In Vivo Subject-Specific Estimation of Cervical Spine Disc Material Properties

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Introduction

Background

- Biomechanical cadaver testing has shown cervical arthrodesis leads to increased motion and stress in discs adjacent to one-level arthrodesis [1].
- However, *in vivo* data indicates adjacent segment motion does not necessarily increase after arthrodesis [2], therefore, it is unclear if *in vivo* disc stress increases after arthrodesis.
- In conventional FE modeling, disc properties are assigned, however disc properties vary with age and degeneration
- Non-invasive assessment of disc health, such as inverse material characterization (Figure 1), could help to identify patients at risk for developing adjacent segment disease.

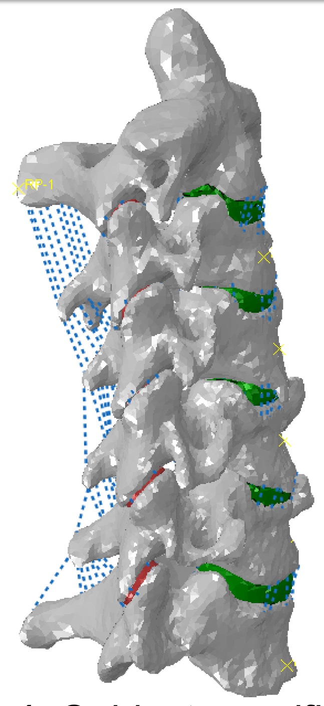

Figure 1: *Subject-specific cervical spine model used in inverse material characterization. Inverse material characterization uses morphology and kinematics to estimate tissue properties.*

Aim

- To **non-invasively estimate the subject-specific material properties for the annulus of each disc within the cervical spine** in a patient scheduled to undergo cervical fusion and an age matched control.

Methods

Data Collection

- CT scans of the cervical spine (0.3x0.3x1.0mm) were acquired and bone tissue was segmented to create 3D bone geometries.
- Biplane radiography [2] measured *in vivo* kinematics of the cervical spine.

Data Processing

- Subject-specific 3D FEA models were created from the CT scan (Table 1).
- Inverse material characterization approach was used to evaluate disc stiffness (Figure 2).
  - Material properties were estimated using gradient-based optimization which minimized the difference between measured kinematics and that calculated by the model in three frames of data (small flexion, large flexion, extension).
  - Points on the anterior vertebral body and posterior spinous process of C2 through C7 were established and used in error calculations.

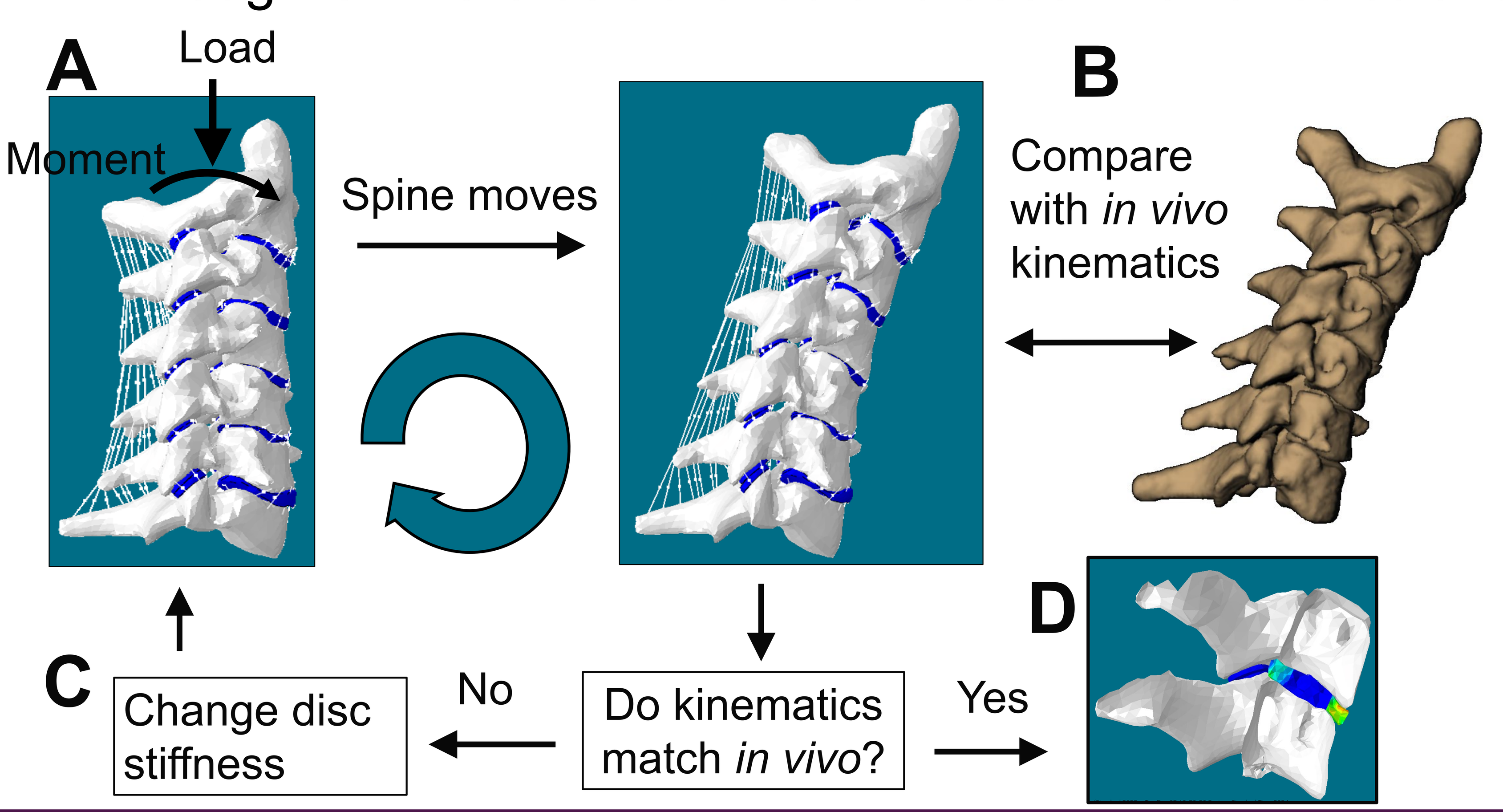

Figure 2: Inverse material characterization modeling approach. ***(A)*** *Cervical spine model is loaded, causing the model to move.* ***(B)*** *These kinematics are compared with the captured in vivo kinematics.* ***(C)*** *If they do not match, a change in the disc stiffness occurs, then the process repeats. If the kinematics do match,* ***(D)*** *disc material properties are extracted from the model.*

Results

Table 1. Modeling geometries and properties [3].

Tissue	Geometry	Material Properties
Disc, Nucleus	Spacing between vertebrae; 40-50% of volume of disc	Linear elastic; E = 2MPa, ν = 0.49
Disc, Annulus	Spacing between vertebrae; collagen fibers included	Neo-Hookean solid: $U = C_{10}(\bar{I}_1 - 3) + \frac{1}{D_1}(J-1)^2$
Facets	Derived space between adjacent facets	Linear elastic; E = 10.4MPa, ν = 0.4
Ligaments	1-D connector elements	Tension-only nonlinear connectors [1]

- The optimization process was performed for a female subject, 47 years, scheduled to undergo a C5-C6 anterior cervical discectomy and fusion surgery along with an age/sex matched control.
- Estimated material properties indicated diseased C56 disc stiffness was approximately 1/3rd that of the reference C23 disc, while the stiffness of all discs in the healthy control were within 10% of the reference disc (Table 2).
- Average error in kinematics per vertebra ranged from 0.6mm to 7.5mm in the patient while the error ranged from 0.7mm to 1.8mm in the control (Table 2).

Table 2. Inverse material estimation results.

	Final Objective Function (mm)	C_{10} Estimate (MPa)					Cumulative Error (mm)		
		C23	C34	C45	C56	C67	Small Flex	Large Flex	Extension
Patient	8.2	1.10	0.74	0.88	0.32	0.78	3.4	4.0	4.5
Control	16.2	1.10	1.08	0.98	1.02	1.03	4.2	5.5	10.7

Discussion

- The model indicated a much lower stiffness constant at the diseased C56 disc compared to all other discs in subjects, suggesting these modeling methods could be used to estimate subject-specific material properties of the intervertebral discs non-invasively.
- Kinematic errors of 1°-2° per motion segment suggest some modifications in the modeling process may be necessary to produce more accurate results.
- Future work includes expanding the cohort to assess generalizability of results and to assess the effects of arthrodesis on adjacent segment disc stress.

Clinical Significance

- **This computational technique has the potential to non-invasively assess disc health as well as enhance the accuracy and subject-specificity of spine computational models.**

References and Acknowledgements

[1] Y. H. Kim et al. (2018), J. Mech. Sci. Technol; [2] LeVasseur CM et al. (2022), Ann Biomed Eng; [3] S.-H. Lee et al. (2011), Spine.

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