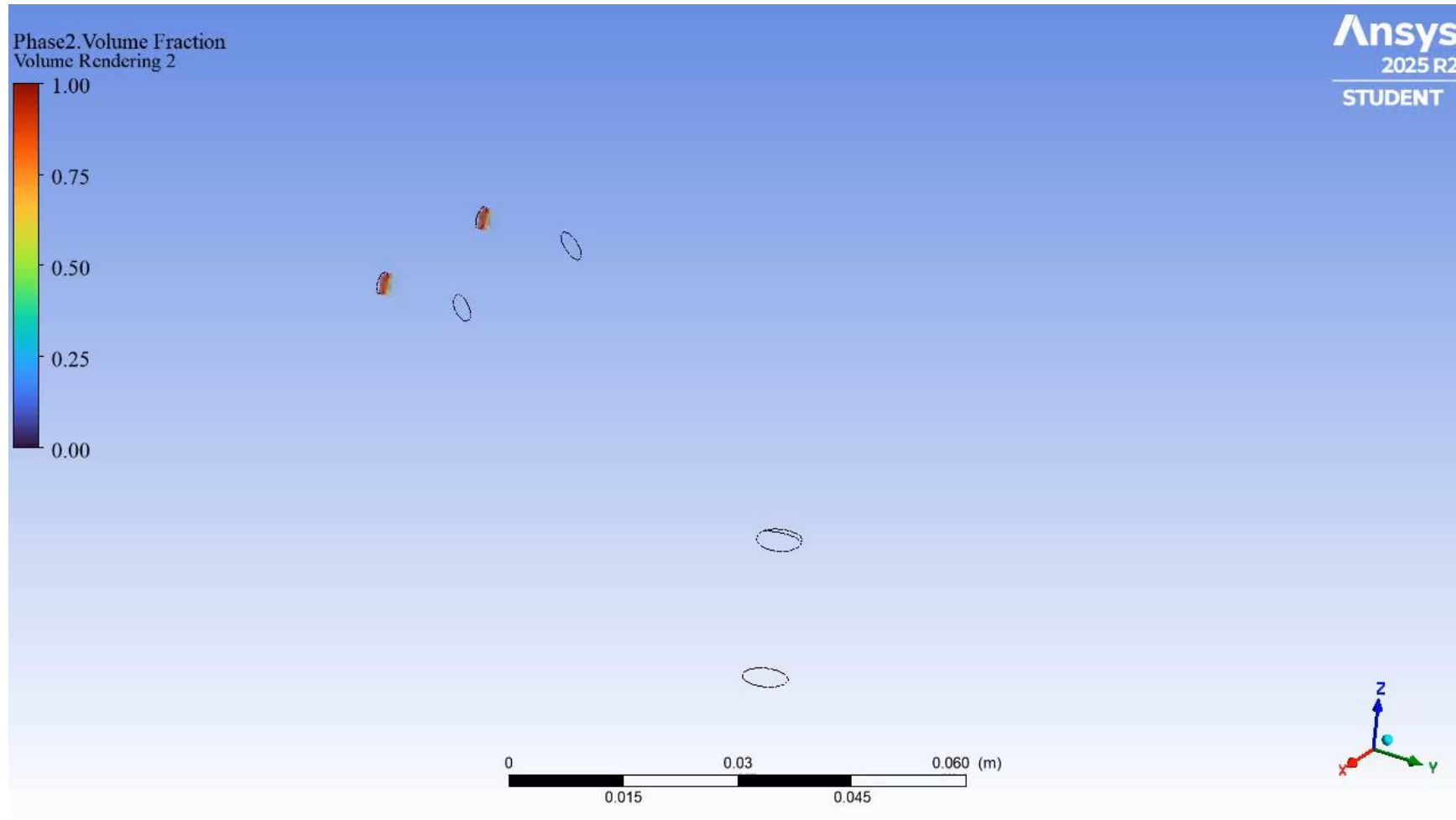
600 mL



700 mL

Result

- Volume Fraction



Conclusion & Future Work

결론 (Conclusions)

- FSI 모델을 통해 100–700 mL 총만 과정의 유체 분포와 방광벽 변형을 성공적으로 재현
- 유체 압력 증가에 따른 변형 패턴과 최대 변위 위치를 확인
- System Coupling 기반의 안정적인 유체-구조 연성 계산 구현

향후 연구 (Future Work)

- 모델 검증: 문헌·임상 데이터와 비교
- 민감도 분석: 메쉬·시간 간격·재료 상수 영향 평가
- 모델 고도화: 능동근·점탄성 고려
- 디지털 트윈 확장: 환자 맞춤형 적용



Thank You
