Interpatient variability and validation of simplified L4-L5 Finite Element Model

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Summary

This study analyses the effects of interpatient geometric variability on the Range of Motion (ROM) of the lumbar spine following stepwise resection of ligaments and vertebral arches. Patient specific FE models are built using simplified linear elastic material models for all elements. The results are compared to the experimental data by Heuer [2], highlighting both the potential and the limitations of this approach.

Introduction

Assessing spinal stability under ligament and vertebral arch resections is crucial for understanding clinical scenarios such as decompression surgeries. Published FE models have focused on calibrating one generic model using different material models and varying the disc shape. This work focuses on keeping these parameters constant and linear and assessing the interpatient variability.

Methods

Six patient-specific FE models (three female, mean age 42.7 years) were generated from MDCT images. Vertebral bodies (L4–L5) were automatically segmented, meshed, and intensity mapped into 50 heterogeneous linear elastic properties [1]. The intervertebral disc was modeled by extruding each endplate, maintaining a constant nucleus pulposus (NP) volume ratio of 46±1% of the total disc. A linear-elastic annulus fibrosus (AF) was represented by solid elements, while the NP was modeled as a fluid-filled cavity. The seven major spinal ligaments were included as truss elements with linear elastic properties. Following Heuer et al. [2], the ligaments and vertebral arch were progressively resected, and the simulated ROM was compared to the experimental measurements. Interpatient variability was also examined across all simulation steps.

Results and Discussion

Figure 1 shows the simulated ROM (mean, min., max.) alongside Heuer's [2] experimental range (gray area). In flexion, the simulations initially underestimate the experimental ROM, a finding consistent with other published FE studies. As resection progressed, however, the simulated ROM moved within the experimental data, suggesting that the current ligament definitions might be overly stiff. Similar trends were observed in extension.

Axial Rotation on the other hand lies well within the range of the experimental results from the intact phase up until the reduction step without VA. In this step the vertebral arches are cut by removing the posterior element. The notable higher ROM observed after this resection in the simulation results suggests that the AF does not resist the torsion sufficiently. This is to be expected in a linear elastic model, which simplifies/neglects the collagen fiber reinforcement. Lateral bending shows a constant trend in both the simulation and experiment and is uninfluenced by the reduction steps. The reduced ROM in the simulation can therefore be accounted to the modeling of the AF.

Interpatient variability has an increased impact on all ranges of motions based on the increased deviations of the means seen with progressing resections. This may be attributed to the changes in disc height between the patients and constant material properties and number of the ligaments across the patients.

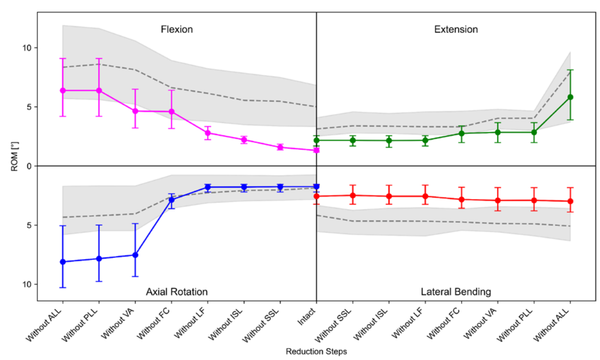

Figure 1: ROM comparison for the reduction steps in four different ROMs.

Conclusions

Overall, the trend of the simulated ROM closely follows the experimental data, supporting the validity of the modeling approach. The results underscore the limitations of a purely linear-elastic model for ligaments, particularly in flexion, and for the AF in axial rotation and lateral bending. The simplified model may assist in designing new implants for the L4-L5 level.

References

[1] Strack, D., et al. (2024), Reduction of material groups for vertebral bone finite element simulation: cross comparison of grouping methods. *CMBBE*: in press.

[2] Heuer, F., et. al (2007), Stepwise reduction of functional spinal structures increase range of motion and change lordosis angle. *J Biomech*.;**40(2)**:271-80.