CT-Based Finite Element Modeling of the Lumbar Spine for Evaluation of LLIF Construct Biomechanics

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INTRODUCTION: Spinal fusion is a widely used procedure for the treatment of lower back pain and various spinal pathologies, such as degenerative disc disease, deformity, and neoplasia. Lateral lumbar interbody fusion (LLIF) is a minimally invasive spinal fusion technique that accesses the intervertebral disc space through a lateral approach and can be extended to multilevel fusions. However, fusing spinal segments can alter load distribution and lead to adjacent segment pathology. Cadaveric studies have been used to quantify these biomechanical changes, but they are limited by high costs, challenges with preservation, and sample variability. Finite element analysis (FEA) offers a computational alternative that allows realistic simulation of lumbar biomechanics and provides a validated framework to study spinal motion and optimize implant design. The objective of this study was to develop and validate a finite element model of the lumbar segment that integrates hyperelastic soft-tissue behavior, cage insertion, and pedicle screw fixation, enabling analysis of intersegmental motion and implant influence across clinically relevant postures.

METHODS: The finite element model was generated from a CT scan of the lumbar portion (L1-5) of a vertebral column. Material properties were assigned to the vertebral segment by dividing CT grayscale values into 35 bins to represent spatial variations in bone stiffness. The cartilaginous endplate was removed in the model to mimic LLIF surgery, a technique that allows bone to fuse directly and better connect the vertebra to the cage. A 26 mm anterior-posterior cage was selected to distribute axial load over a larger surface area and reduce localized endplate stress. Pedicle screw fit analysis confirmed that screws measuring 5 mm in diameter and 50 mm in length could be safely positioned within L1-L5 vertebrae without crossing cortical boundaries. Similar to image-guided planning for real-life screw placement, a transparent view was used in the pedicle fit analysis to determine safe insertion margins. The finite element model was then validated against eight human cadaveric L1-L5 specimens across various loading conditions, and its performance was compared with other finite element models.

RESULTS: The standalone LLIF model preserved range of motion (ROM) values most similar to the healthy spine model, whereas constructs with greater supplemental fixation demonstrated reduced motion and greater rigidity. During flexion-extension, the standalone model had the lowest percentage reduction in ROM (56.6% at L1–L2, 57.7% at L2–L3, and 54.2% at L3–L4). Under axial and torsional loading, the LLIF standalone model maintained ROM closest to the intact spine, especially at L4-L5 where there was only a 1.01% reduction of motion. For lateral bending, the LLIF with bilateral rods construct preserved the most motion at L4–L5 (73.0%) but exhibited greater rigidity at upper segments compared with the standalone construct.

DISCUSSION: CT-based material assignment of the lumbar spine produced a physiologically realistic biomechanical response, with the finite element model showing agreement with experimental data. Standalone LLIF preserved the most motion, while bilateral fixation increased total lumbar stiffness and fusion stability. Motion analysis showed that even non-fused, neighboring segments demonstrated reduced flexibility. Clinically, standalone LLIF may be most suitable for single-level disease or cases where motion preservation is preferred, whereas bilateral fixation may be ideal for enhanced stability. The CT-based model demonstrated significant correlation with experimental results, confirming grayscale mapping as an accurate method for assigning material properties across vertebral segments.

SIGNIFICANCE/CLINICAL RELEVANCE: FEA provides a reproducible, cost-effective alternative to cadaveric testing for studying lumbar spine biomechanics. Validated finite element models can be used for preclinical evaluation of implants and fusion techniques under realistic physiological conditions, allowing for enhancements in implant design and surgical strategies that will ultimately improve patient outcomes.