Development, Calibration & Validation of a Lumbosacral Spine FE Model for Simulating Fusion Constructs.

PMRF Annual Review

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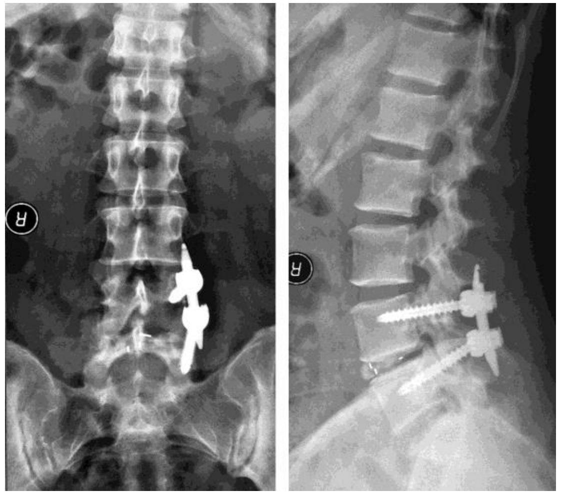
Contents

Introduction

- Lumbar spinal instability is addressed here.
- Lumbar spondylolisthesis results in back pain, reduced mobility and poor quality of life.
- Surgical interbody fusion of degenerative levels is an effective treatment option to
  - Stabilize the painful motion segment
  - Decompression of the neural elements
  - Restore Lordosis & correct deformity.

Objective

- To develop a lumbosacral Finite Element morphological base mesh model for simulations.
- Validation and benchmarking of the developed FE model for physiological loading using in-vitro experimental corridor data from the literature.
- Understand kinematic changes caused due to instrumented fusion constructs in the spine using computer simulations
- Perform a sensitivity analysis to evaluate the role of morphological parameters on kinematic output parameters of the vertebral column
- Analyze unilateral vertebral fusion technique for different spine morphologies and compare its outcomes with bilateral fusion technique using simulations.

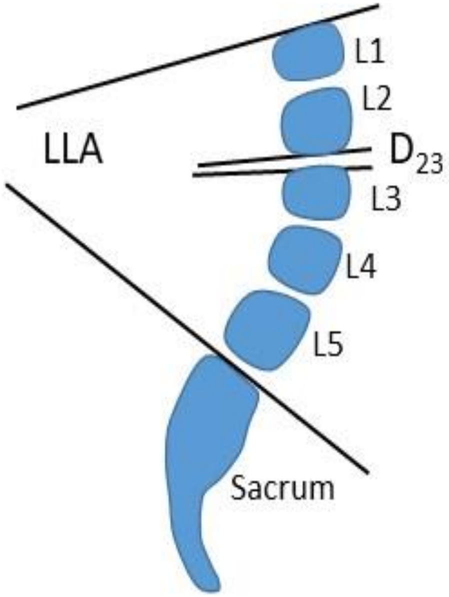


Unilateral Fusion:Posterior &Lateral Views

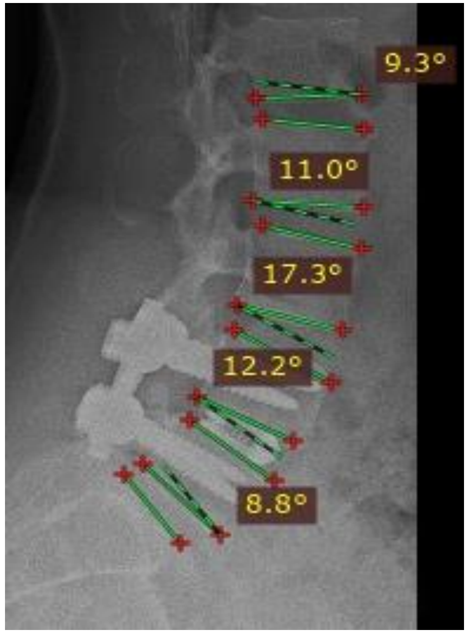
Bilateral Fusion:Posterior &Lateral Views
(Shen et al.2014)

Methodology:Clinical Study

- A radiographic study was undertaken to find the clinical effects of Lumbar Inter body fusion on L4-L5 Patients at CMC Vellore
- 69 Patients within a 2-year follow-up duration included in the study
- Hypothesized that the change in intervertebral disc angle significantly alters the biomechanics of the adjacent segments superiorly and inferiorly
- IVD* angles measured from L1-L2 to L5-S1 for flexion-extension & neutral views pre & postoperatively.



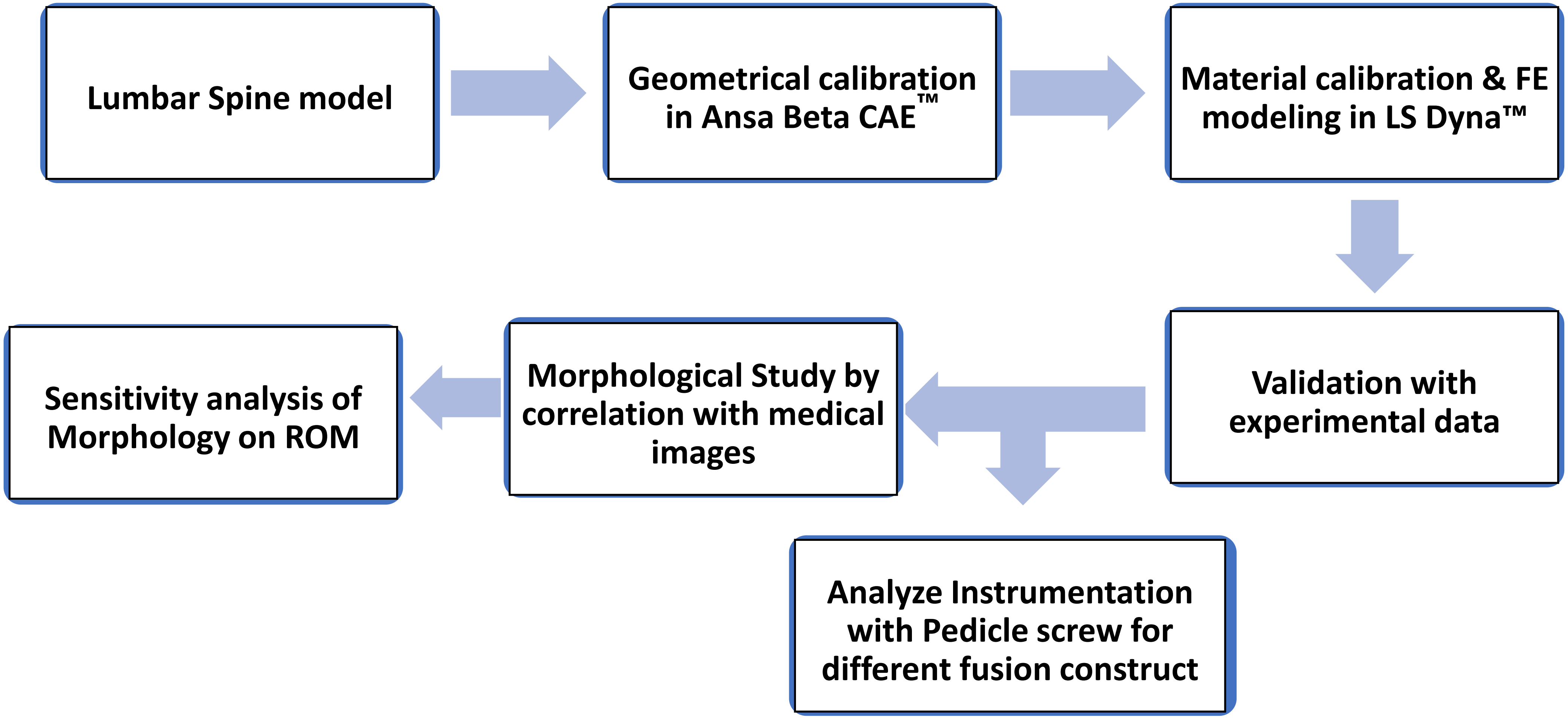
Schematic of lumbar spine showing disk angles(D), and lumbar lordosis angle (LLA)



A radiographic image with disc measurements

**IVD-intervertebral disk*

Methodology



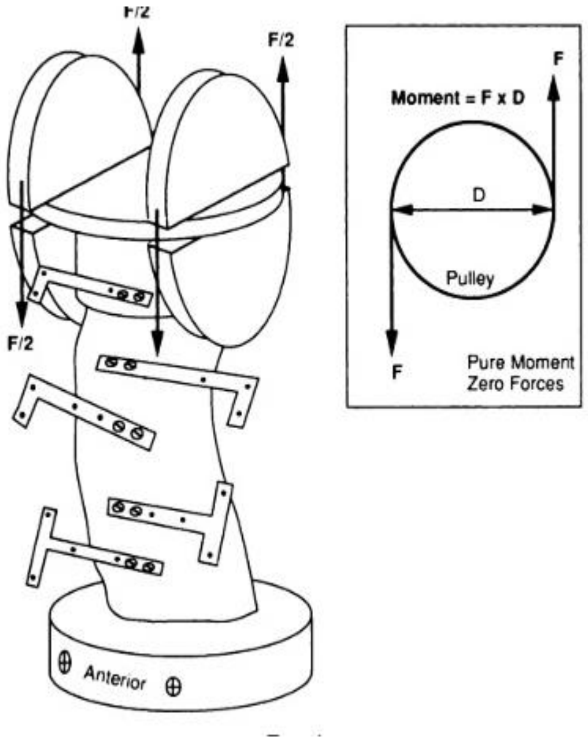
Model Calibration

- A single FSU*(L1-L2) was initially simulated with physiological conditions for calibration purpose.
- The kinematic output parameters were monitored, and the mesh model was calibrated in terms of the material properties, facet contact orientations and intervertebral disk angles(IVD).
- The IVD angles were altered in such a way that the anterior and posterior disc height lied in the anthropometric corridor values.
- Direct morphing tool in ANSA BETA CAE™ employed.
- FSU* was simulated for pure moment & compressive loading and the output were cross checked with *in vitro* results .
- After repeated rectification of errors and fine-tuning the results came in the experimental corridor limits.

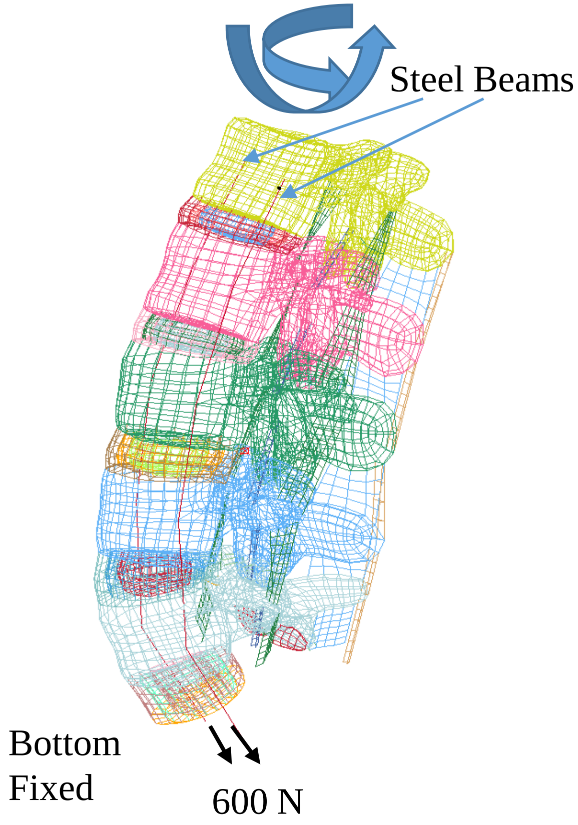
**FSU-functional spine unit*

Loading and Boundary condition

- The bottom end plate of L5-S1 was fixed in all DOF
- The top end plate of L1 was applied a compressive load or moment load through a rigid plate.
- The Lumbosacral model was applied with a follower load using CONSTRAINED_BEAM_IN_SOLID keyword in LS Dyna.
- Simple moment(10 Nm), compressive(300 N,1000 N and 1200 N) and combined(7.5 Nm+1200 N) physiological loads applied.
- Static explicit nonlinear simulation solved in LS Dyna™



Experimental Setup (Panjabi et al.1992)



Results: Hypothesis test

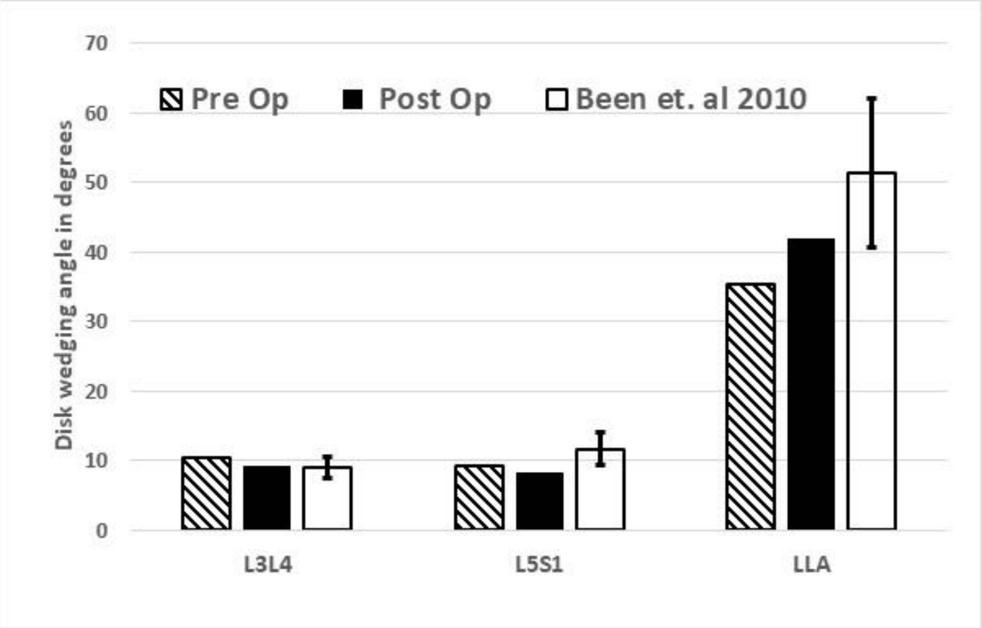
- A paired *t*-test was done on lordosis neutral angles (top plate of L1 to top plate of S1) of the specimens, both preoperatively and postoperatively.
- The hypothesis tested here is whether a process alteration occurred in the post-operative neutral angle measurements distribution compared to the pre-operative of the same patients.
- The *p*-value computed was > 0.05, which means that the null hypothesis is rejected.
- The *t*-test value for combined ROM for the superior segment and inferior segments stood at 0.478(>0.05) and 0.22(>0.05), respectively, inferring that the disk angle ROM computations in both levels were significantly different.

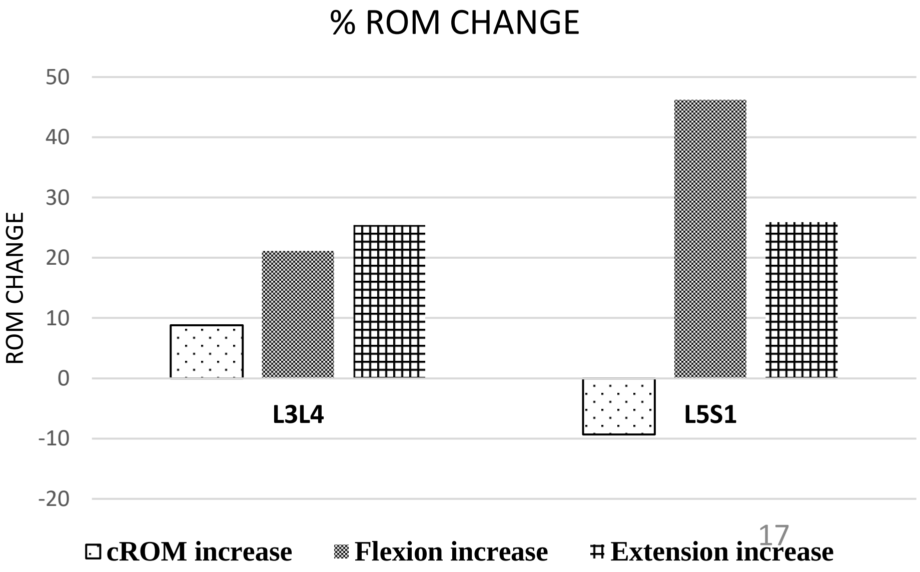
Results-Range of motions

- Averages of neutral disk angles were computed as shown in Figure.
- Reinstating Lumbar Lordosis angle to normal range.
- The flexional compensational increase was high at the inferior segment (L5-S1) by 46% and the extensional compensational increase was high at the superior segment (L3-L4) by 21%.
- Corresponding combined ROM % change in L3L4 is 8.77 % & 7.5, respectively
- The neighboring segments need to work more toward the extremes of their functional ranges of motion
- This result correlated well with the findings on adjacent segment degeneration clinically(Quinnell and Stockdale, 1981)

ROM-Range of motion

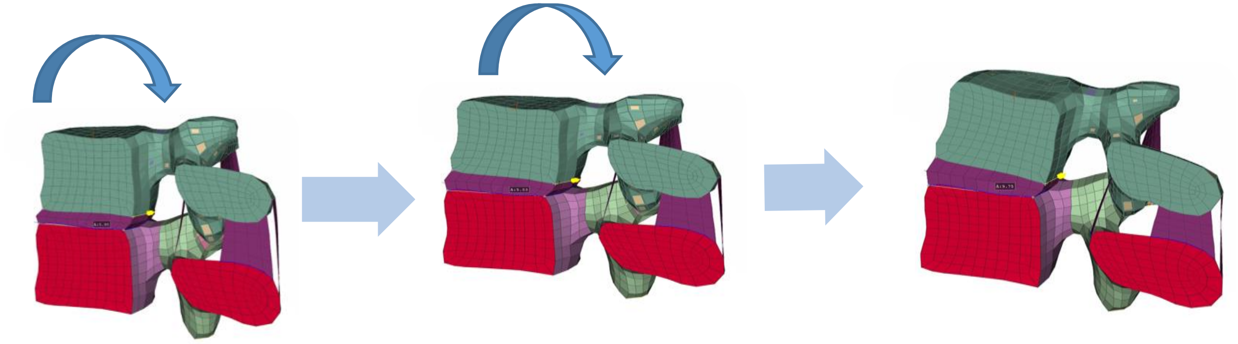
*Submitted to European Spine Journal," **A pilot study on change in Range of motion of adjacent segments following Single Level Lumbar Fusion"***



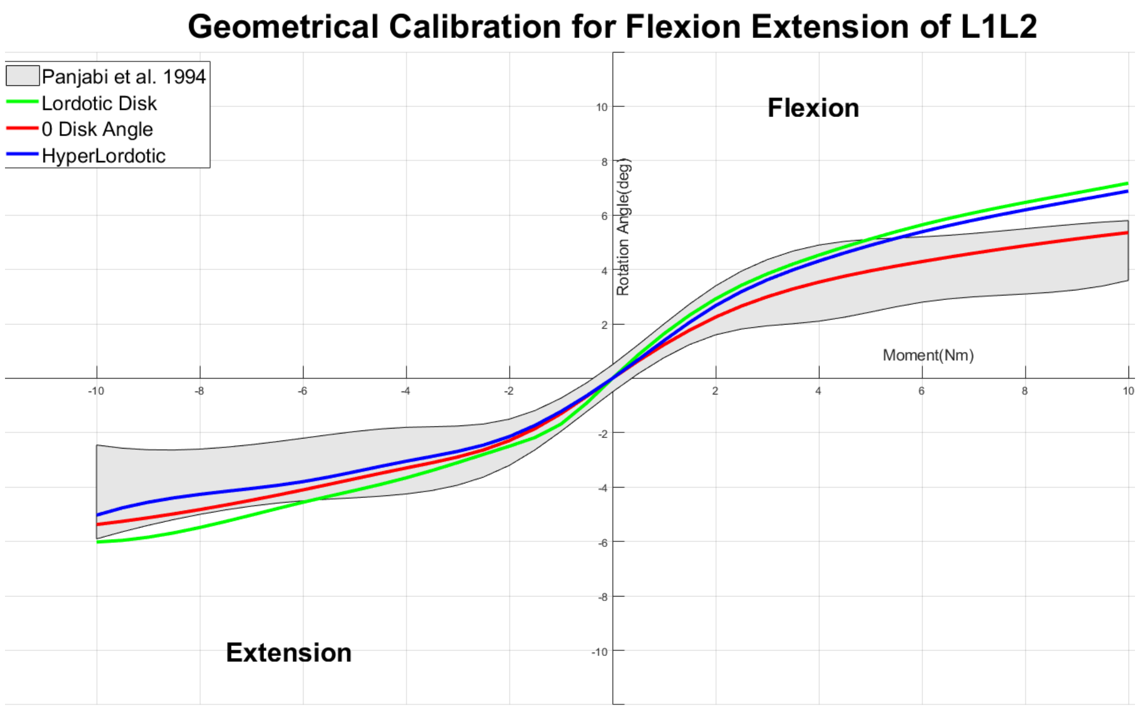


Results-Geometric calibration by direct morphing

- Sagittal rotation performed
- Hard tissue-rigid transformation
- Soft tissue-non rigid transformations



Straight(Disk angle =0^0) Lordotic(Disk angle=5.83^0) Hyper-Lordotic(Disk angle=9.75^0)



Results–Anatomical Parameters

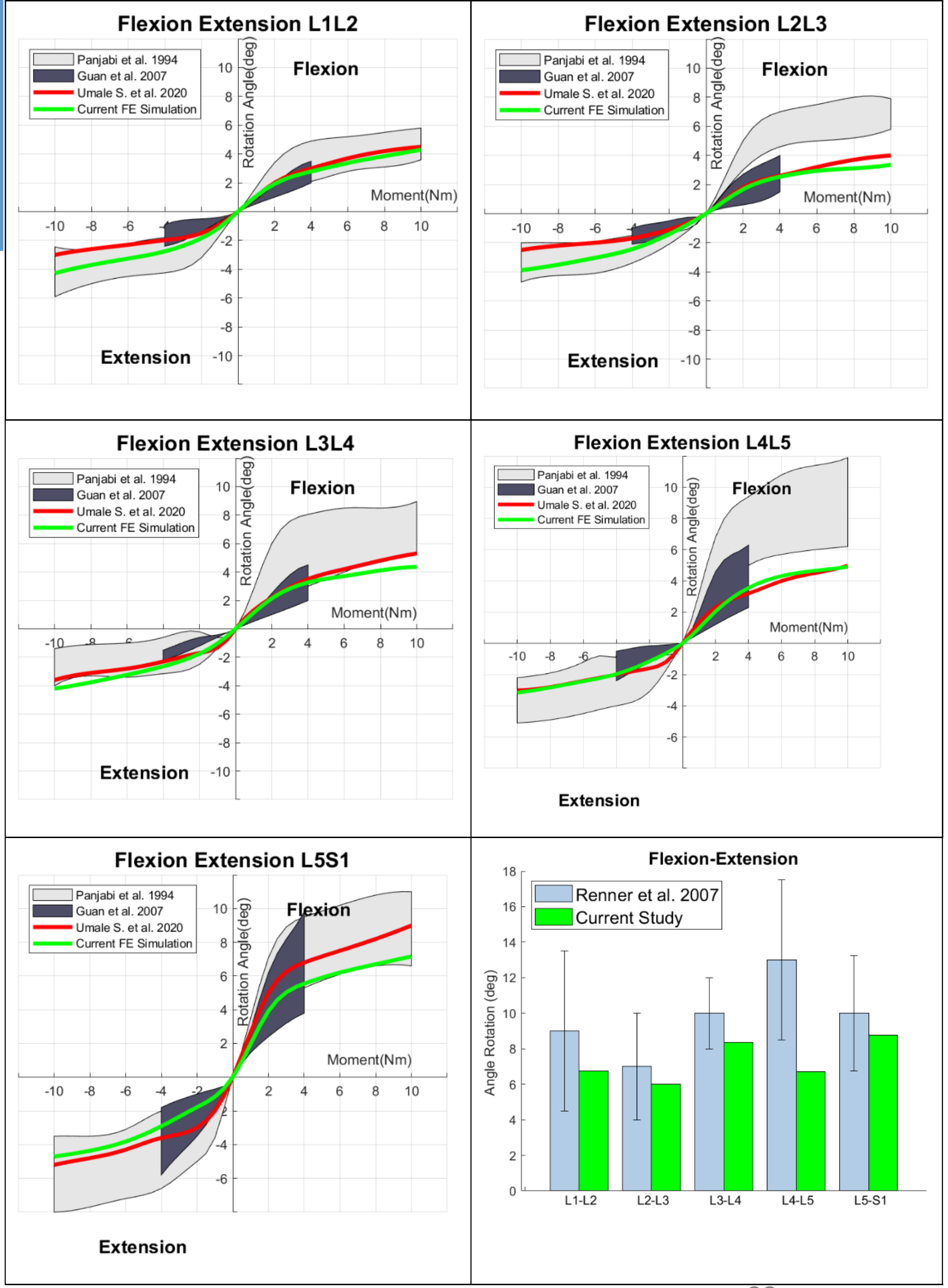
- The developed model was validated extensively for flexion, extension, bending & axial rotation modes.
- The facet joint forces are also compared to check whether the engagement between the superior and inferior facet joints are happening properly.
- The disc pressures and disc compressional displacements are also monitored to ensure the functionality of the discs.
- The procedure was explicit, and the simulation ran for 12 S. The simulation time was based on in vitro experiments.

Anatomical parameters	**Current FE Model**	**Reference Values** (Umale et al., 2020)
Elements	27479	144,018
Node	19339	109,096
Vertebral height		(Scoles et al., 1988)
L1	27	25.7–34.5
L3	29.5	28.3–35.9
L5	28.43	29.7–39.4
Antero Posterior Diameter		(Scoles et al., 1988)
L1	27.4427	25.7–34.5
L3	29.75	28.3–35.9
L5	31.1699	29.7–39.4
Transverse diameter		(Scoles et al., 1988)
L1	38	37.5–49.5
L3	41.18	39.7–54.9
L5	43.2	44.7–64.3
Disc height(mm)		(Gilad and Nissan, 1984)
L1-L2	8.67	6±1.4
L2-L3	10.19	8.9±1.6
L3-L4	10.57	10.3±1.8
L4-L5	10.47	12 ±1.8
L5-S1	14.45	14.1± 2.2

Flexion Extension- Non-Linear Curves

- The initial large displacement was observed in all the profiles suggestive of the contribution of the geometric & material nonlinearity.
- The flexion ranges were within the experimental corridor values of Guan et al.[20]
- The peak extension facet contact force was recorded at 110 N

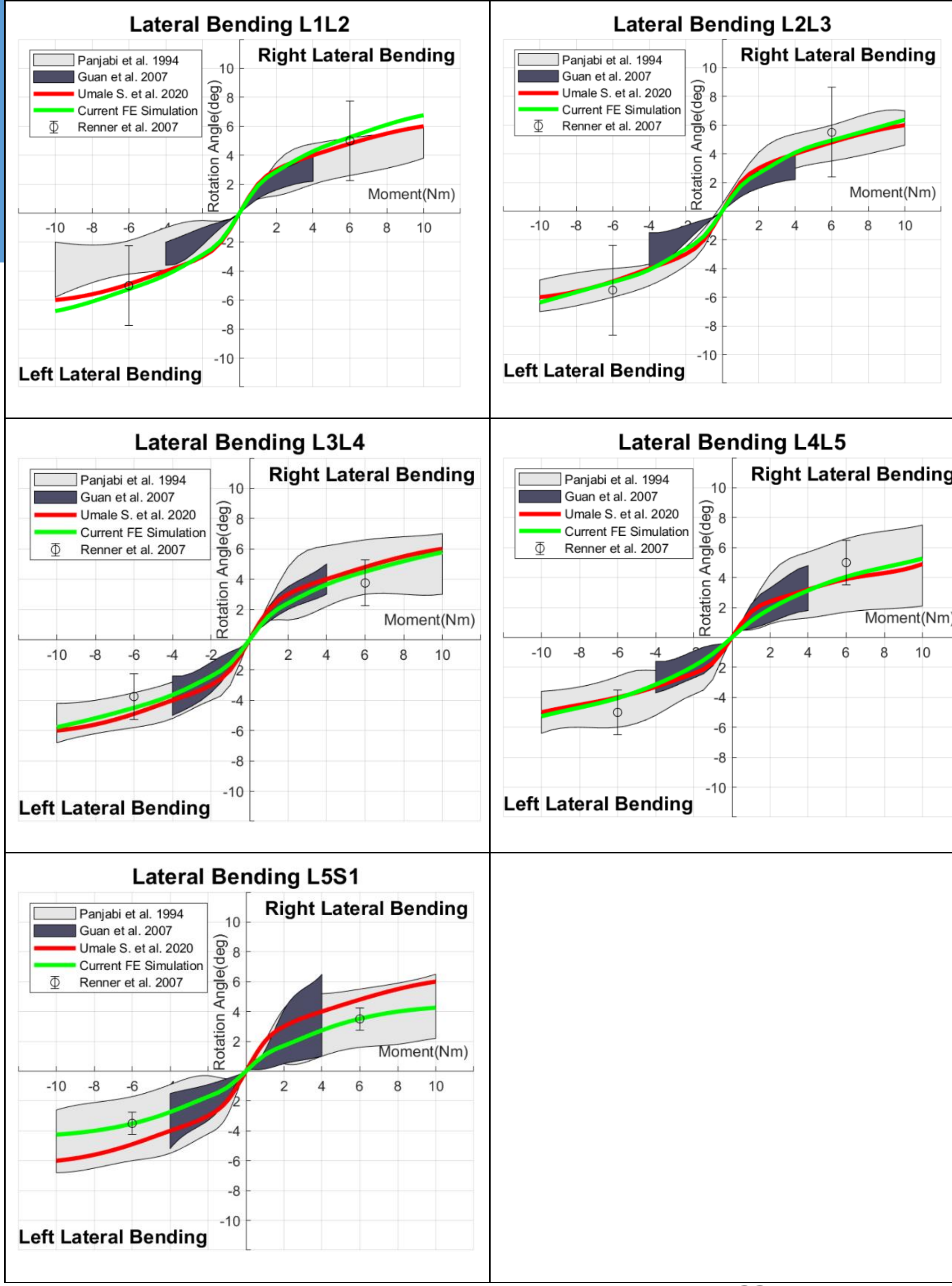
Maximum Ranges	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Flexion	4.07	3.3	4	3.99	5.3
Extension	4.32	4.01	4.25	3.18	4.7



Left-Right bending

Maximum Ranges	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Bending	6.840	6.510	5.980	5.570	4.00

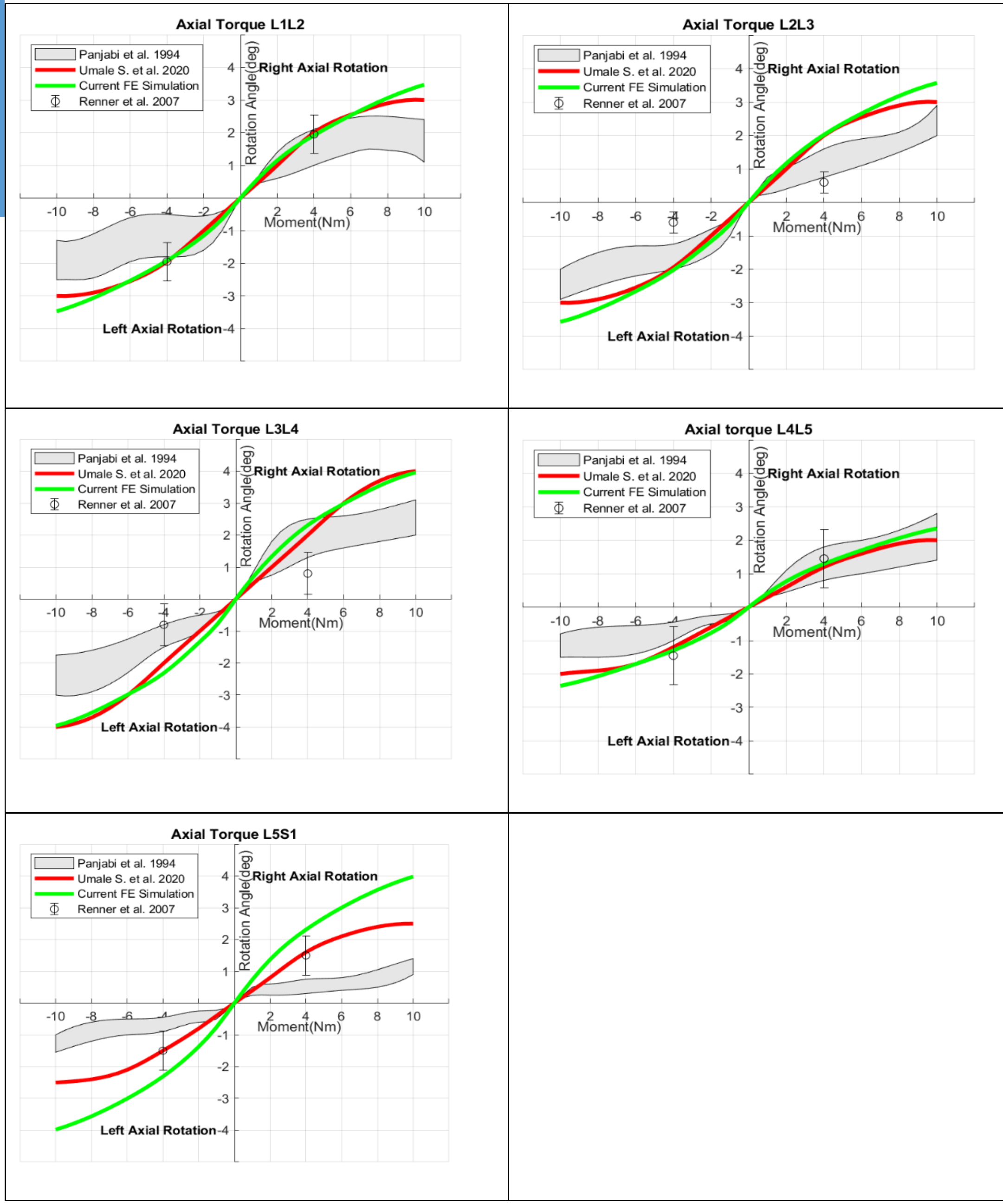
- The bending profiles showed closer agreements with previous simulation results(Umale et al., 2020)
- The bending motion had a peak contact force of 80 N at L4-L5 facet contact.



Axial rotation

Maximum Ranges	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Axial torque	2.120	2.240	2.420	2.470	4.310

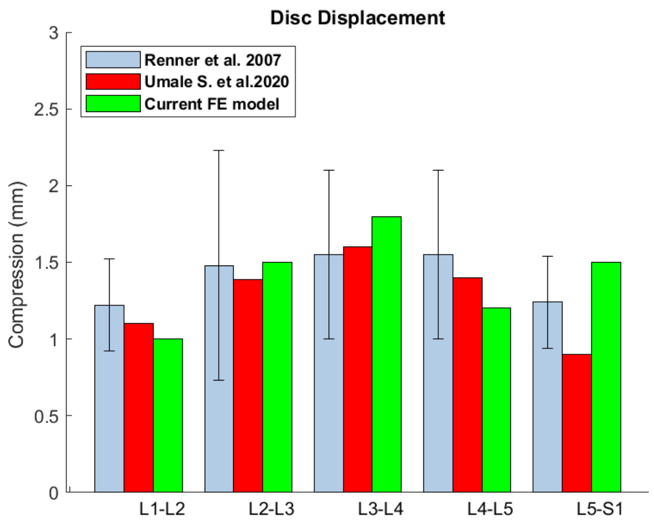
- The comparison of the motion with Renner et al (Renner et al., 2007) at 4 Nm moment rendered L1-L2 & L4-L5 to lie in the range, and L5-S1 rotation was slightly over-predicted by 10%.
- The peak facet force of 140 N was found at the engagement of inferior & superior contact of L1&L2
- Axial Rotation had the lowest ranges as it was limited by facet joints.
- The lumbar Spine is stiffer in the axial direction(Umale et al.,2021), so the experimental results show a lesser range of motion for the same.

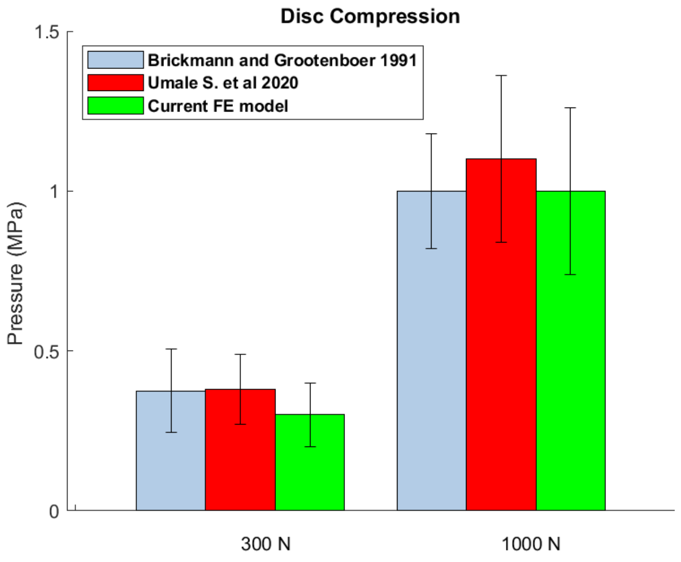


Compression Results

- The disc displacement for follower pure compression load of 1200 N shown

	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Disc displacement	**1**	**1.5**	**1.8**	**1.2**	**1.5**
Renner *et al.*, 2007	**1.2 ±0.4**	**1.5±0.8**	**1.5± 0.5**	**1.5± 0.5**	**1.3±0.5**





- The average disc pressure for the FE model lumbar spine disc segments for 300 N and 1000 N was 0.3 MPa and 1 MPa, compared to 0.38 ± 0.11 MPa and 1.02 ± 0.26 MPa, (Brinckmann & Grootenboer, 1991)
- The peak facet contact force in this loading was found to be 60 N.

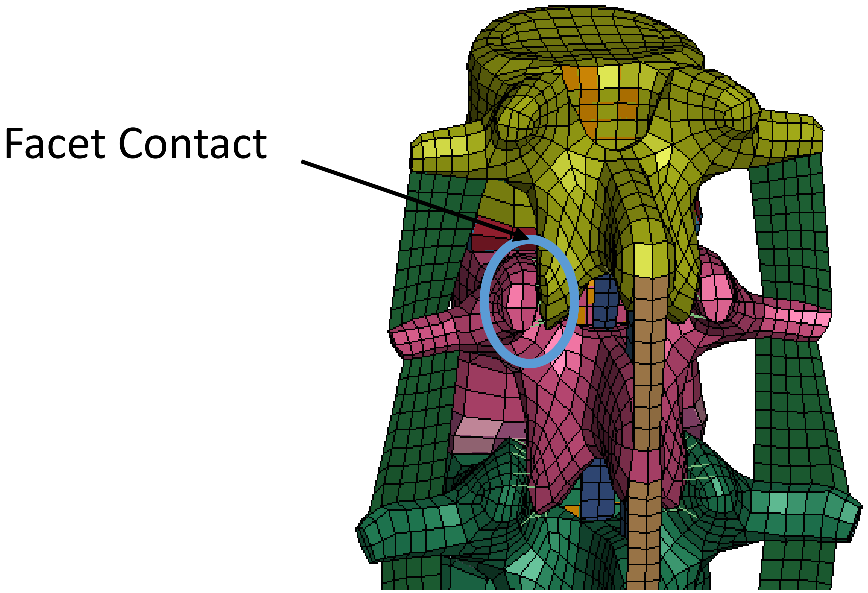
Facet Contact Force

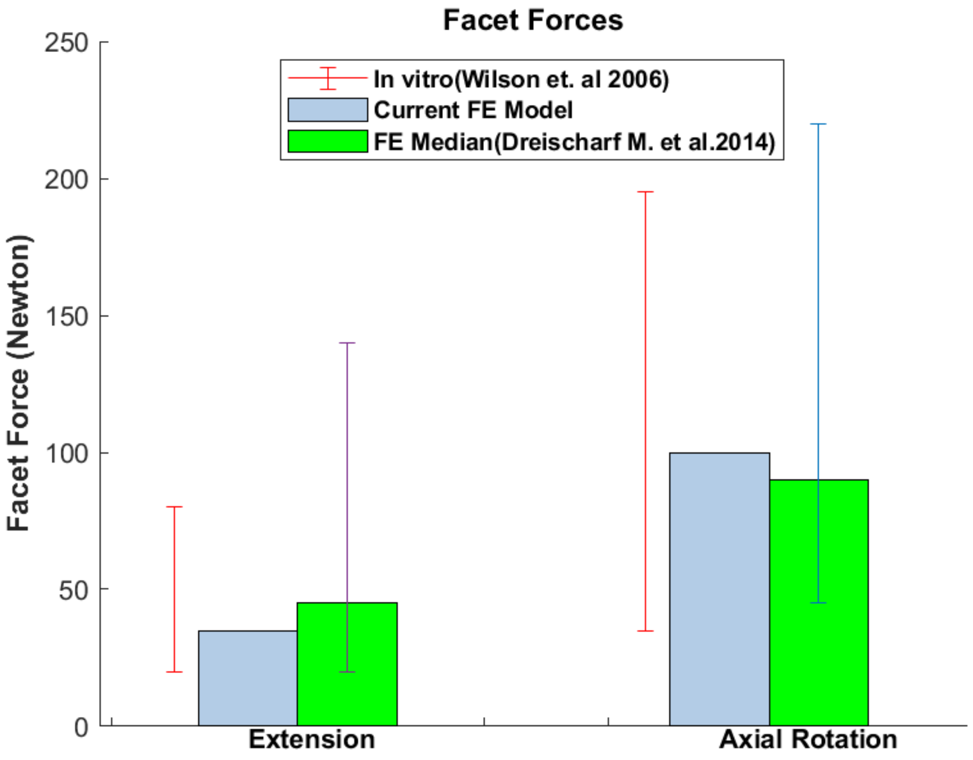
Facet contact forces (N)	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
Axial rotation	160	85	120	45	105
Extension	15	45	45	80	110

- The median of contact forces were compared with experimental and numerical values and were found to lie within

- As expected, the facet forces(median) in axial rotation were more than (higher than 2 times) that of the extensional force.

- Both these are expected to increase post-surgical fusion and hence significant parameters.

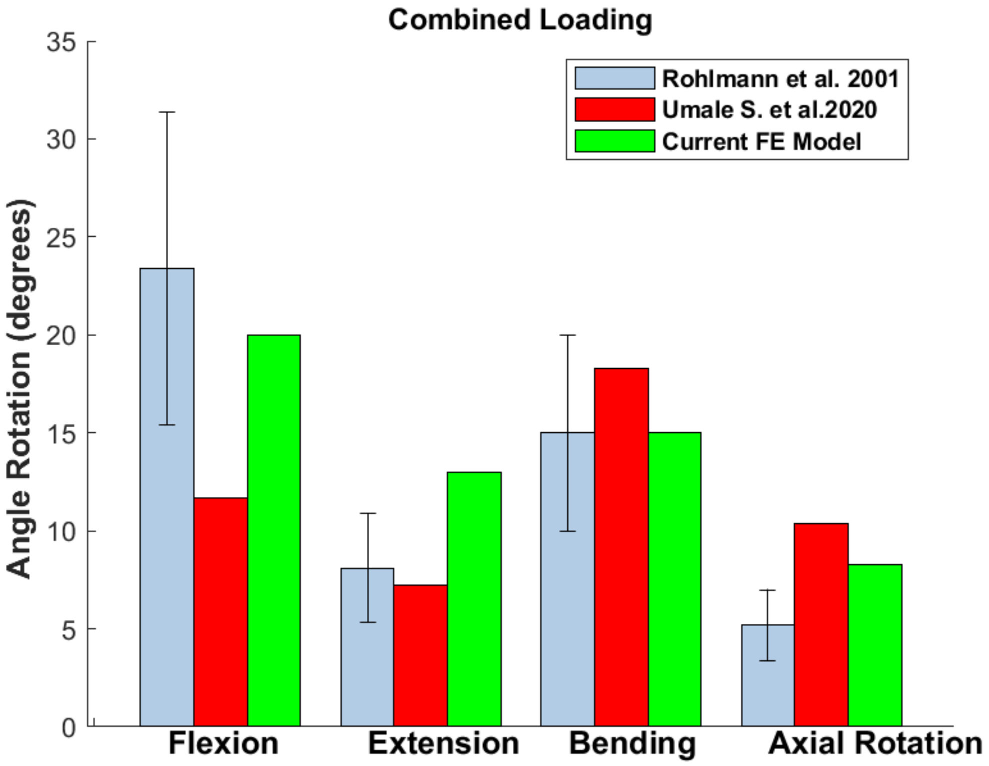




Combined Loading

- In combined loading (280 N follower load and 7.5 Nm moment), the total range of motion of the L1-L5 spine is shown.
- The results were slightly over predicted for extension and axial rotation as shown
- The orientation and contact model differences between the Facet joints in the experimental & FE models were responsible for this variation

Total Range of motion(degrees)	Flexion	Extension	Bending	Axial Rotation
Current Simulation	**20**	**13**	**15**	**8.3**
Rohlmann et al. 2001	23.4 ± 8	8.1 ± 2.8	15 ± 5	5.2 ± 1.8



Conclusion

- Clinical study on ROM* was done to quantify adjacent segment degeneration
- The work has developed a Lumbosacral FE model utilizing the potential of direct morphing features (Ansa Preprocessor^{TM})along with accurate hexahedral meshes.
- The mesh density of the model is 5 times lesser compared to recent work (Umale et al., 2020)
- This is since when a structured hexahedral element is used with an efficient meshing technique, it can yield better volume-efficient meshing & hence accurate results.
- This would ensure faster computation in explicit simulations as the model involves Geometric material and boundary condition nonlinearity.
- The facet contact forces are the main parameter to check in pedicle instrumentation as they can increase abnormally when one or more segments are fused(Zhang et al., 2018).
- The model thus developed is being developed further to be used for instrumentation study. The pedicle instrumentation in FE model is in progress.

*ROM-Range of motion

Visible outcome

- Secured **“Dr G.D Sundararaj Best Paper Award”** at CME on Spine Surgery organized by Dept. of Spine Surgery **Christian Medical College Vellore** for the paper titled “A pilot study on change in range of motion of adjacent segments following single level lumbar fusion using disk angle”.
- Manuscript titled “A pilot study on change in range of motion of adjacent segments following single-level lumbar fusion” submitted to *European Spine Journal*(Manuscript ID:ESJO-D-22-01838).
- Abstract accepted for “Nonlinear calibration of a lumbar motion unit using a morphing approach” submitted to 20th international conference on Experimental Mechanics, Portugal, July 2023.
- George, S. P., Saravana Kumar G & Venkatesh K., “Influence of Vertebral Disc angle on Interbody fusion Range of Motions”, Fourth International Conference on Biomechanics Clinical Spine and Orthopedics”, Indian Spinal Injury Centre, Delhi, India (2021).
- Abstract on “Study on change in Range of motion of adjacent segments following Single Level Lumbar Fusion using disk angle” submitted for Conference Spine week, 2023, Melbourne.
- Abstract on “Validation of a Novel Lumbar Functional Spine Unit” submitted to 18th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering,2023, France
- Abstract on “Sensitivity of a lumbar Motion unit disk angle to the range of motion” submitted to BETA CAE Systems India Open Meeting, 2023.

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