2nd WORKSHOP ON SCIENTIFIC COMPUTING IN HEALTH APPLICATIONS

6 a 8 de agosto de 2012

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MEDICINA ASSISTIDA POR COMPUTAÇÃO CIENTÍFICA
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http://macc.lncc.br/2nd_WSCHA2012/

A Comparative Study of Lumbar Spine Stabilization Devices

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Laboratório de Engenharia BioMecânica

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Surgery Department

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Mech. Engineering Department

LEBm - Laboratory of Biomechanical Engineering

University Hospital
Universidade Federal de Santa Catarina
Florianópolis – SC, Brasil

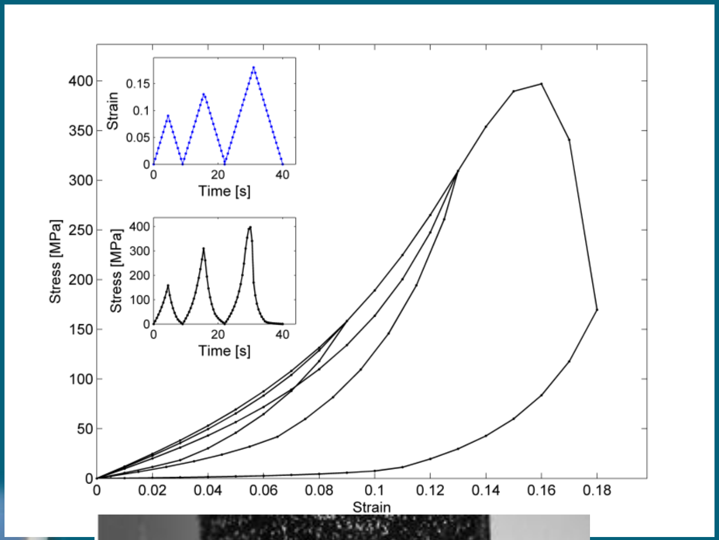
Laboratório de Engenharia BioMecânica

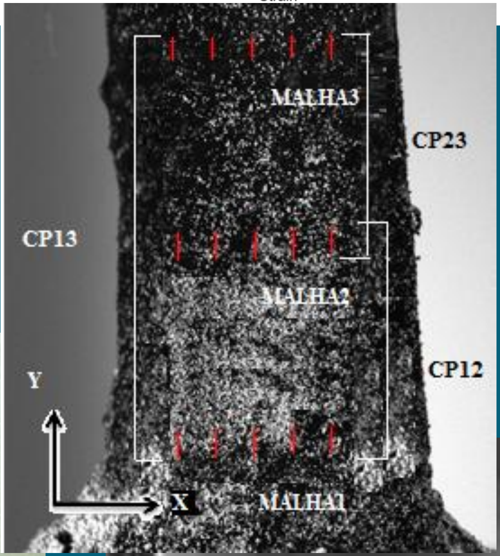
LEBm - permanent staff

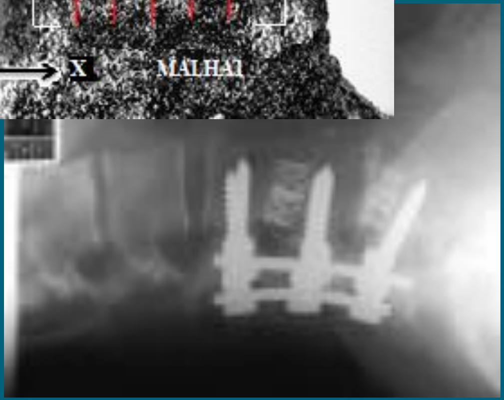
- Ari Digiacomo Ocampo Moré, Surgeon, Surgery Dep. (Director)
- Carlos Rodrigo de Mello Roesler, Mech. Eng. – Mech. Dep.
- Edison da Rosa, Mech. Eng. – Mech. Dep.
- Eduardo Alberto Fancello, Mech. Eng. – Mech. Dep.
- Gean Vitor Salmoria, Chem. Eng. – Mech. Dep.

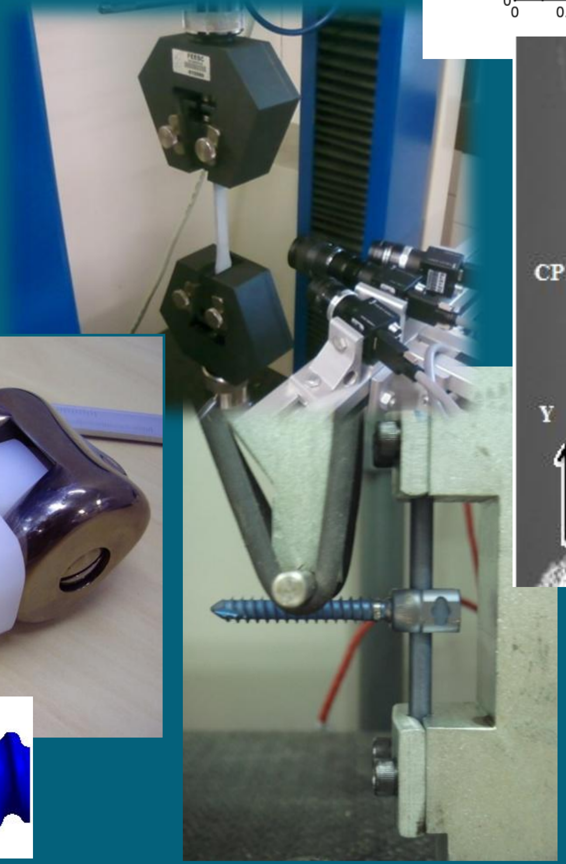
LEBm activities

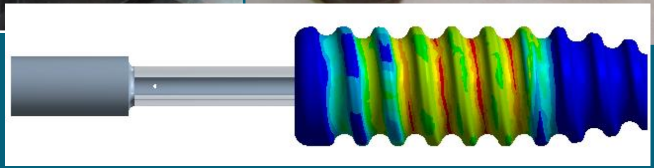
- Implant testing
- Orthopedic Biomechanics
  - Evaluation of orthopedic surgical techniques
  - Support for development of orthopedic implants
  - Constitutive Modeling











Content

Spine Biomechanics

Background

- The spine is a very complex structure:
  - flexibility for movement
  - support for weight bearing
  - protection of spinal cord and nerves
  - mobile column divided in 24 segments

Spine Biomechanics

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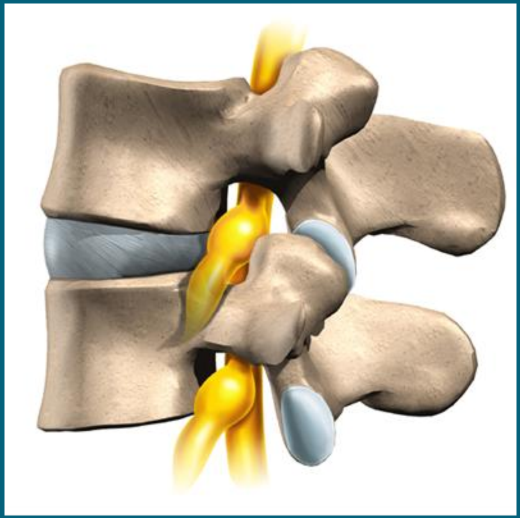
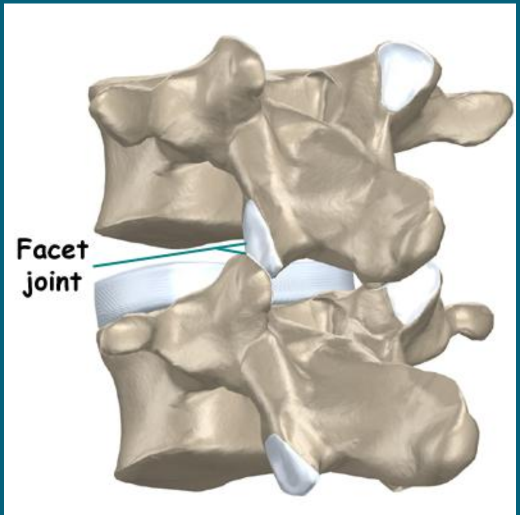
Background

- The spine is a very complex structure:
- The segment is the Spinal Functional Unit (FSU): the minor part capable of movement





- Each typical segment is composed of 2 vertebras articulated by a triarticular complex composed of 2 facet joints and the intervertebral disc

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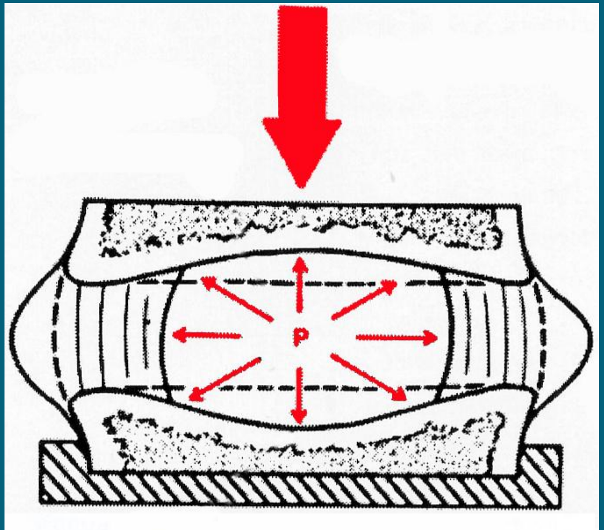
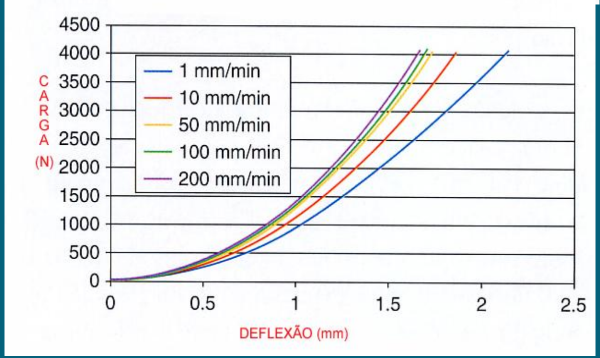
Background

- The spine is a very complex structure:
- The intervertebral disc is a unique kind of joint:
  - complete viscoelastic cushion
  - act as a shock absorber





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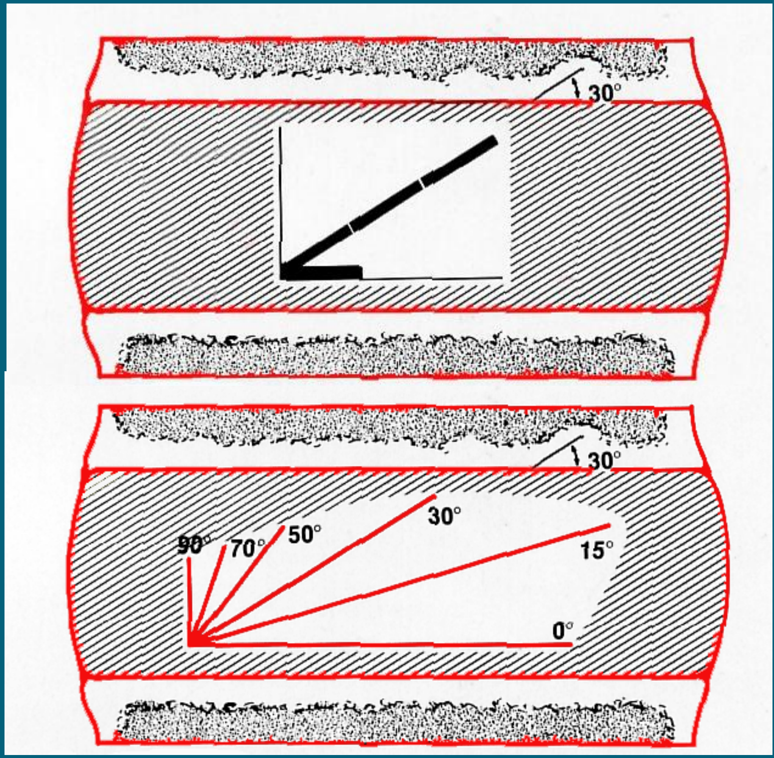
Background

- The spine is a very complex structure:

- The intervertebral disc is a unique kind of joint:
  - complete viscoelastic cushion
  - act as a shock absorber
  - high grade of anisotropy

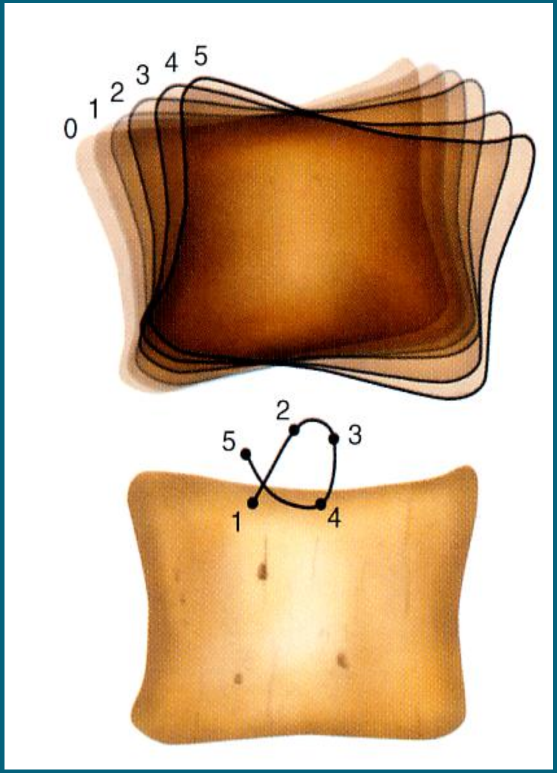


Spine Biomechanics

Background

- The spine is a very complex structure:

- The intervertebral disc is a unique kind of joint:
    - complete viscoelastic cushion
    - act as a shock absorber
    - high grade of anisotropy
    - allows limited movement
    - unconstrained center of rotation



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Background

- The spine is a very complex structure:

- Provides flexibility for movement, support for weight bearing and protection of the spinal cord and nerve roots.
- The dynamic and supportive properties of the normal spine are provided by 25 moveable vertebrae, over 100 elaborate joints, 24 intervertebral discs, more than 220 specialized ligaments, an intricate network of blood vessels and countless specialized nerve endings.

In this scenario, it is very difficult to anticipate the actual impact of any intervention

Spine Biomechanics

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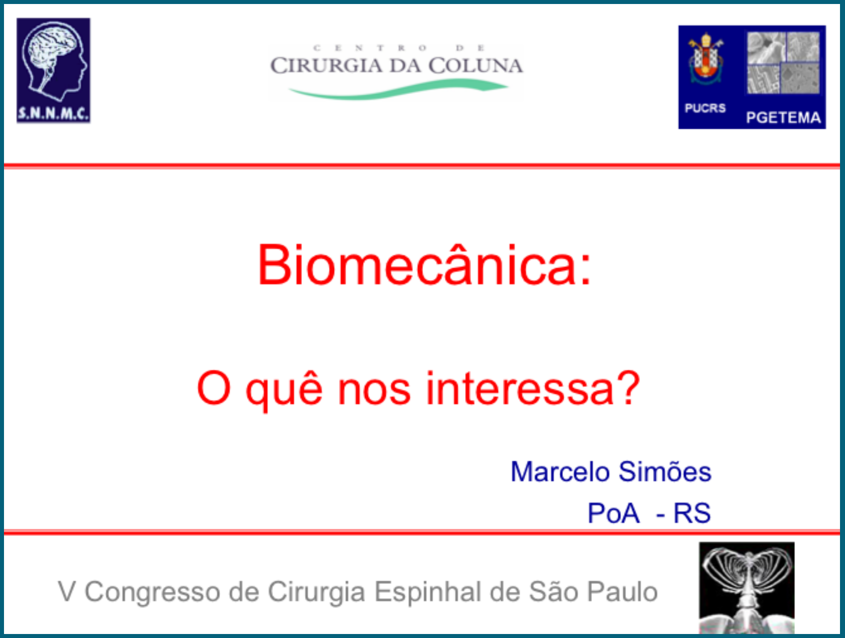
Background

- Most spine surgeons do not have any kind of training or even knowledge on biomechanics



What's the true importance of biomechanics on the practice of the spine surgeon?

'not so important'

Spine Biomechanics

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Background

- Traditional surgical interventions:
  - logic rationale
  - clinical experimentation
  - clinical results

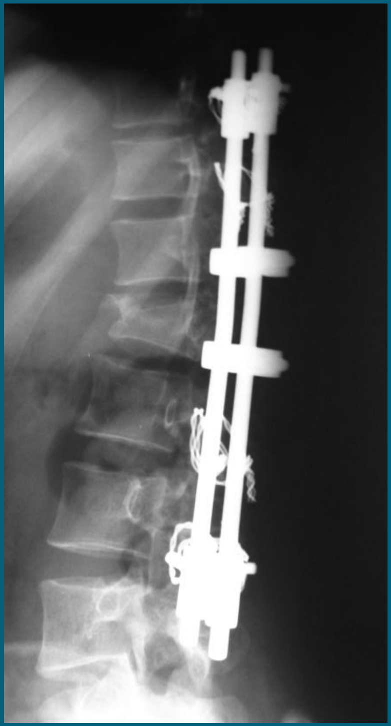
Clinical outcome will always be the ultimate quality control,
but the context of spine surgery suffered a number of changes…

Spine Biomechanics

Background

- Before the 90's:

- serious pathologies- fractures, deformities, tumors, infection, etc.
- armamentarium- rods, hooks, wires → levers acting on a number of segments



The goal was to keep people alive and walking!

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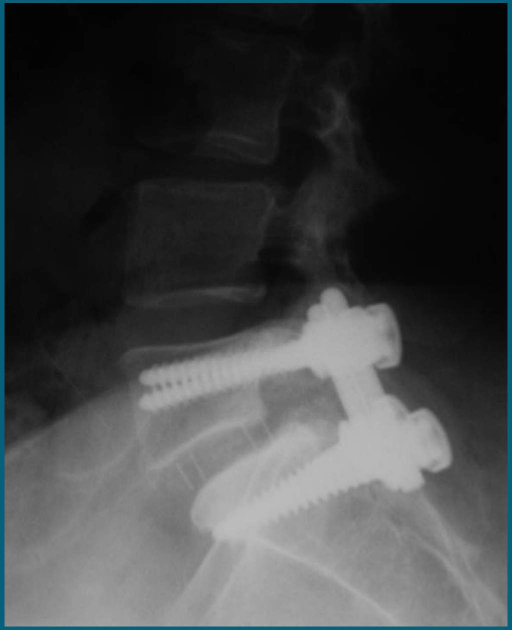
Background

- Implants that act on an isolated segment (segmental instrumentation)



effects imposed to a restricted area of pathology

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Spine Biomechanics

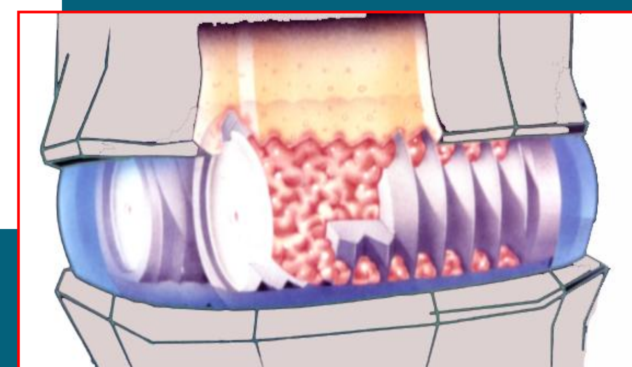
Background

- Segmental implants were the cornerstone to surgery for pain or spine degeneration

SPINE Volume 22, Number 6, pp 667–680

Threaded Titanium Cages for Lumbar Interbody Fusions

Charles Dean Ray, MD, FACS, FRSH (Lond.)



- 2001-2010 was 'The Decade of the Spine'
  - appearance of many new techniques
  - popularization of spine surgery

Spine Biomechanics

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Background

- Segmental implants were the cornerstone to surgery for pain or spine degeneration

development of surgical tools

↓

development of surgical techniques

↓

industry driven medical practice...

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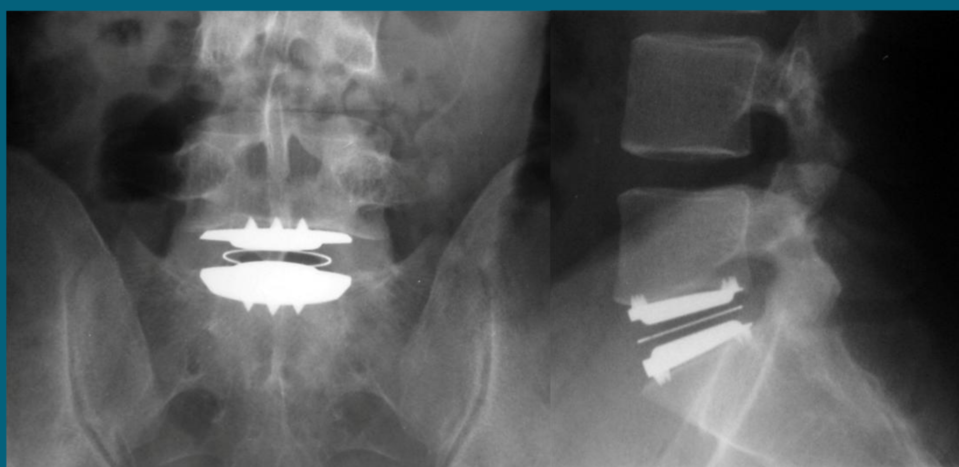
Spine Biomechanics

Background

- New kinds of treatments are being introduced



  - same clinical outcomes when compared to traditional techniques
  - introduction of new complications
  - justified by pure biomechanical rationalizations

Spine Biomechanics

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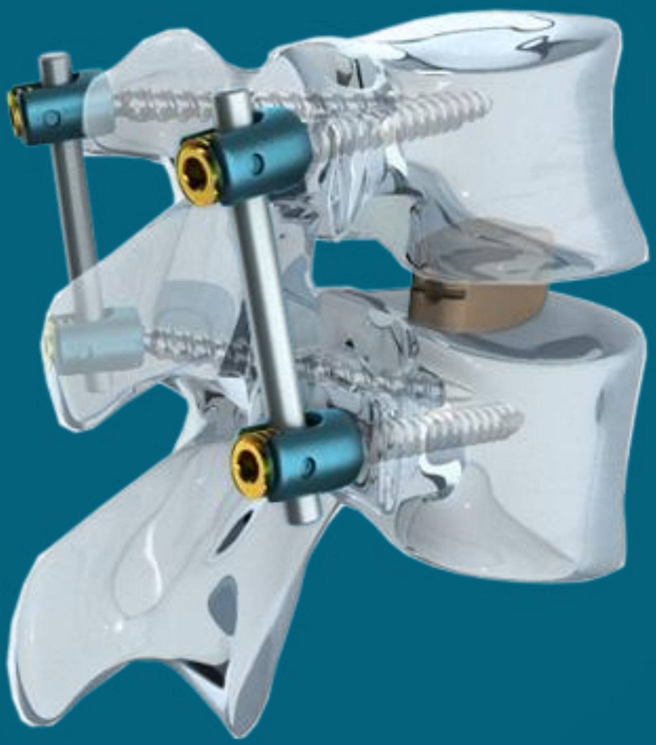
Background

- Spinal Fusion:
  - eliminates movement and load transmission



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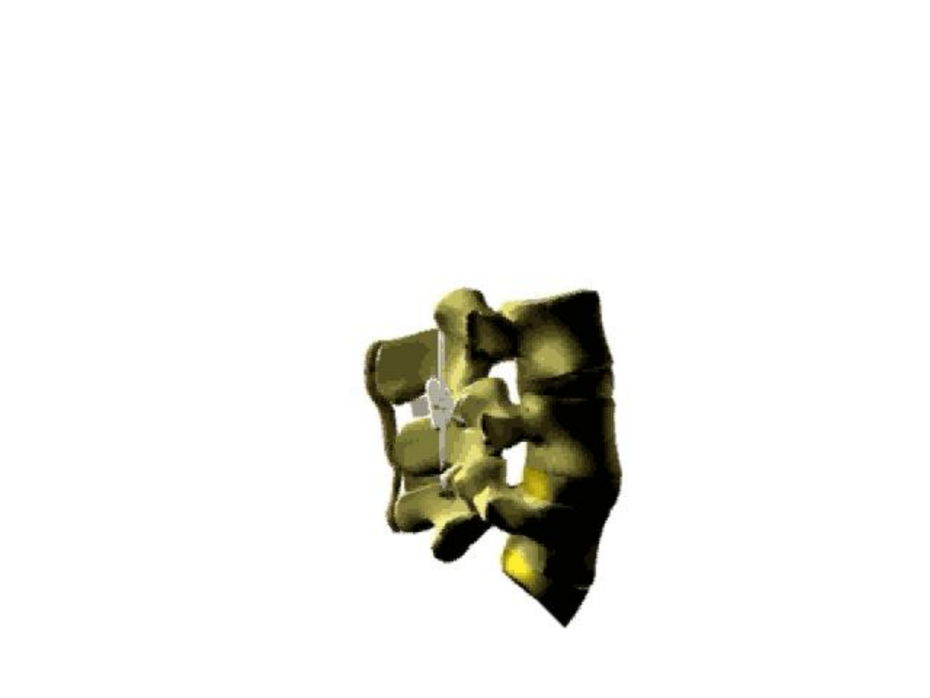
Background

- Dynamic Fixation:
    - introduces in the segment an implant to restore balance between spine components, aiming to bring movement and load transmission back to normal



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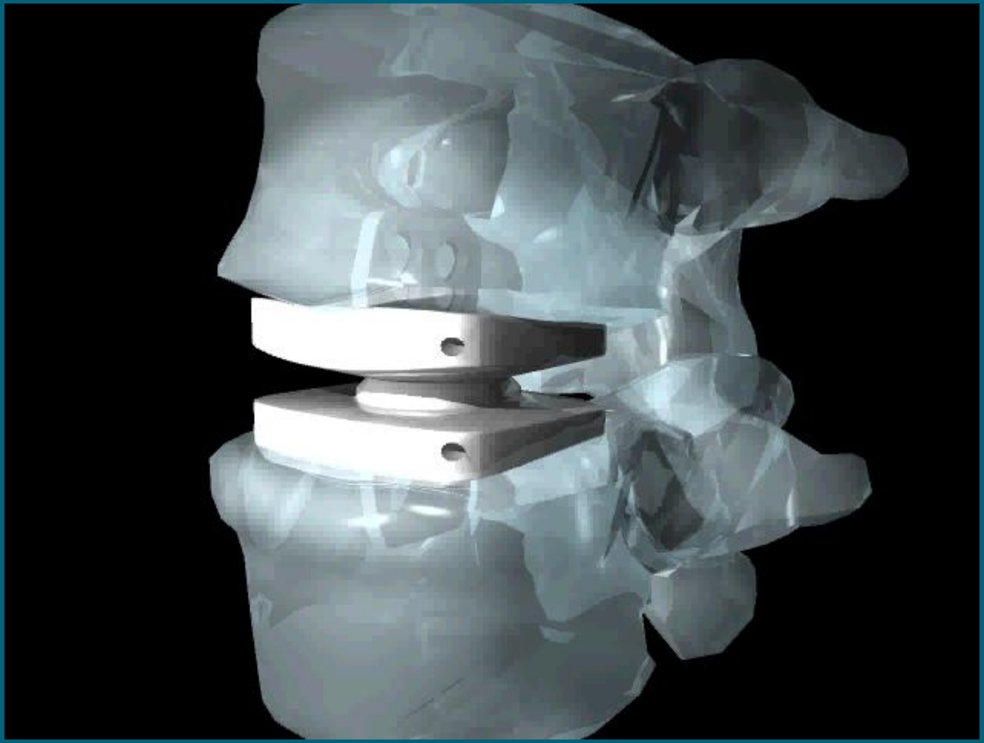
Background

- Disc Arthroplasty:
  - substitutes the damaged component of the segment for an implant, trying to bring movement and load transmission back to normal



Spine Biomechanics

Background

- Today we consider surgery for young people with minor problems that causes only pain – <u>healthy people / goal of enhancing life quality</u>

Spine Biomechanics

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Background

- Today we consider surgery for young people with minor problems that causes only pain – <u>healthy people / goal of enhancing life quality</u>
- much bigger responsibility / precision much more important

Spine Biomechanics

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Background

- Today we consider surgery for young people with minor problems that causes only pain – healthy people / goal of enhancing life quality
- much bigger responsibility / precision much more important
- The spine surgeon have to consider some questions:
  - Is the effect of the procedure really restricted to the disease? **NO.**

Spine Biomechanics

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  - What happens in the rest of spine?
  - Am I doing something that can result in more damage in the future?
  - Is there any technical detail that can make my procedure better?

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Those questions can't be solved with observation of
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Biomechanical research started being of immediate significance
to the surgeon.

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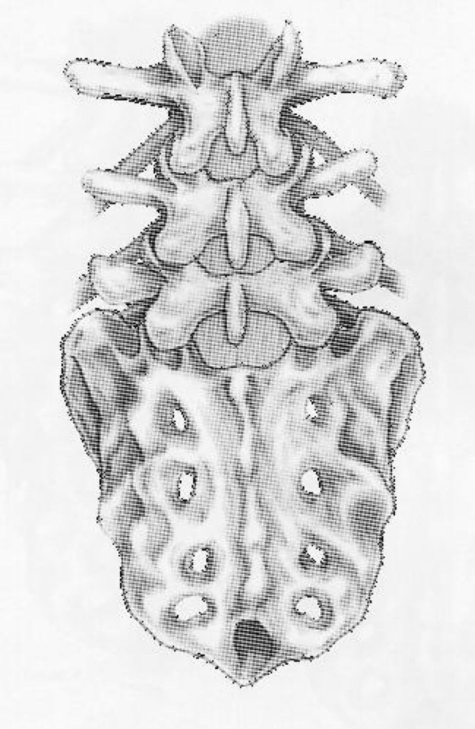
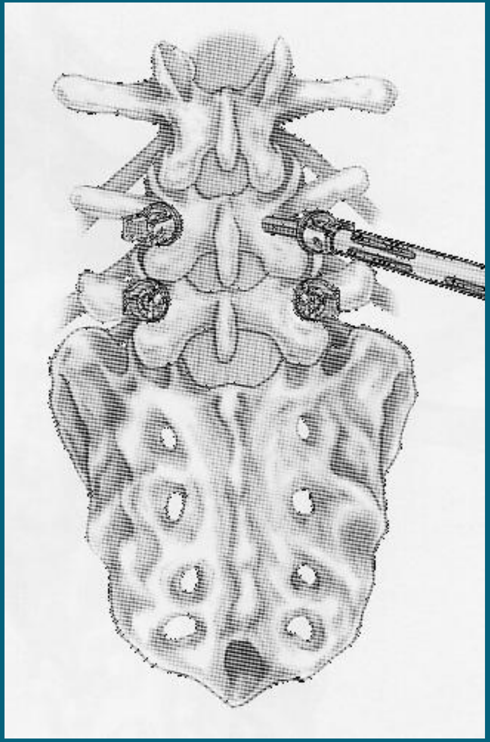
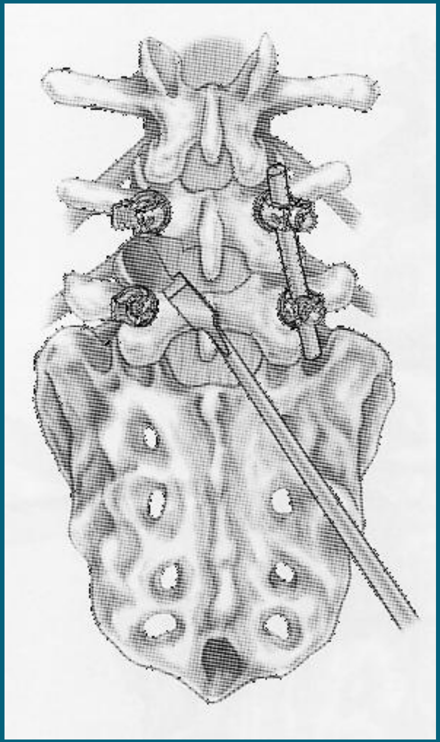
Background

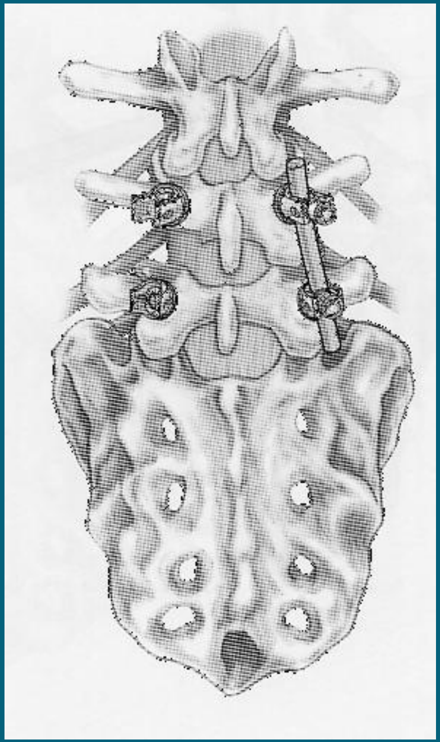




Spine Biomechanics

Background





Spine Biomechanics

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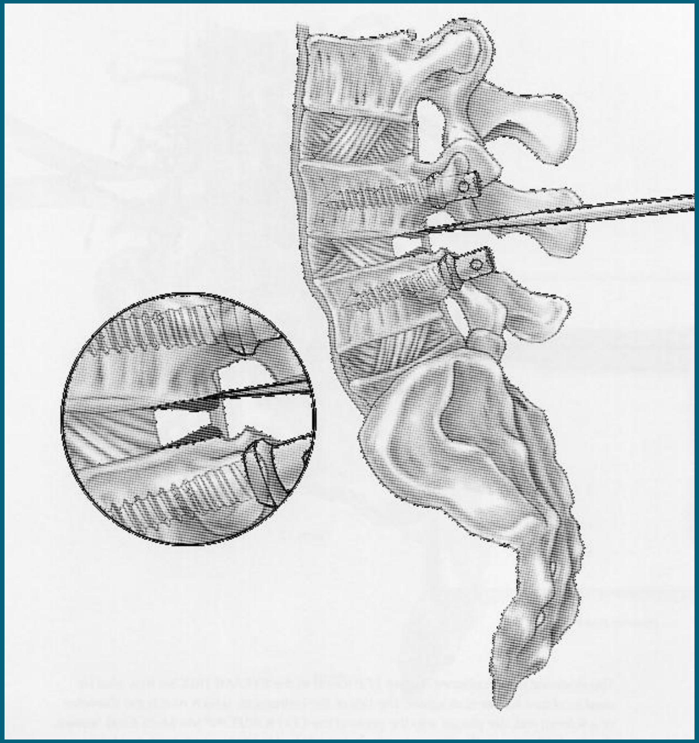
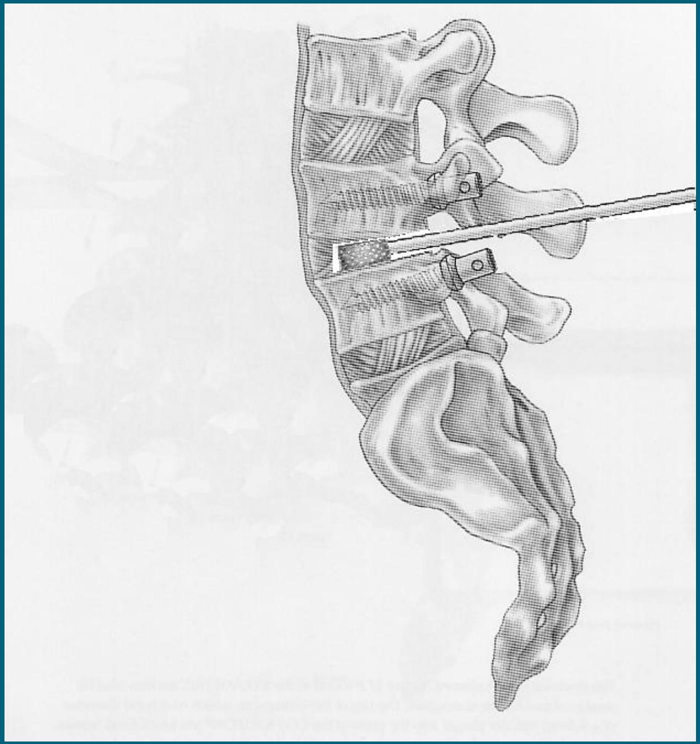


Spine Biomechanics



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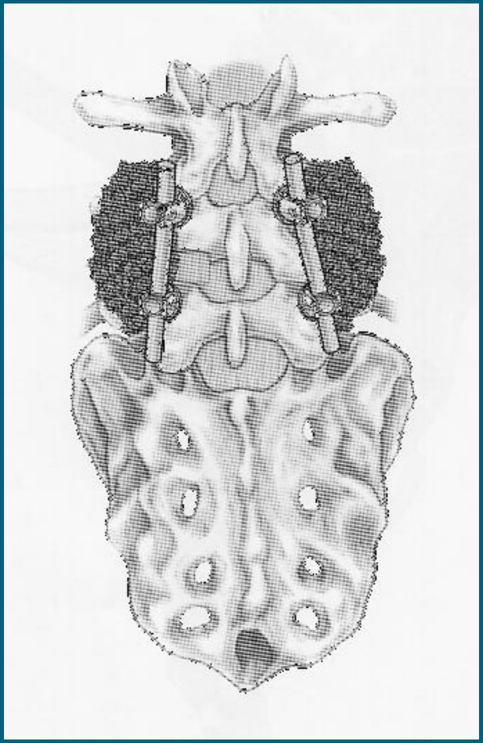
Background



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Specific Topics

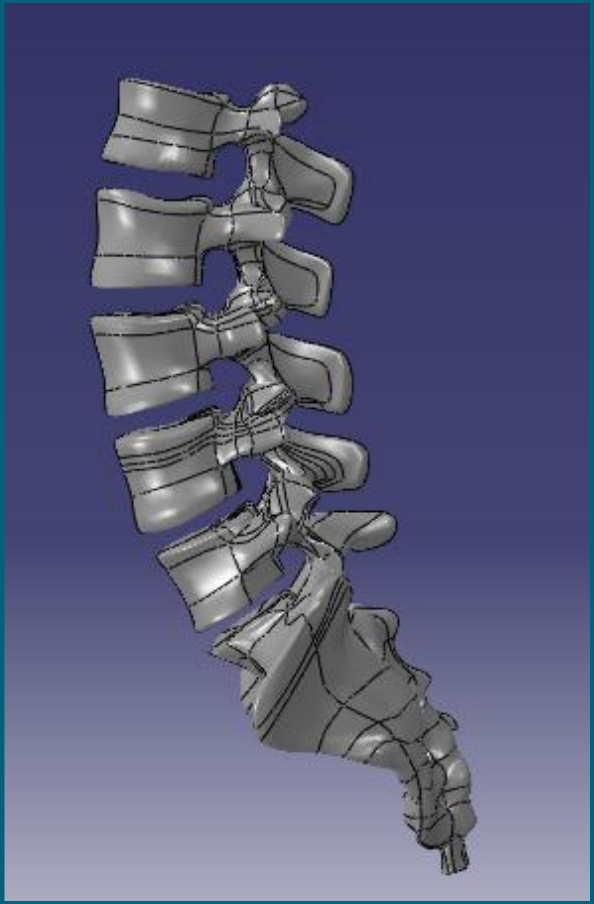
1. Better understanding of mechanical response of the healthy lumbosacral spine at different flexion-extension amplitudes
2. Mechanical response of a healthy spine compared with that stabilized with fusion device.
3. Impact of segment stabilization on adjacent segments
4. Does the stiffness of the stabilization system produce significant differences on the post-operatory scenario?

Simulation by Finite Elements

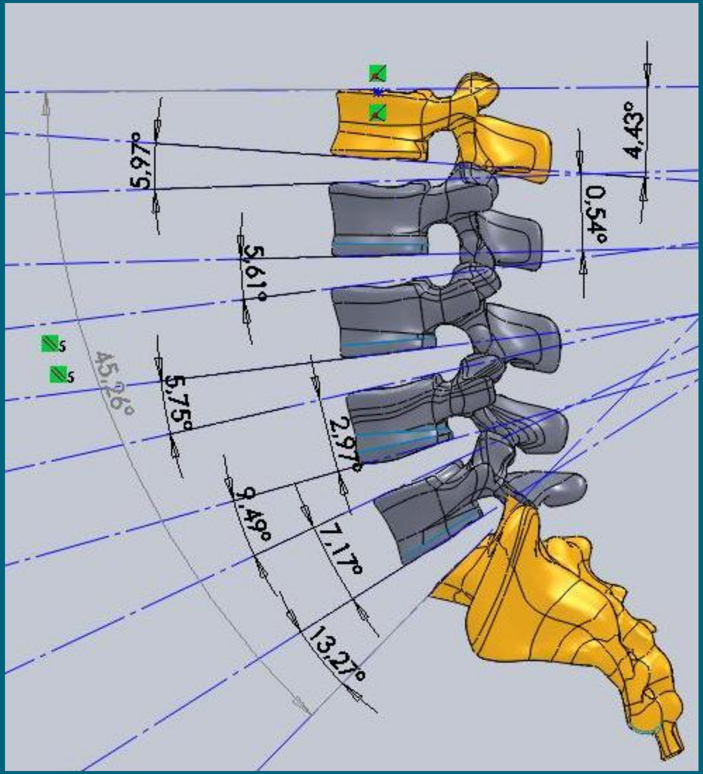
The FE Model

LS spine geometry:

Geometry obtained form Zygote Media Group company



After comparison with anthropometric studies, the angle of lordosis of the vertebrae and discs were changed



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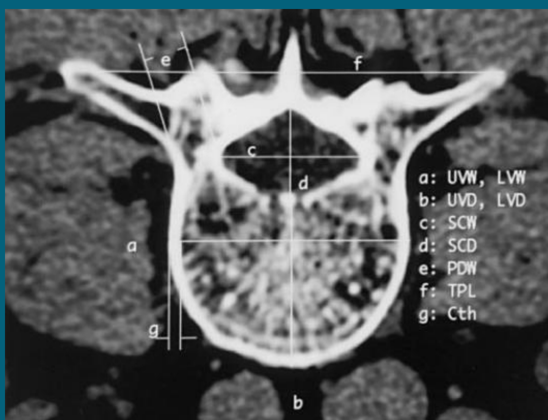
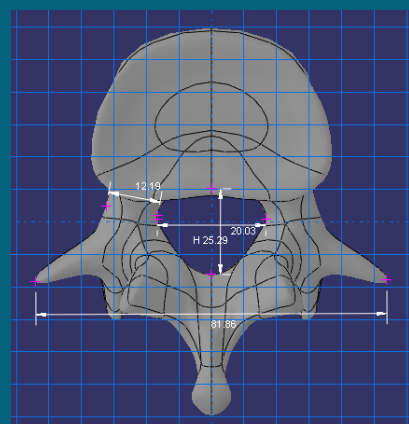
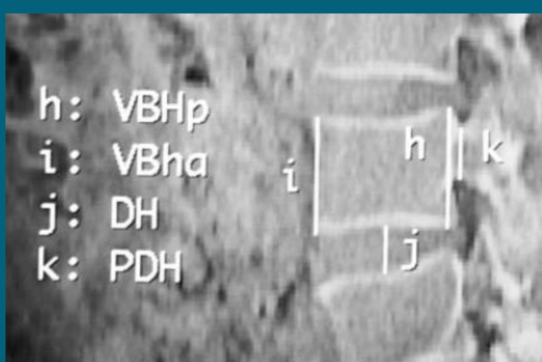
The FE Model

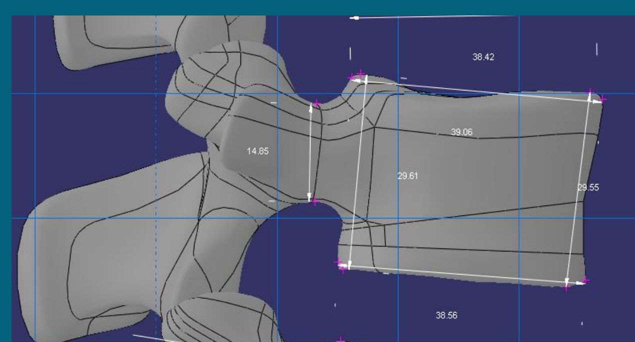
Vertebrae geometry:

Geometry modified in order to follow anthropometric study of **Zhou et al**: computerized **tomography measurements of the L3-L5 vertebrae of 126 patients**







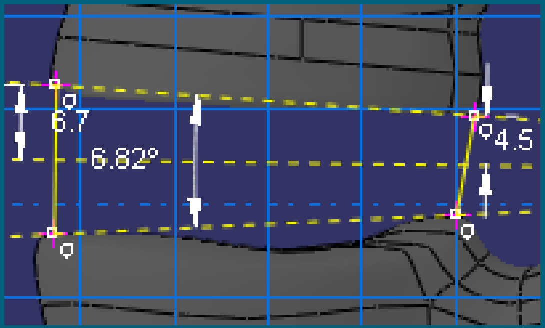


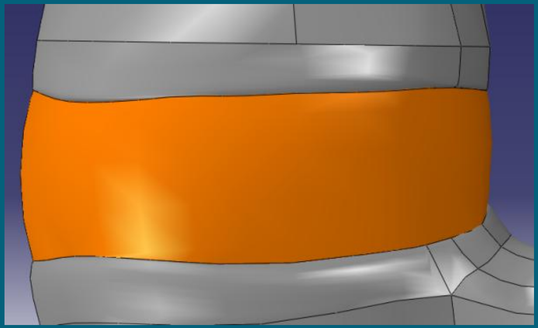
		ZHOU	MODEL	%Error
UVW	L3	46,1	49,46	7,29
	L4	50,8	50,87	0,14
	L5	54,5	54,00	0,92
UVD	L3	34,1	39,44	15,66
	L4	36,4	38,9	6,87
	L5	37,6	38,91	3,48
LVD	L3	37,4	38,56	3,10
	L4	38,6	39,71	2,88
	L5	38,3	37,88	1,10
LVW	L3	54,8	55,87	1,95
	L4	55,1	54,21	1,62
	L5	56,7	54,96	3,07
VBHb	L3	30,70	29,61	3,55
	L4	29,60	29,1	1,69
	L5	26,7	27,02	1,20
VBHa	L3	30,60	29,55	3,43
	L4	31,00	30,47	1,71
	L5	31,5	30,87	2,00

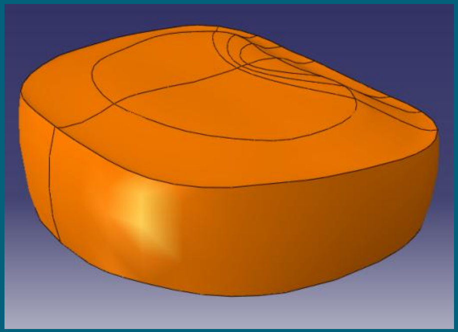
The FE Model

Intervertebral disk Geometry:

- ✓ Modified to follow statistical lordosis angle and heights
- ✓ The relative positions of vertebrae was modified
- ✓ Lower and upper surface shapes follow that of vertebrae





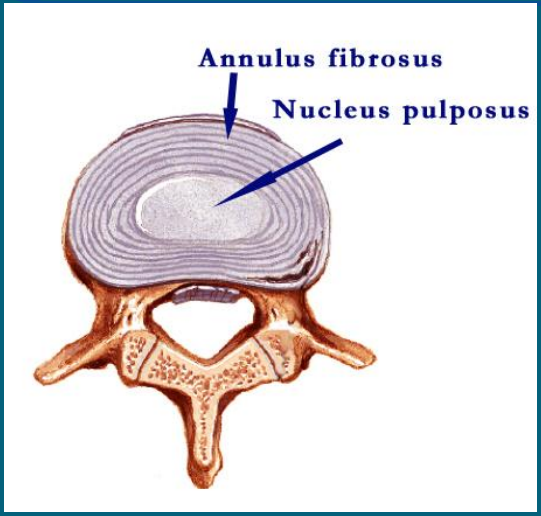


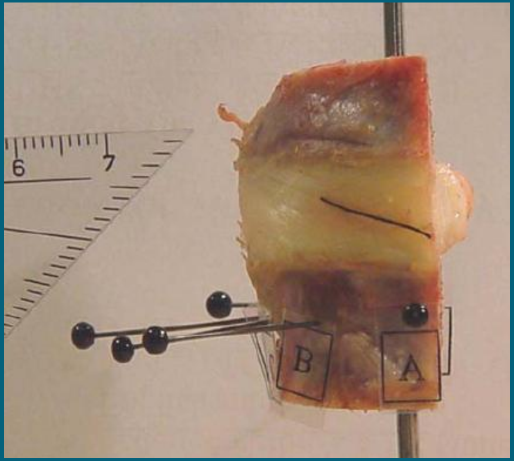
Intervertebral disk

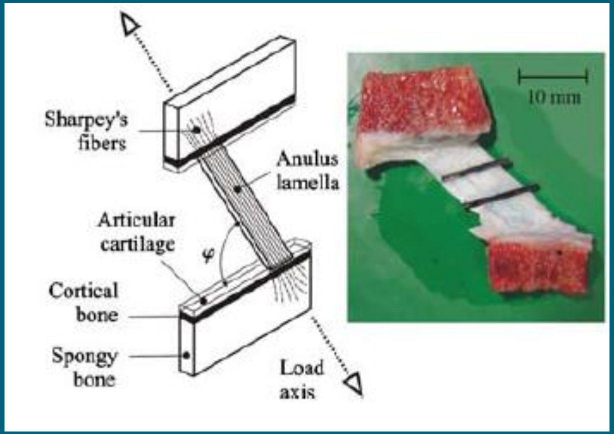
Characteristics:

➢ **Nucleus Pulposus**: gelatinous incompressible material. Distribution of pressure on the Fibrosus annulus when compressed.

➢ Annulus Fibrosus: highly anisotropic fiber reinforced tissue around the nucleus. Fibers oriented along an helicoidally distribution.







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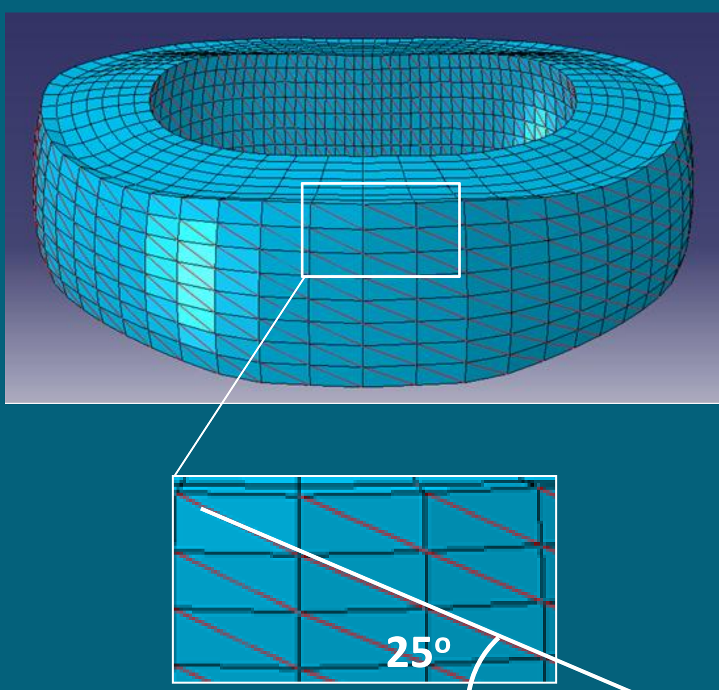
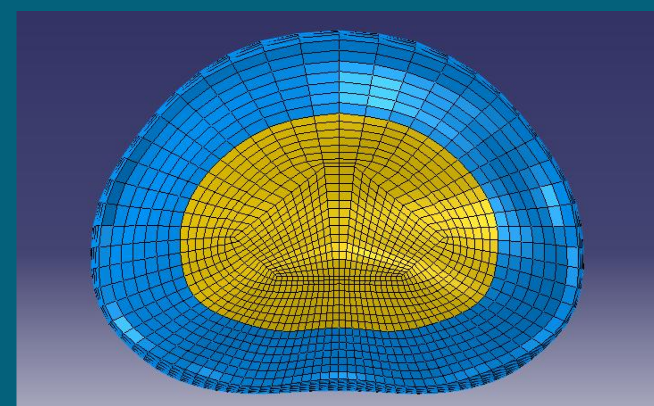
Intervertebral disk

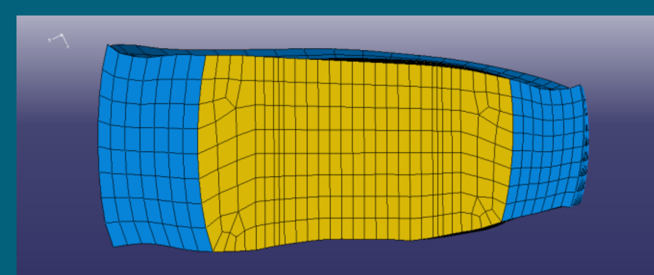
Modeling

- Ground substance: hyperelastic incompressible (Mooney Rivlin / Ogden)

- Orientation of fibers with horizontal plane: from 25º at anterior region to 50º at posterior region.



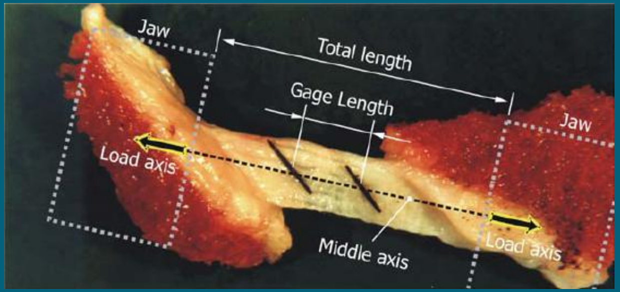




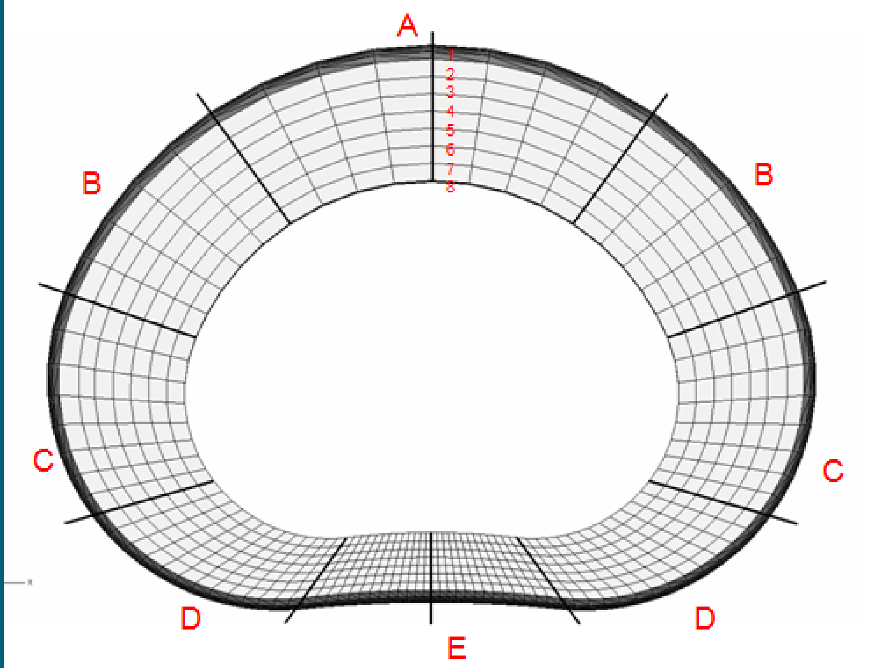
Intervertebral disk

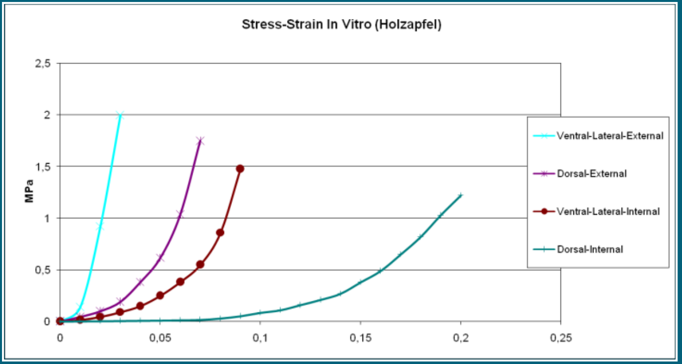
Modeling

Stiffness of fibers obtained from in vitro study [Holzapfel],



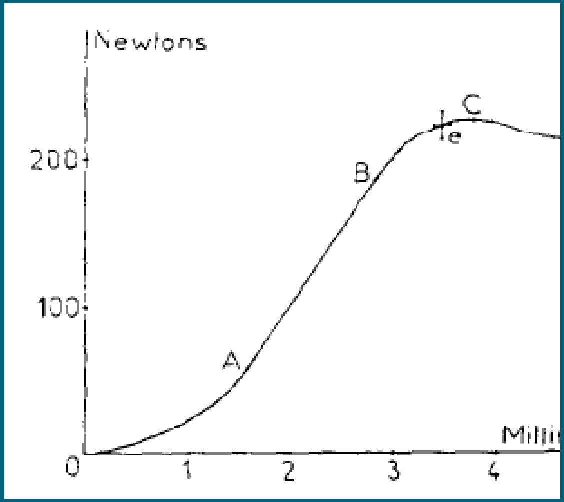
Geometry divided in 8 regions in radial direction and 5 regions in circumferential directions. The 4 curves were combined and conveniently adapted to each region.

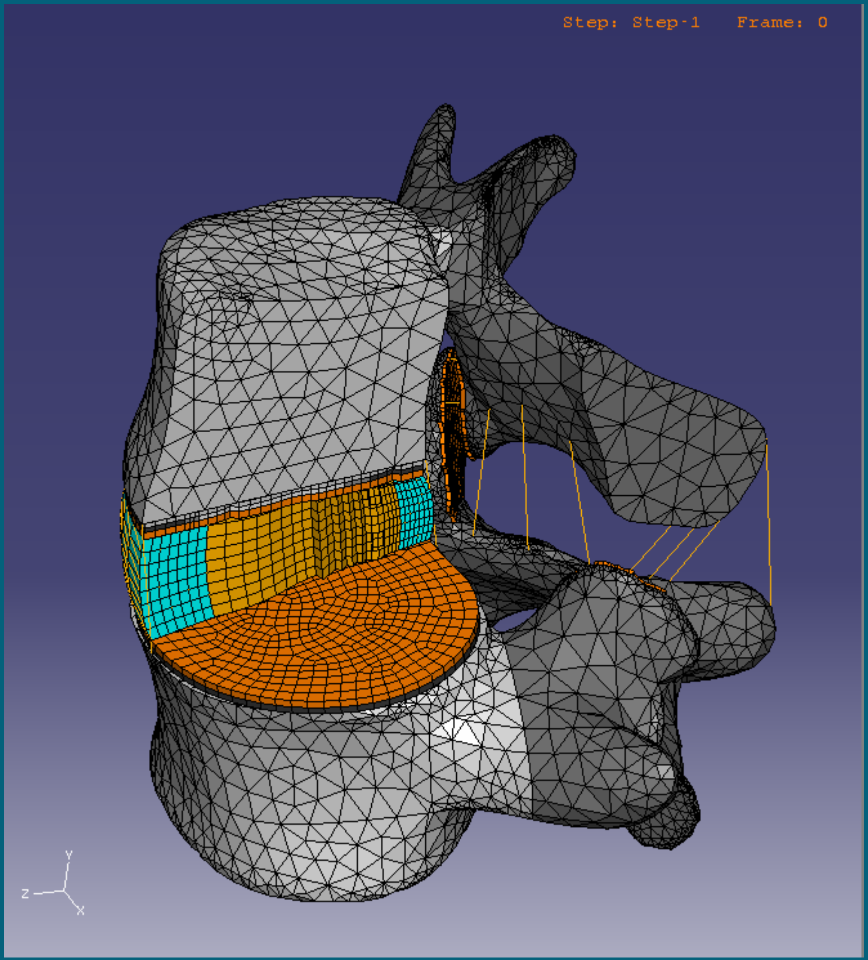




Ligaments

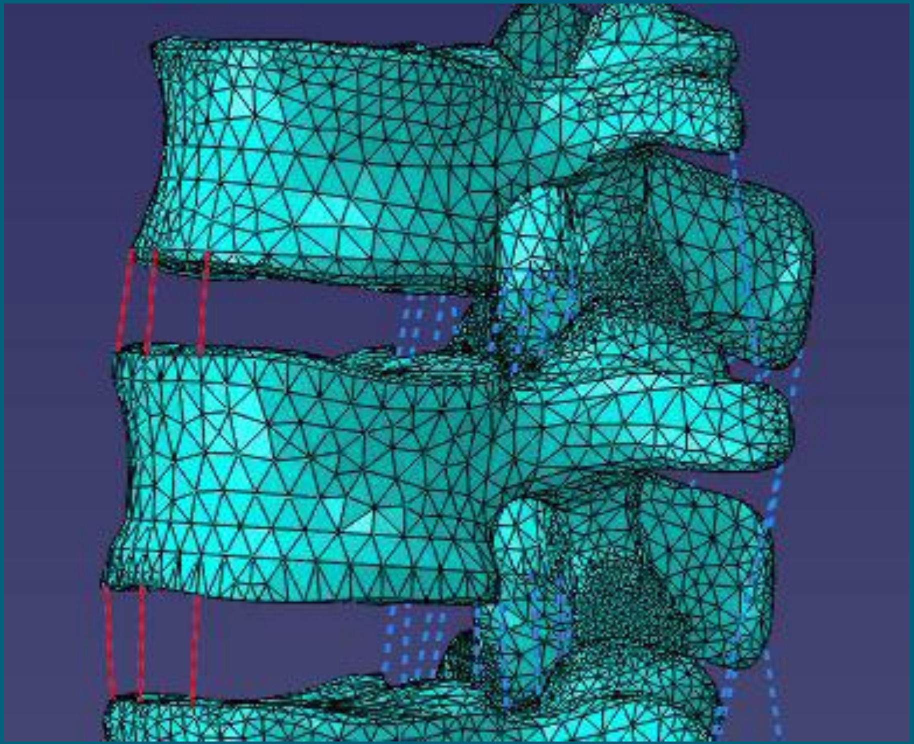
- Highly oriented structures with zero stiffness to compressive strains
- Spine stability and movements constraints.
- Model: Nonlinear uniaxial elements

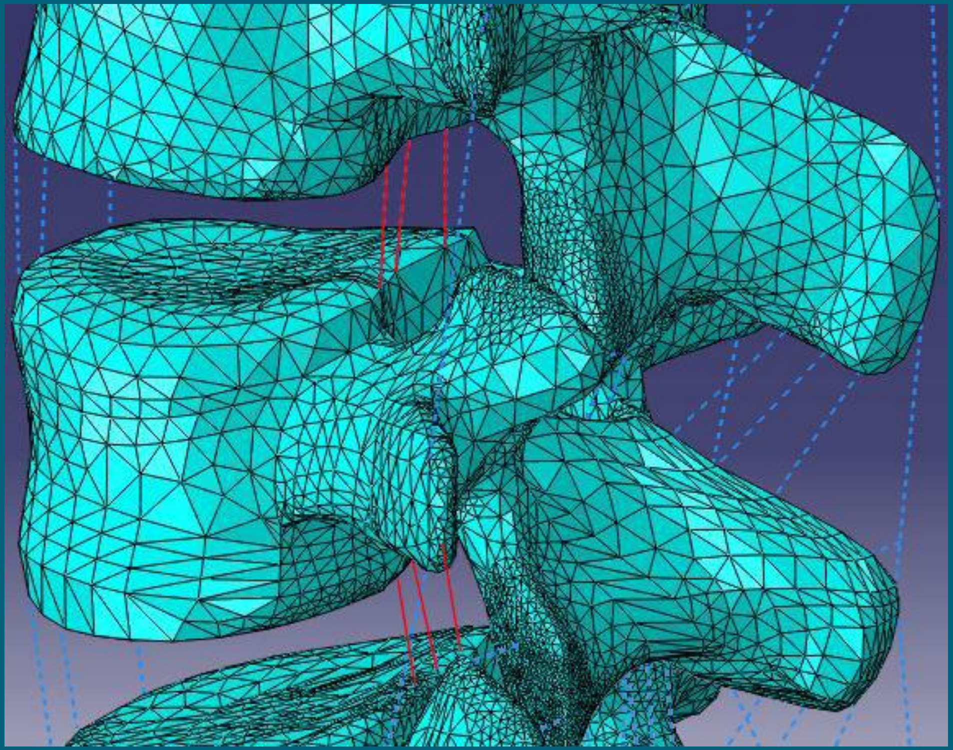




Ligaments

Anterior Longitudinal & Posterior Longitudinal





Ligaments

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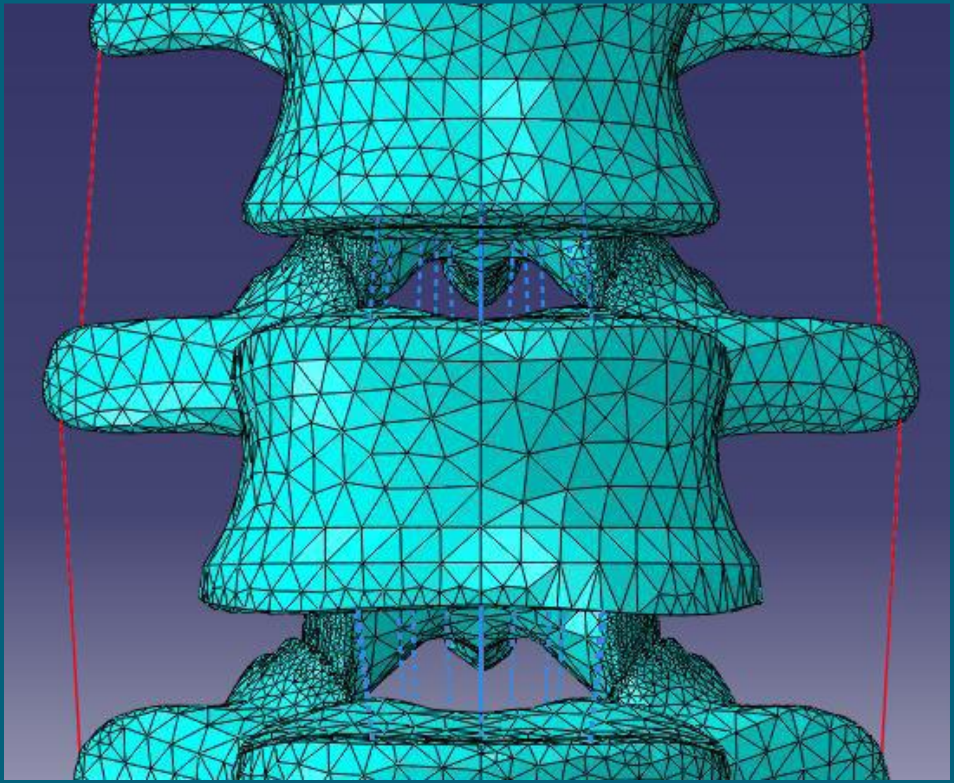
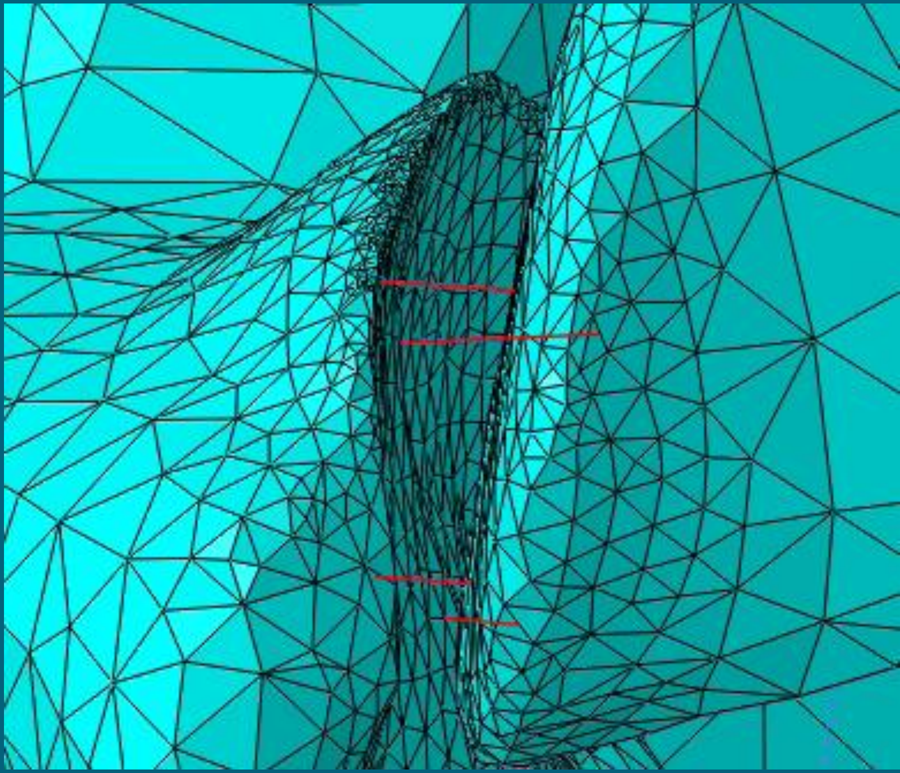
Inter Transverse & Capsular





Ligaments

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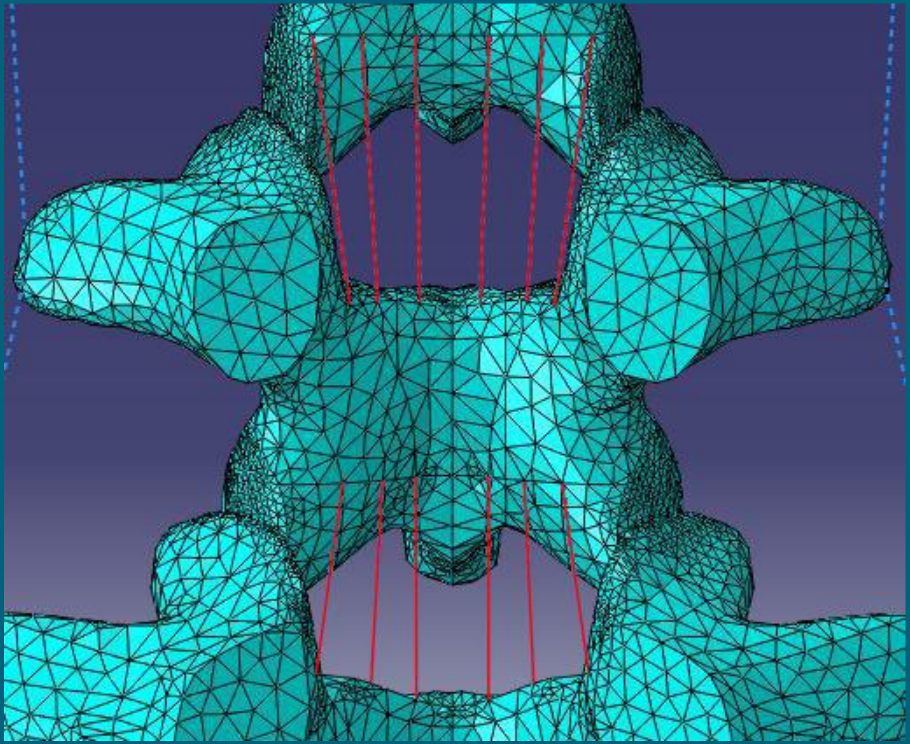
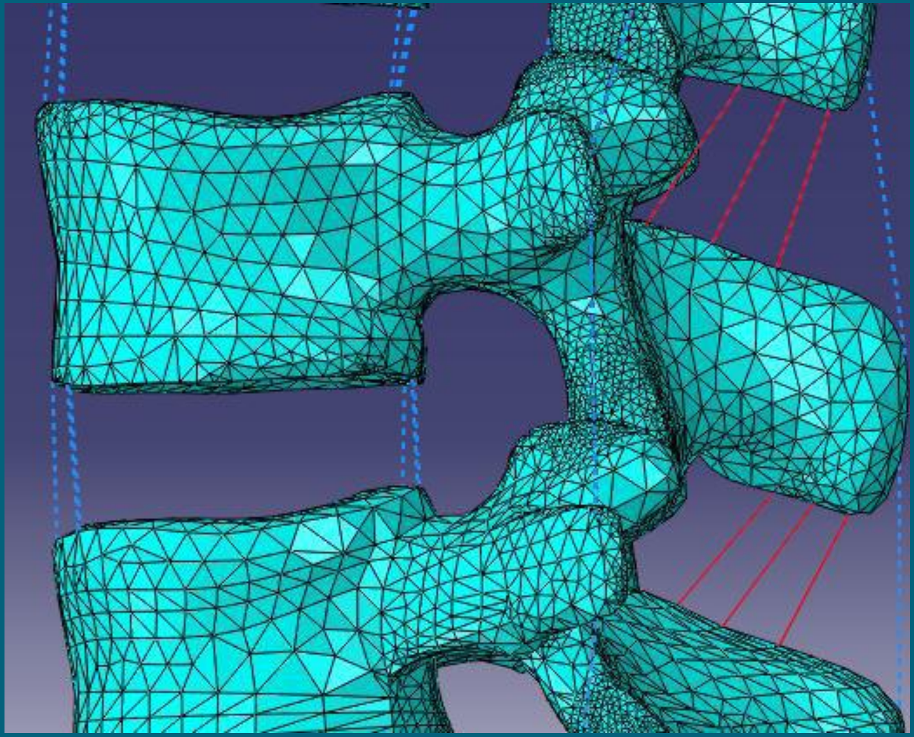
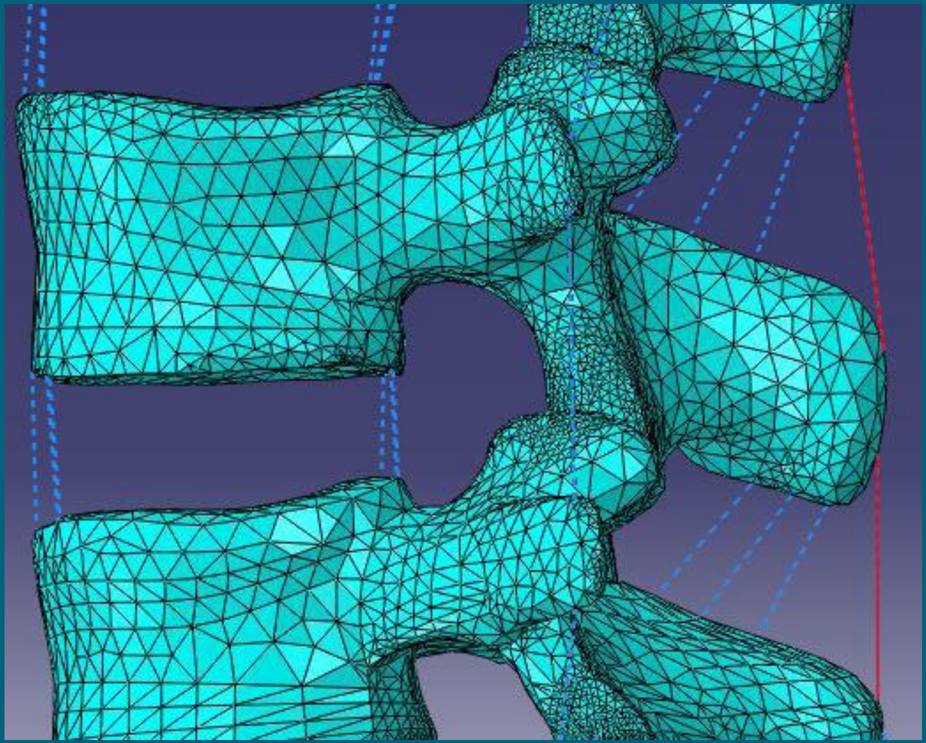
Yellow (Flavum) & Inter Spinous

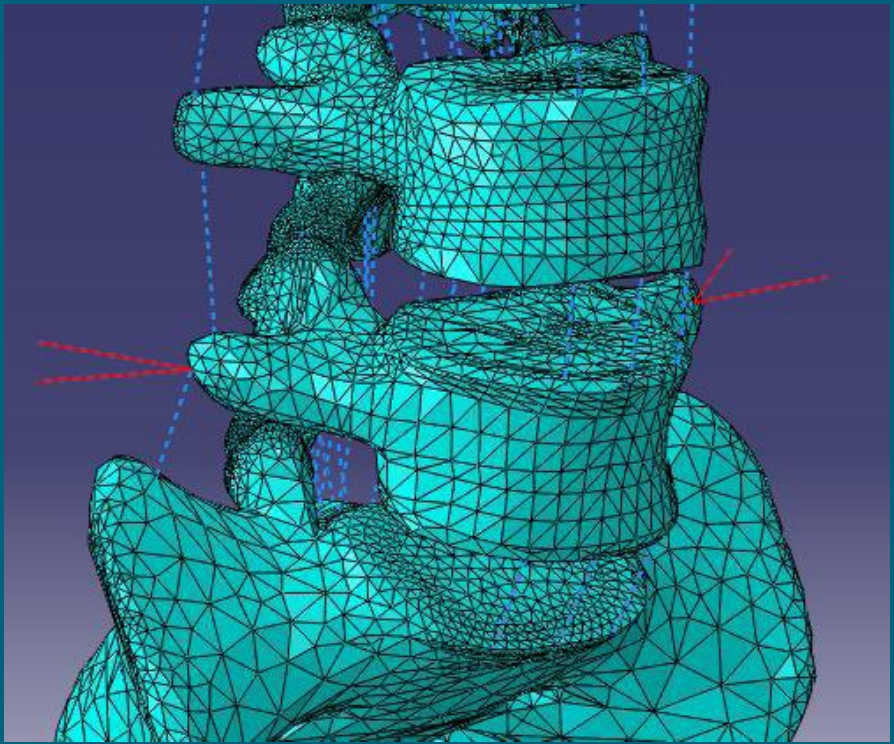




Ligaments

Supra Spinous & Ileo Lumbar





Facet Joints

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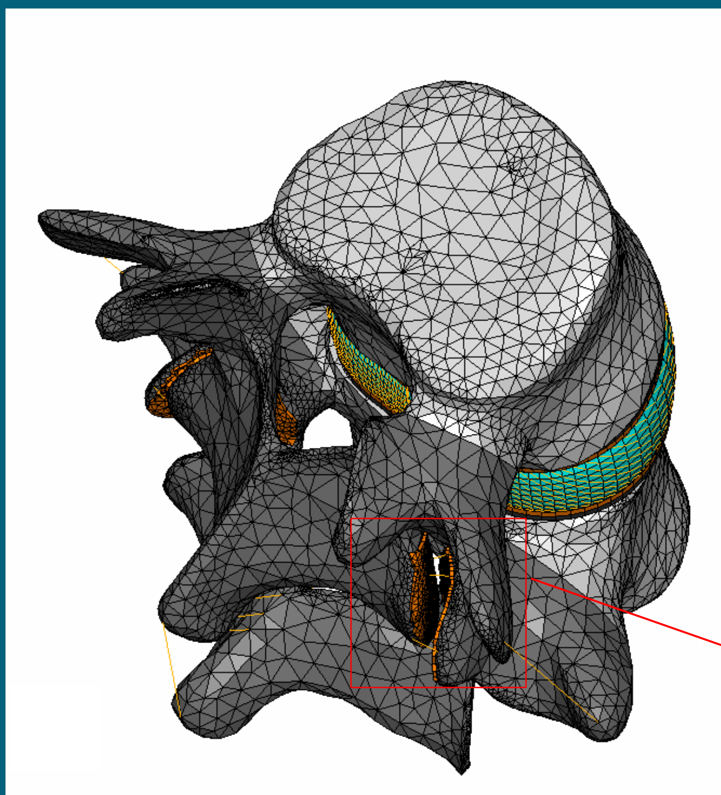
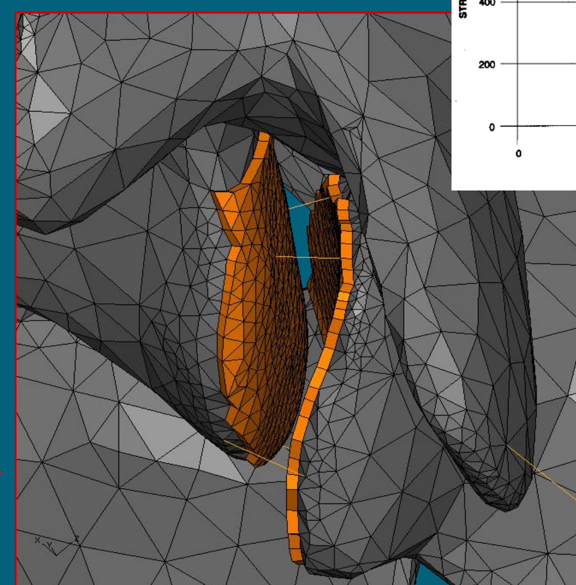
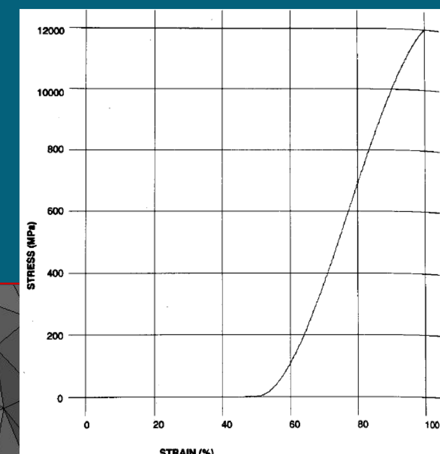
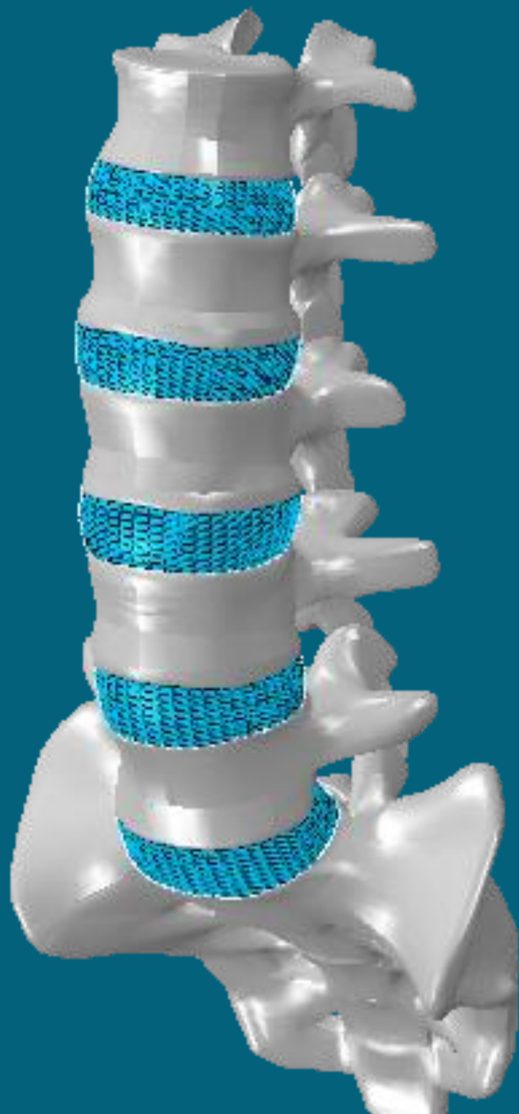
- Stability function
- Movement constraints
- Nonlinear frictionless contact model [5]







Material Properties



Material	E (MPa)	Possion's ratio	Element Type
Cancellous bone	Exx=140 Eyy=200 Ezz=140 Gxy=48.3 Gyz=48.3 Gxz=48.3	γxy=0.315 γyz=0.315 γxz=0.450	Hexaedrals
Cortical bone	12000	γ=0.2	Hexahedral
Bony posterior elements	3500	γ=0.25	Hexahedrals and Tetrahedrals
Nucleus	Mooney-Rivlin c1=0.12, c2=0.03 Incompressible		Hexahedrals
Annulus ground substance	Hyper-elastic Ogden incompressible		Hexahedrals
Annulus fibers	Stress-strain curves		No-compression uniaxial connectors
Outer Bony Endplate	12000	γ=0.3	Hexahedral
Intermediate Bony Endplate	6000	γ=0.3	Hexahedral
Inner Bony Endplate	2000	γ=0.3	Hexahedral
Ligaments	Stress-strain curves (Calibrated)		No-compression uniaxial connectors

Calibration of segment L4-L5

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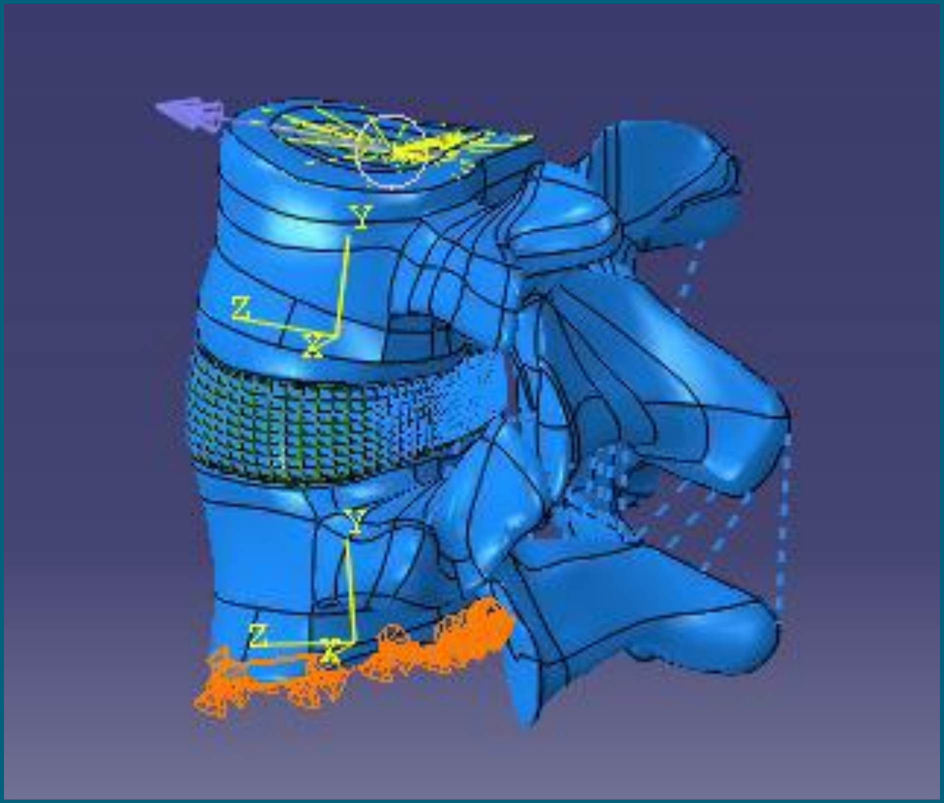
✓ **Heuer** measured the movements of segment L4-L5 in flexion, extension, lateral bending and torsion.

✓Measurements were performed with an intact segment and **after removing several structures, sequentially:** SSL, ISL, YL, CL, facet joints, PLL, ALL, Nucleous Pulposus

✓Soft tissues behavior was adjusted to obtain a difference of less than 5%, in comparison to the **experimental curves obtained by Heuer**



Calibration of segment L4-L5

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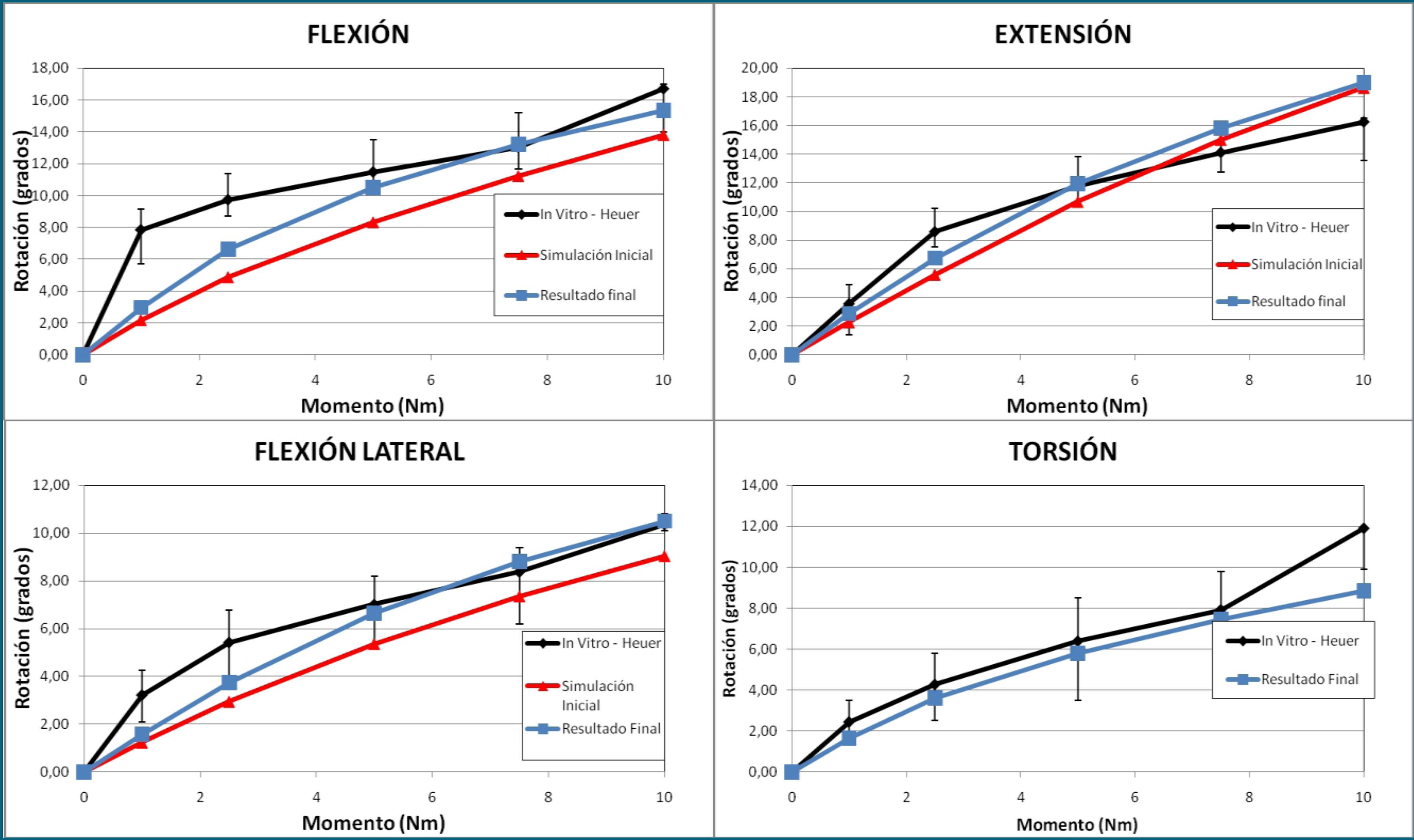
Comparative rotation results after **calibration of Annulus Fibrosus**



Calibration of segment L4-L5

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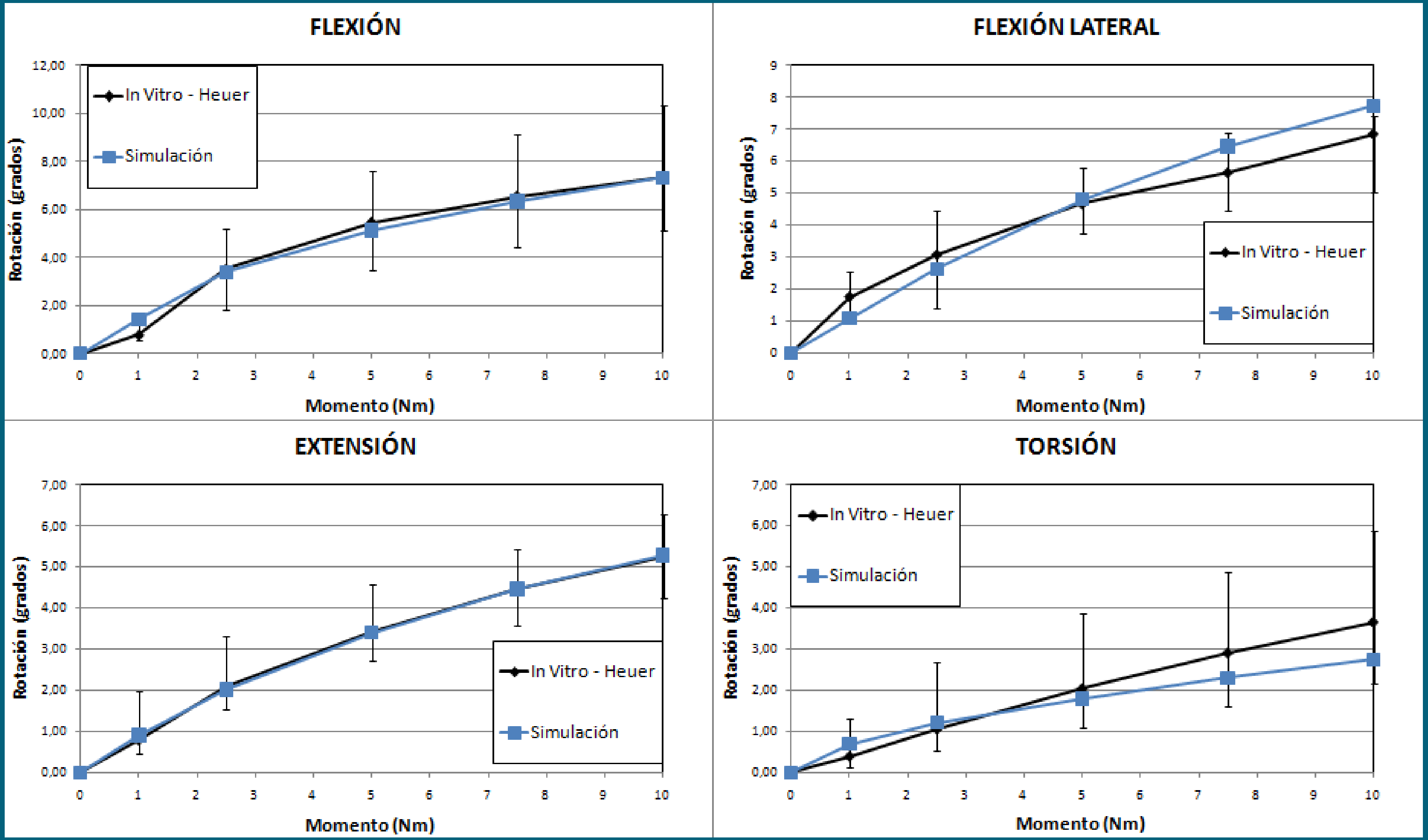
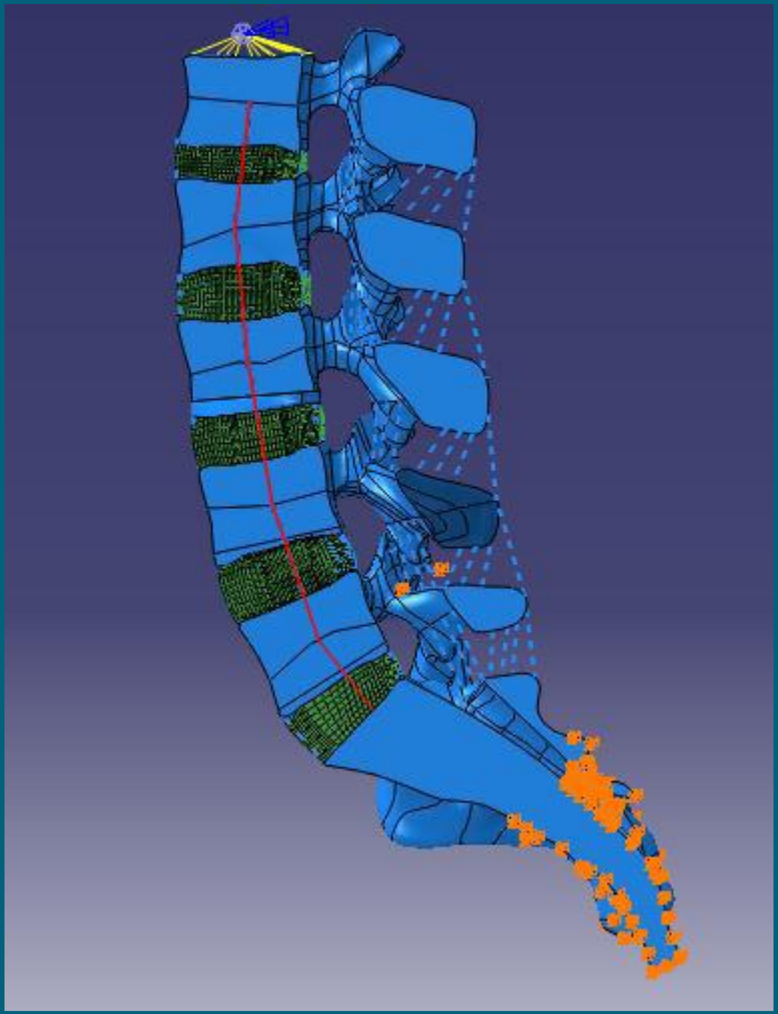
Comparative rotation results after **calibration of ISL** on flexion, extension, lateral bending and torsion



Calibration of complete Lombosacral Segment (L1-S1)

✓ Parametric extrapolation of L4-L5 soft tissues properties to the other segments

✓ Calibration of extrapolated material properties in order to compare with in vitro rotation measurements of Panjabi [29], Yamamoto [51], Guan [14] and Rohlmann [38]



Loads: Weight + Muscular Forces

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MUSCLES

Local Muscles:

- ✓Connect adjacent vertebrae
- ✓Provide compressive loads that stabilize the column

Global Muscles

- ✓Control the spine movement: flexion, extension, lateral bending and torsion

MODEL

- ✓ Erector Spinae: Applied at 40mm dorsal from L1 superior endplate.
- ✓ Rectus Abdominus: Applied 153mm ventral from L1 superior endplate.
- ✓ Weigh: Applied at 200 mm cranial and 30 mm anterior from the L1 superior endplate.
- ✓ Follower Load : Simulate Local Muscles; 200N compressive load at each pair of vertebrae

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Loads: Weight + Muscular Forces

Global muscular force calculation: 6 load cases

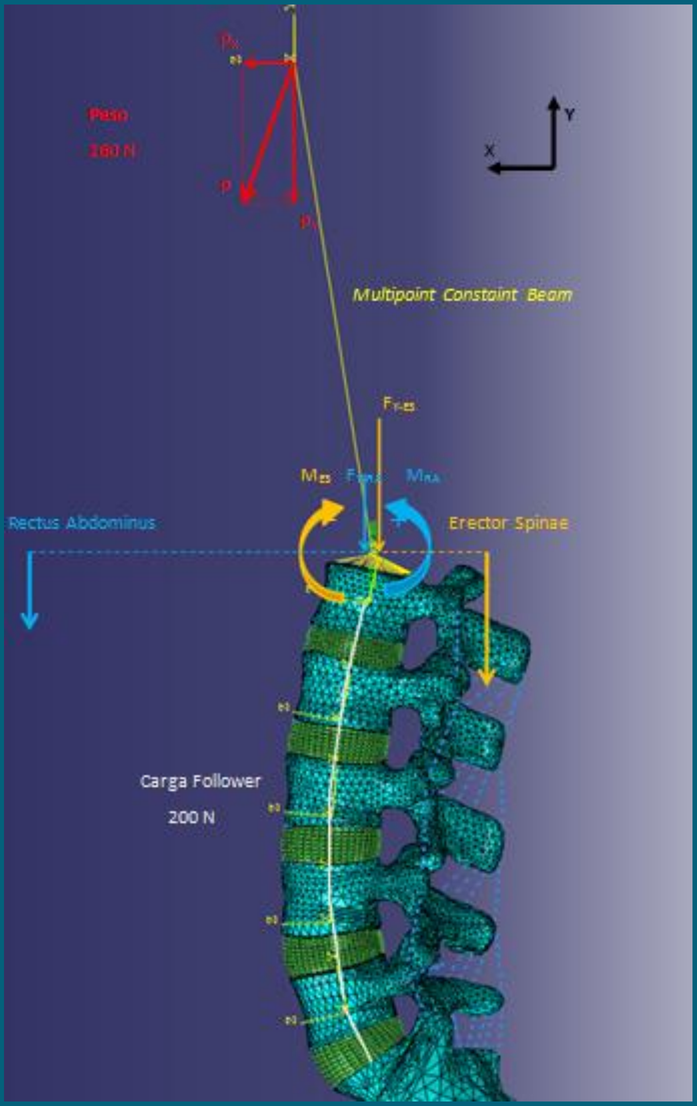
- 50 Flexion (30 Hip / 20 Spine)
- 30 Flexion (20 Hip / 10 Spine)
- 15 Flexion (10 Hip / 5 Spine)
- Neutral Position
- -15 Extension (- 5 Hip / -10 Spine)
- - 25 Extension (-10 Hip / -15 Spine)

Technique used by Wilke

1) Apply the desired flexion angle at L1 superior endplate
2) Apply weight force
3) Modify iteratively the muscular forces in order to obtain zero value of momentum reaction at the L1 superior endplate

Local muscular forces

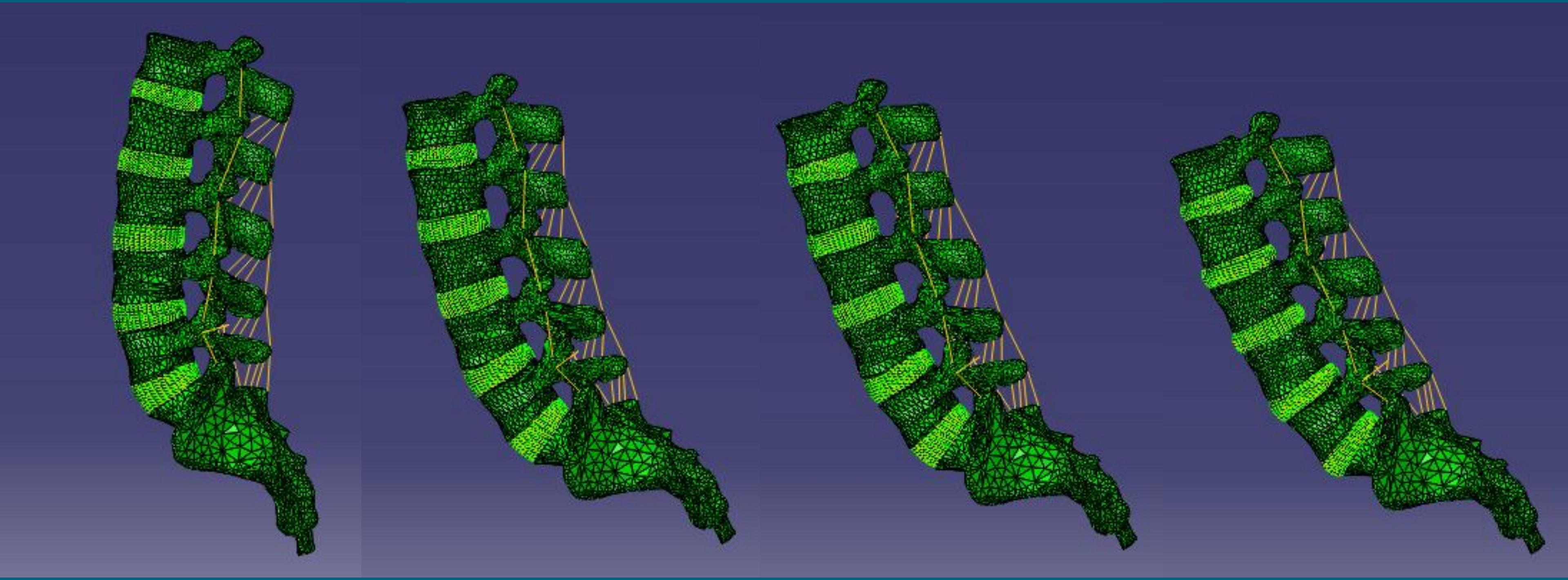
- 200 N at each pair of vertebrae



Loads: Weight + Muscular Forces

Example: 30 degrees flexion (20 degrees hip, 10 degrees spine)

Unloaded | Hip flexion angle | L1 flexion angle | Final loaded case



Loads: Weight + Muscular Forces

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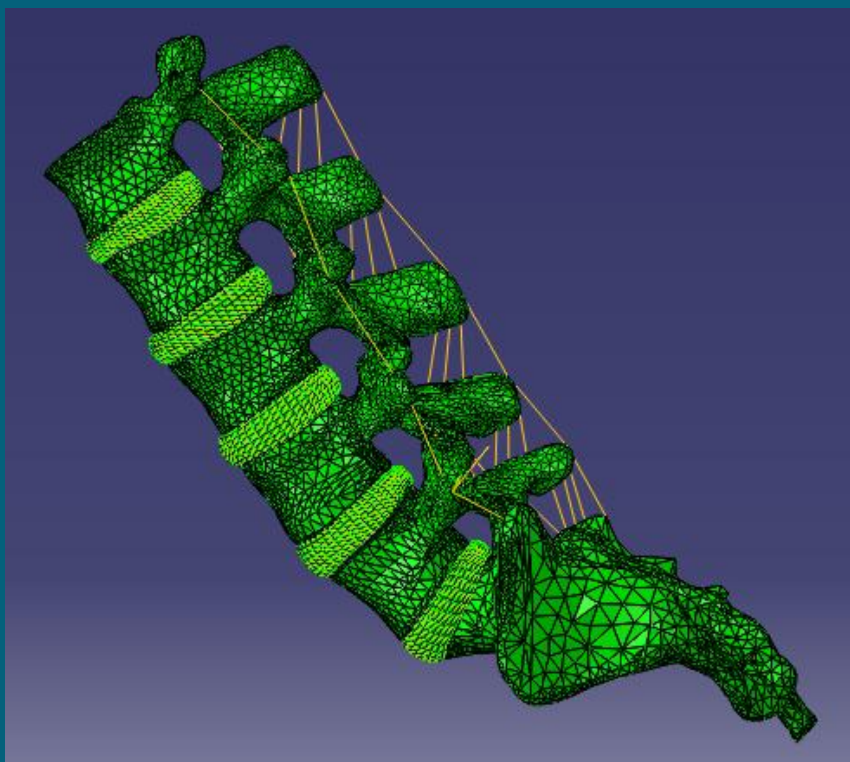
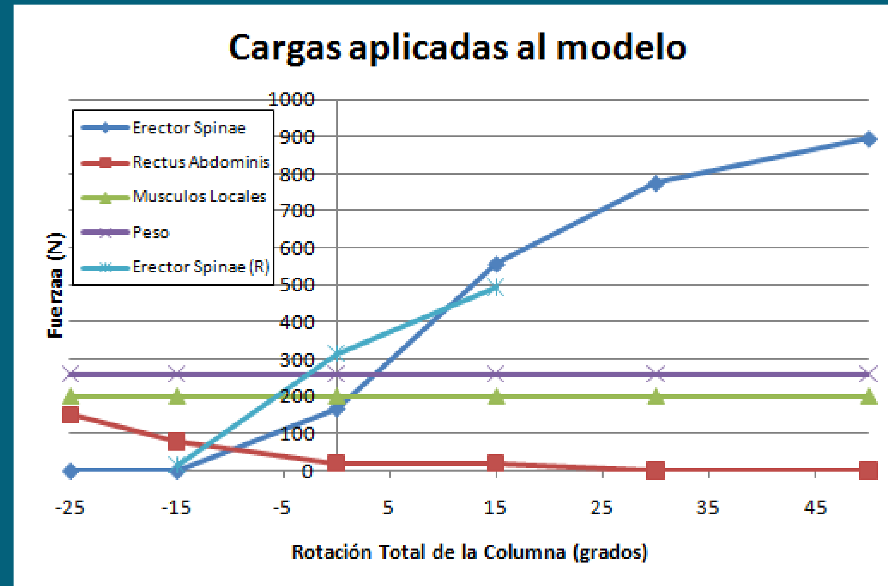
RESULTS

50^0 Flexion (30^0 hip; 20^0 spine)





	Rotación (grados)	Fuerzas de Contacto FJ (N) Izq.	Fuerzas de Contacto FJ (N) Der.	Fuerzas en los Ligamentos (N) ALL	PLL	CL Izq.	CL Der.
L1L2	4.97	0.00	0.00	0.00	-0.38	0.17	0.82
L2L3	4.62	0.00	0.00	0.00	-3.11	8.41	8.29
L3L4	4.54	0.00	0.00	0.00	-4.81	0.00	0.00
L4L5	1.24	19.84	16.82	0.00	-3.98	0.00	0.00
L5S1	4.62	42.83	43.12	0.00	-1.35	0.00	0.00

	Fuerzas en los Ligamentos (N) FL	ISL	SSL	ITL Izq.	ITL Der.	ILL Ant.	ILL Post.
L1L2	18.14	2.38	48.28	7.27	9.14		
L2L3	10.61	2.85	24.26	3.88	3.42		
L3L4	9.77	0.15	13.72	0.33	0.51	19.32	285.79
L4L5	1.84	-3.76	-3.08	0.00	0.00		
L5S1	0.84	0.00	0.00	0.00	0.00		

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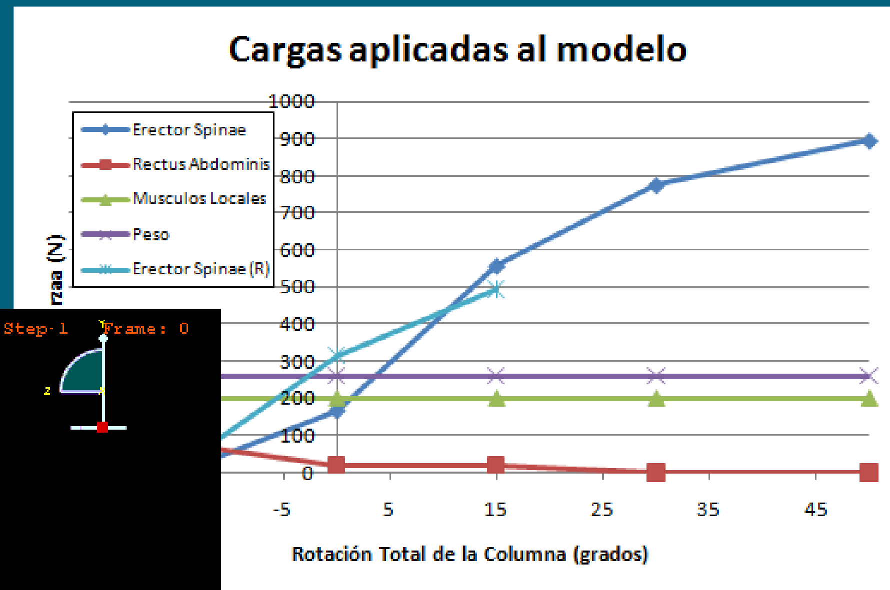
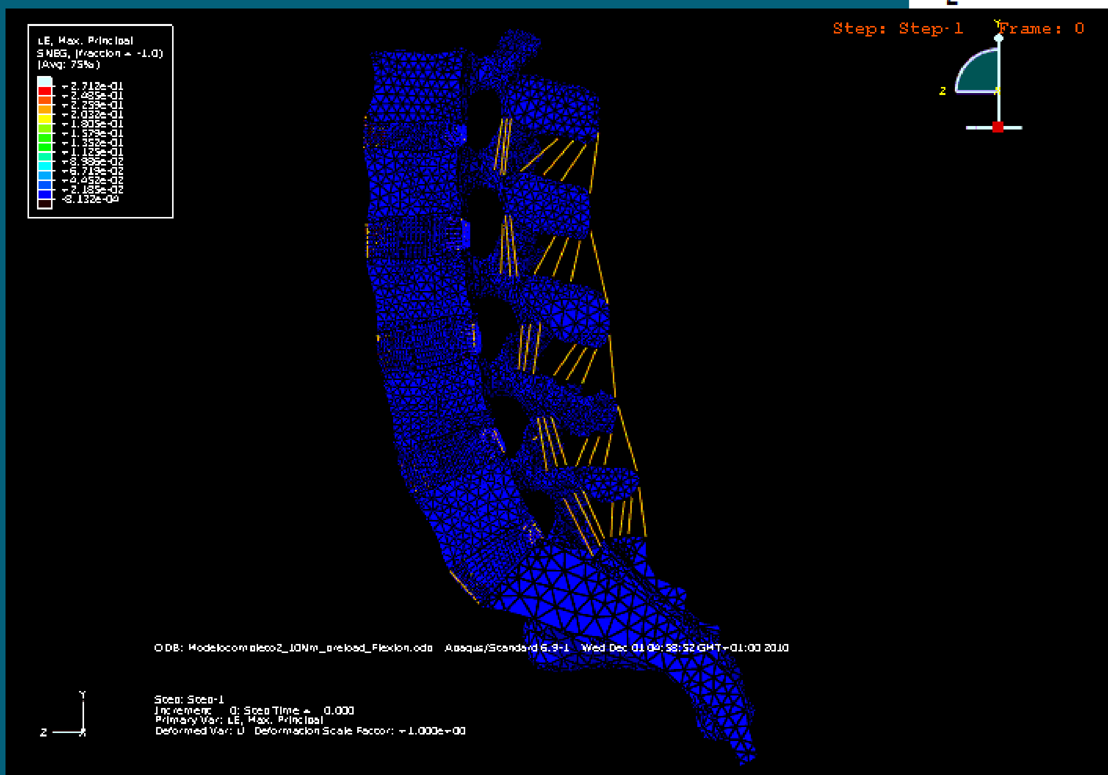
Loads: Weight + Muscular Forces

RESULTS



50^0 Flexion (30^0 hip; 20^0 spine)

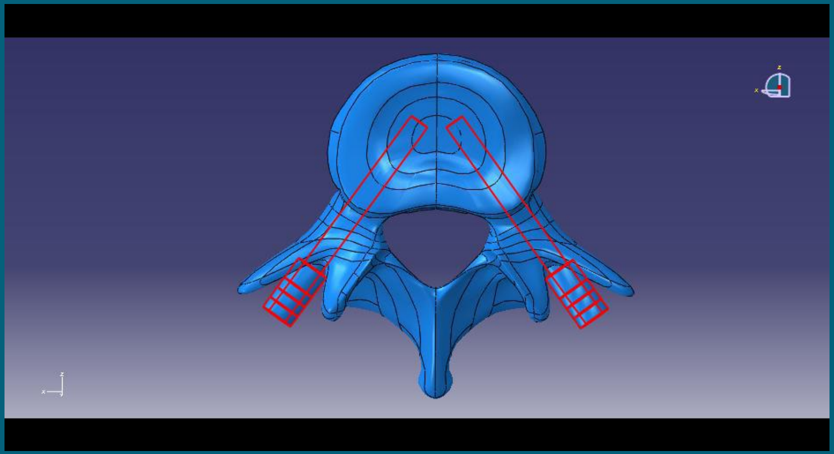


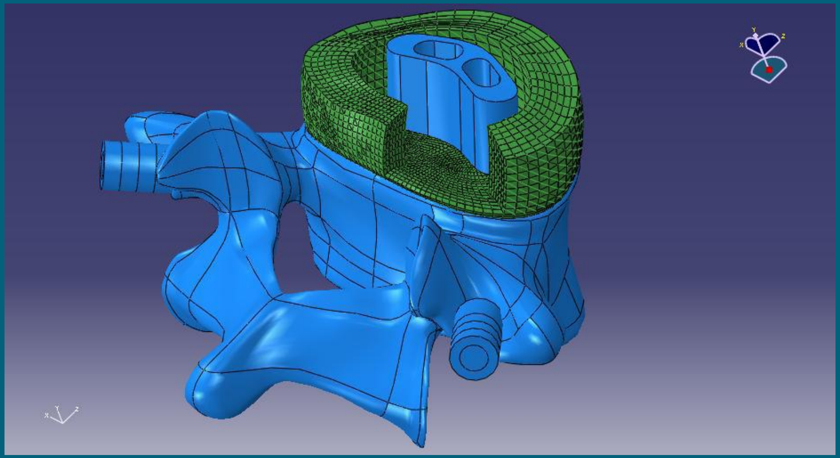
erzas de Contacto FJ (N)		Fuerzas en los Ligamentos (N)			
Izq.	Der.	ALL	PLL	CL Izq.	CL Der.
0.00	0.00	0.00	-0.38	0.17	0.82
0.00	0.00	0.00	-3.11	8.41	8.29
0.00	0.00	0.00	-4.81	0.00	0.00
19.84	16.82	0.00	-3.98	0.00	0.00
42.83	43.12	0.00	-1.35	0.00	0.00

Fuerzas en los Ligamentos (N)					
	SSL	ITL Izq.	ITL Der.	ILL Ant.	ILL Post.
2.38	48.28	7.27	9.14	19.32	285.79
2.85	24.26	3.88	3.42		
0.15	13.72	0.33	0.51		
-3.76	-3.08	0.00	0.00		
0.00	0.00	0.00	0.00		

Evaluation of pedicular fusion implants

- ✓ Insertion of pedicular fusion device in L4-L5 segment consisting in 4 pedicle screws, two rods and intervertebral cage
- ✓ Elimination of Nucleous Pulposus and postero-lateral sector of the Annulus Fibrosus
- ✓ Screws: solid elements
- ✓ Rod: beam elements





Evaluation of pedicular fusion implants

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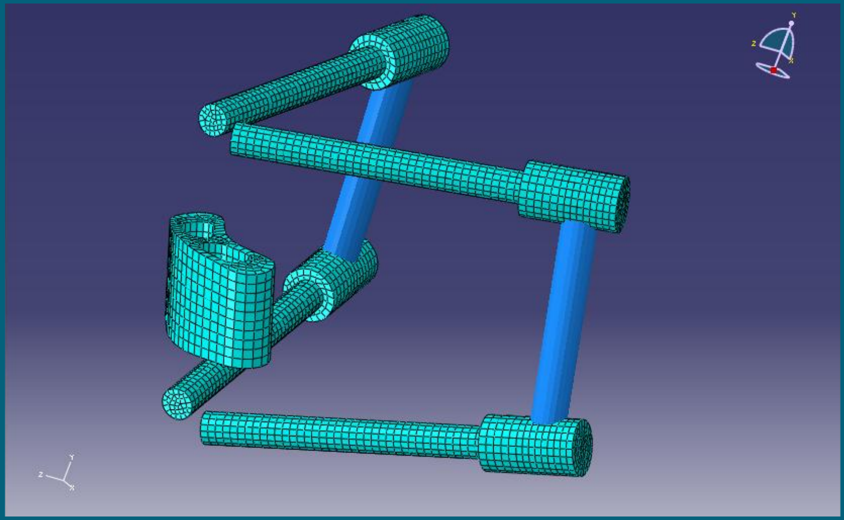

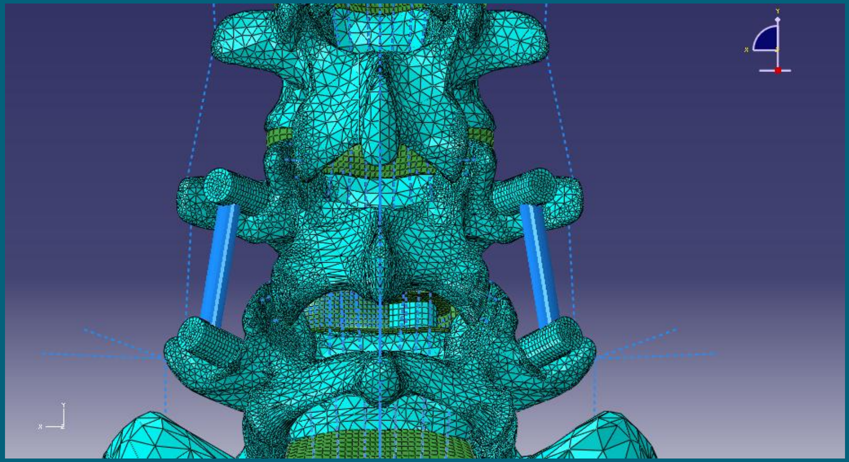

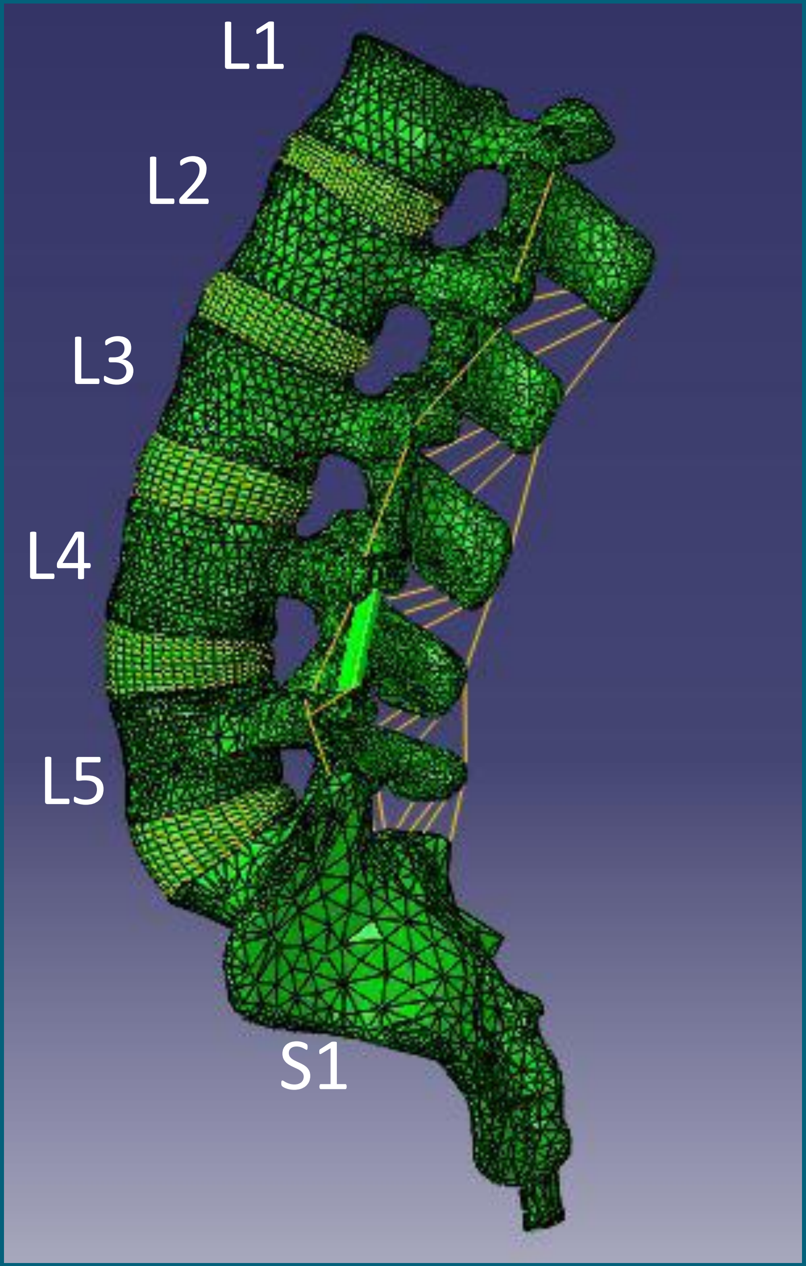
L1
L2
L3
L4
L5
S1

Hypotheses

1. The fusion stabilization device implanted at specified segment increases the relative flexion/extension movement **mainly** at adjacent segments (flexion-extension angle and anterior-posterior displacement);

2. Fusion stabilization devices induce higher facet joint contact forces in adjacent segments;

3. Compliant rods (Peek) cause lower impact than rigid rods (Ti) on at adjacent segments;

4. The load transferred to the intervertebral cage increases with Peek rods (in comparison to Titanium Rods);

Conclusions

1. The load transferred to the intervertebral cage increases with Peek rods (in comparison to Titanium Rods); Verified. Nevertheless, differences are around 10% in most cases

2. The fusion stabilization device implanted at specified segment increases the relative flexion/extension movement at adjacent segments (flexion-extension angle and anterior-posterior displacement); small differences were found. Only slight alteration on flexion/extension angles were found at inferior adjacent level

3. Fusion stabilization devices induce higher facet joint contact forces in adjacent segments; Verified at the superior adjacent segment only

4. Compliant rods (Peek) cause lower impact than rigid rods (Ti) on at adjacent segments; Not verified. TI and Peek devices caused similar mechanical behavior.

Clinical Final Conclusions

- Clinical reported facet joint arthrosis may be a consequence of the identified increment of facet contact forces in adjacent segments
- No clear advantages of Peek rods instead of conventional Ti rods (from a mechanical point of view)

Thank you for your attention