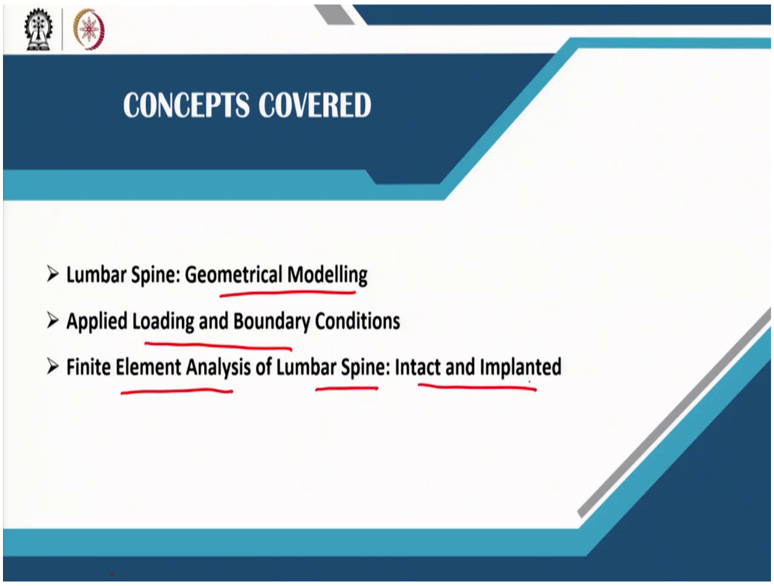
Biomechanics of Joints and Orthopaedic Implants
Professor Sanjay Gupta
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur
Lecture 32
Modelling and Analysis of Intact and Implanted Lumbar Spine

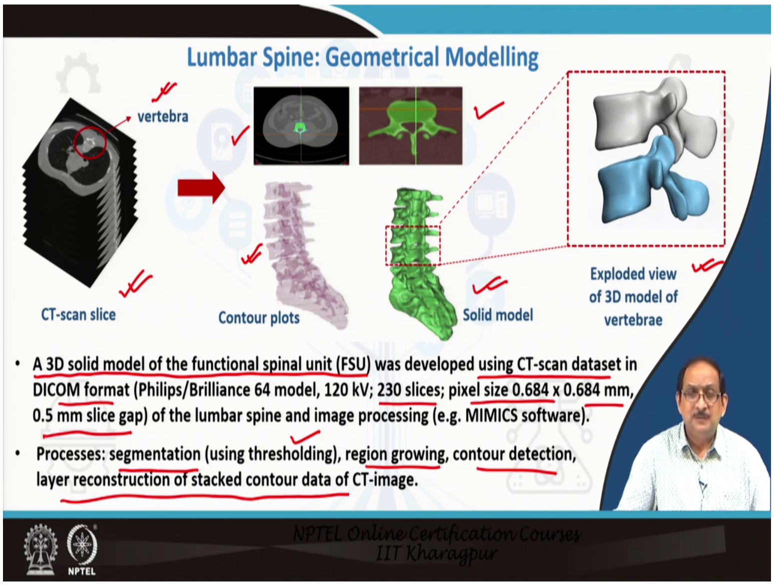
Good afternoon everybody. Welcome to the fourth lecture of module 6, on Modelling and Analysis of Intact and Implanted Lumbar Spine.

(Refer Slide Time: 00:47)



Now in this lecture, we will be concentrating on the modelling and analysis of the lumbar spine. So, we will be discussing about the geometrical modelling aspects, material modelling and the applied loading and boundary conditions that are applicable to the lumbar spine and finally, we will discuss about the finite element analysis of the lumbar spine, both intact and implanted cases.

(Refer Slide Time: 01:27)



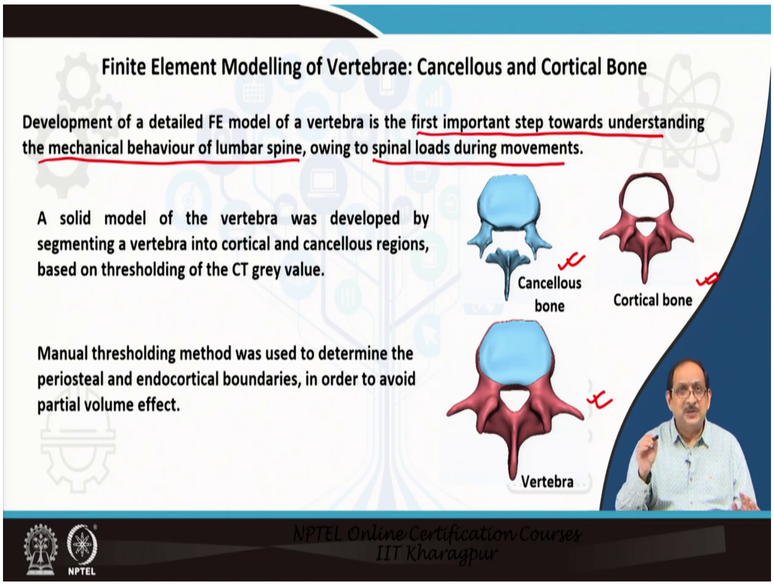
Let us discuss the first topic that is geometric modelling of the lumbar spine. The lumbar spine is more mobile than the thoracic spine and also carries more weight making it the most likely region susceptible to injury in the spine. We therefore, set out to develop a detailed three-dimensional finite element model of the lumbar spine in order to investigate the load transfer within it during physiologic movements.

Now, a 3D solid model of the functional spinal unit was developed using CT scan data set. On the left, as you can see that we have a stack of CT slices, where the vertebra is visible. These CT scan data slices are available in DICOM format and the images were stored in 230 slices of the lumbar spine.

The pixel size is indicated here 0.684 x 0.684 millimeters, and the distance between or the gap between the slices was 0.5 millimeters. So, after acquiring the CT scan data, we use the image processing techniques such as segmentation using thresholding, region growing, contour detection, and layer reconstruction of the stacked contour data of the CT image. This is indicated in the figures presented in the middle.

So, we do segmentation, then we do region growing and then we detect the contour. After plotting the contour, we finally generate the solid model using layer reconstruction of the stacked contour data of the CT image. An exploded view of the 3D model of the vertebra is presented on the right in the slide.

(Refer Slide Time: 03:55)



Now, finite element modelling of the vertebra involves some detailed modelling procedures. It has been observed in some earlier studies that the cortical and cancellous bone regions of the posterior part of a vertebra are modelled as a single unit, and a common material property is assigned to the posterior region of the vertebra.

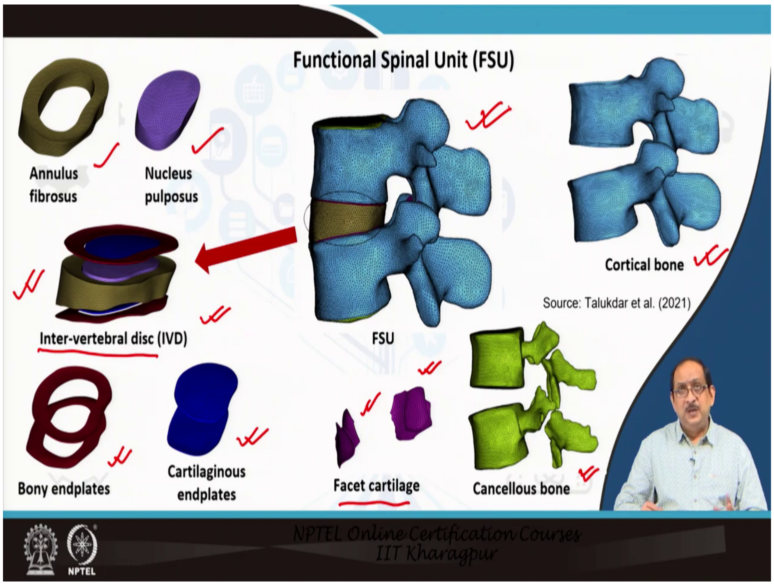
This may lead to doubtful results while investigating stresses and strain near the pedicle screws in an implanted vertebra. Hence, the development of a detailed finite element model of a vertebra is the first important step towards understanding the mechanical behaviour of the lumbar spine, owing to spinal loads during different physiologic movements.

(Refer Slide Time: 05:05)

Now, a solid model of the vertebra was developed by segmenting the vertebra into cortical and cancellous bone regions based on thresholding procedure of the CT grey values. So, in the figure on the right here, the cancellous bone region is separately plotted, and the cortical bone region of the lumbar vertebra plotted is separately, and when we plot the vertebra here, it consists of the cancellous bone region and the cortical bone region.

Manual thresholding method was used to determine the periosteal and endocortical boundaries in order to avoid partial volume effect. So, we have used a precise manual thresholding method to determine the periosteal and endocortical boundaries of the vertebra and then separate the cancellous and cortical bone regions.

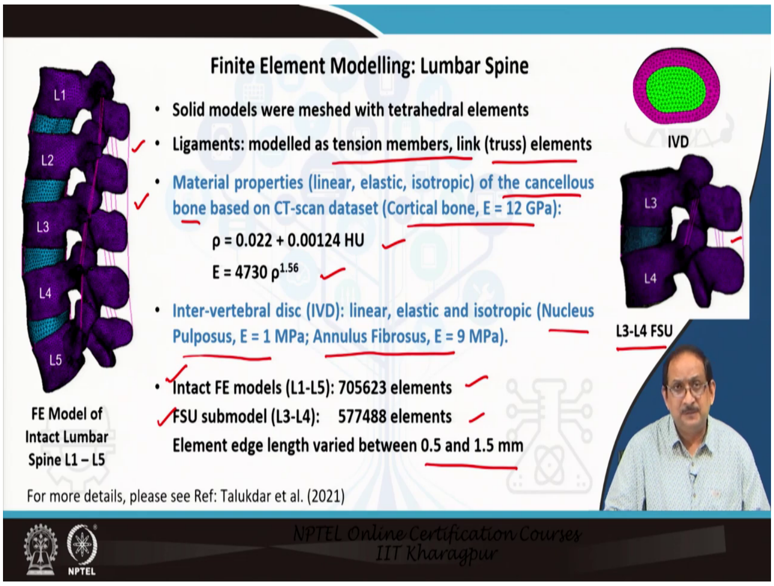
(Refer Slide Time: 06:30)



Now, this slide presents the detailed finite element model of the functional spinal unit. The functional spinal unit consists of the two vertebrae and the intervertebral disc. The intervertebral disc is segmented into nucleus pulposus and annulus fibrosus. The nucleus pulposus covers approximately 44 percent of the entire disc volume. A thickness of 0.5 millimeters generally is assumed for bony endplates on the two sides of the intervertebral discs and the cartilaginous endplates, as indicated here.

Now, if I move towards the right now, in the slide, we can see the finite element model of the cortical bone, the cancellous bone, and the facet cartilages. All these elements together constitute the finite element model of the functional spinal unit.

(Refer Slide Time: 08:16)



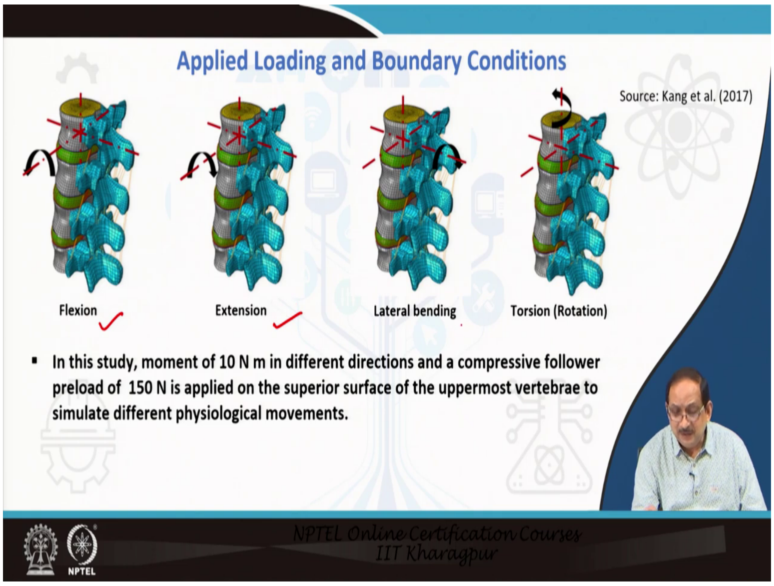
The finite element model of the lumbar spine was created by meshing a solid model with tetrahedral elements. The ligaments were model as tension members; truss elements as shown in the figure presented on the left and also on the line right. Now, the material properties of the cancellous bone were based on the CT scan data set, whereas the cortical bone which was segmented was assigned a material property, Young's modulus equal to 12 GPa.

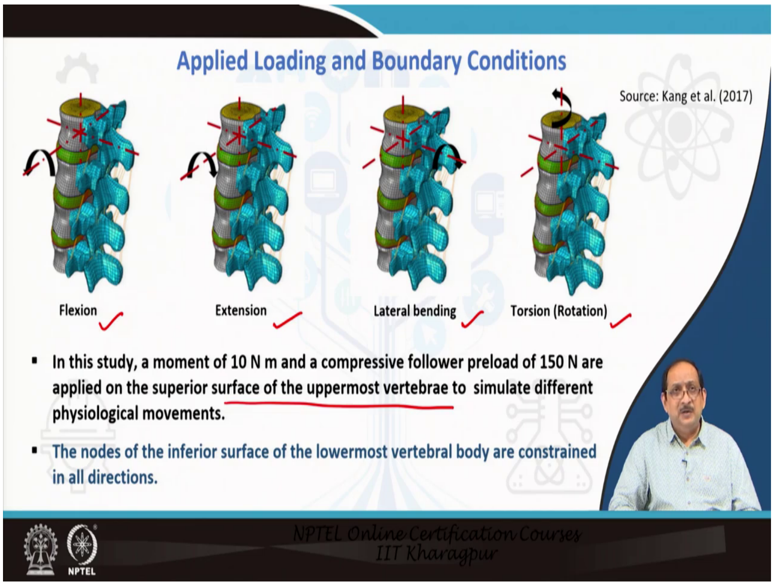
Now, the material properties of the cancellous bone were calibrated with respect to the CT scan data set and using a linear relationship between apparent density and CT grey value in Hounsfield unit and thereafter, a power-law relationship between Young's modulus and the apparent density as stated in the slide.

The intervertebral discs were assumed to have linear elastic properties in this study. However, intervertebral discs are known to have nonlinear viscoelastic properties. So, in this study, we assumed the nucleus pulposus, the E modulus as 1 MPa, and for annulus fibrosus, the E modulus was assumed to be 9 MPa based on data from the literature.

A full intact FE model was generated. An FSU sub-model which consists of the L3-L4 segment; you can see the number of elements for the intact FE model was about 700,000 elements and for the FSU sub-model of L3-L4, about 600,000 elements. The element edge length of these models varied between 0.5 to 1.5 millimetres.

(Refer Slide Time: 11:10)

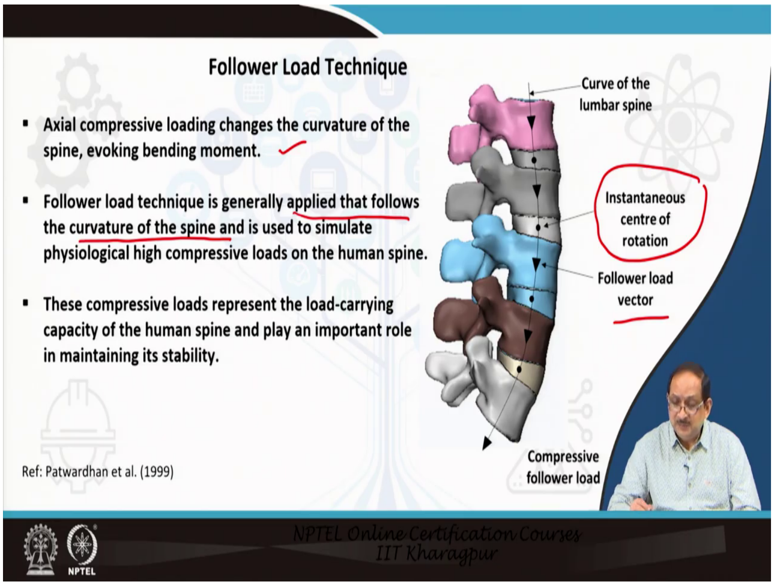




Now, let us come to the applied loading and boundary conditions. The movements of the spine consist of flexion, extension, lateral bending and torsion or rotation. Moment of 2.5 to 10 N-m along different directions and a compressive follower preload of 150 to 1200 N is generally applied on the superior surface of the uppermost vertebra to simulate different physiological movements, as observed in earlier studies.

However, in this study, a moment of 10 N-m and a compressive follower preload of 150 N is applied on the superior surface of the uppermost vertebra to simulate different physiological movements. The nodes of the inferior surface of the lowermost vertebra are constrained in all directions.

(Refer Slide Time: 12:32)



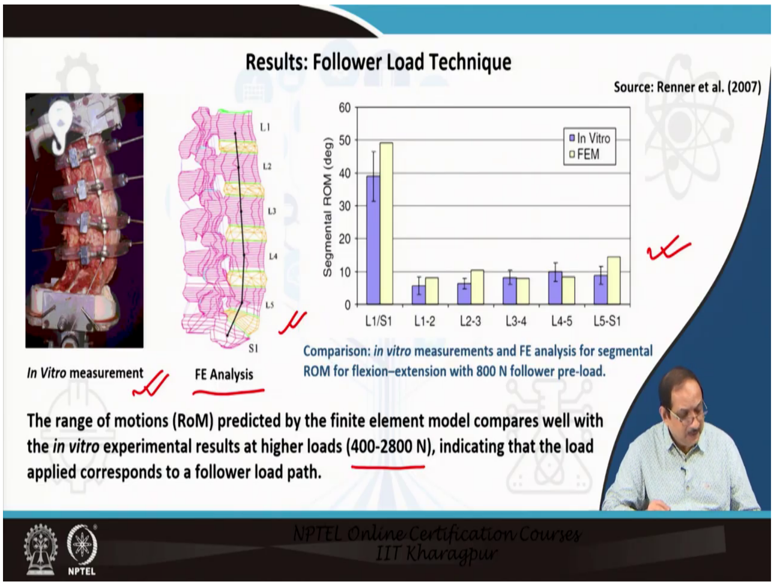
Now, let us discuss about the important technique that has been used by a few researchers, while applying loads on a finite element model of a lumbar spine. So, this technique is known as the follower load technique. Now, when we have discussed the structure and function of the lumbar spine or spine as a whole, we have observed that the spine is actually a curved structure and is also subject to bending moments or bending loads.

Now, when a compressive load is applied on the lumbar spine along the vertical direction, bending moments are induced because of the inherent curvature of the lumbar spine. Now, if we further increase the load, it can actually cause damage to the soft tissue or bony structure. Therefore, a follower load technique is applied for the whole lumbar spine to sustain large compressive loads without causing any damage to the structure.

Now, as you can see here, axial compressive load changes the structure of the spine, evoking bending moment. The follower load technique is generally applied that follows the curvature of the spine and is used to simulate physiological high compressive loads on the human spine. Now, these compressive loads represent the load-carrying capacity of the human spine and play an important role in maintaining its stability.

The follower load technique is based on the calculation of the instantaneous centre of rotation of each segment. It can be based on the instantaneous centre of rotation of vertebra or intervertebral disc and thereafter, we define a path of the load vector along the spine, as indicated here. In the figure, we define a path of load vector along the spine that follows the curvature of the spine without generating moment under high compressive loads. So, this technique is clearly indicated in the figure as presented in the slide.

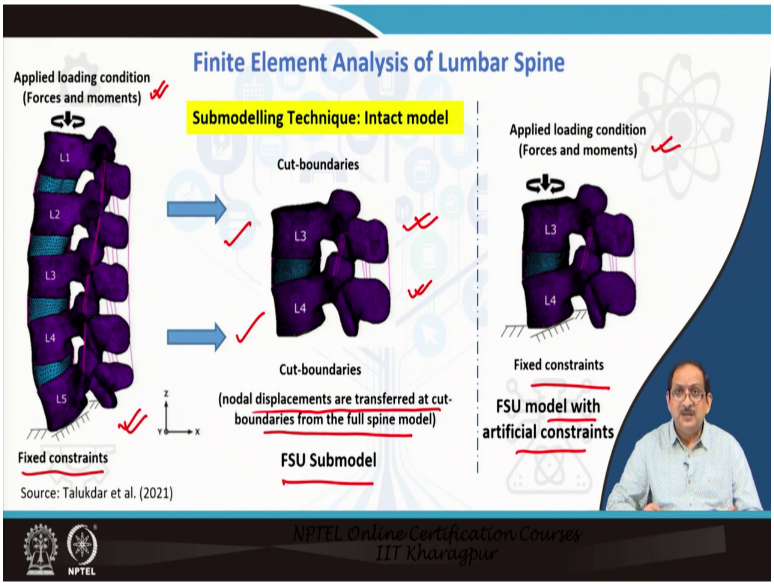
(Refer Slide Time: 15:52)



Now, let us discuss the results corresponding to this follower load technique. Now, a 3D FE model of the lumbar spine was developed and analysed to determine the effect of large compressive follower preloads on the range of motion in three planes, and the model using the follower load technique was validated by comparing the disc compression at all levels in the lumbar spine with the corresponding results obtained by compressing cadaveric lumbar spines in an in vitro measurement or in an experiment.

So, as you can see here on the right, the results of the in vitro measurement and the finite element analysis following the follower load technique have been presented as a bar diagram. The range of motion predicted by the finite element model compares well with the in vitro experimental results at high loads varying from 400 to 2800 N, indicating that the load applied corresponds to a follower load path.

(Refer Slide Time: 17:49)



Now, let us discuss the second topic of this lecture, which is finite element analysis of the lumbar spine. So, we will first take up the case of the intact spine and thereafter, we will take up the case of the implanted spine. The figure presented on the left shows a full model or overall model of the lumbar spine from L1 to L5, where we actually apply forces and moments as applied loading conditions, and we prescribe fixed constraint at the distal end or inferior end of L5 as fixed boundary condition.

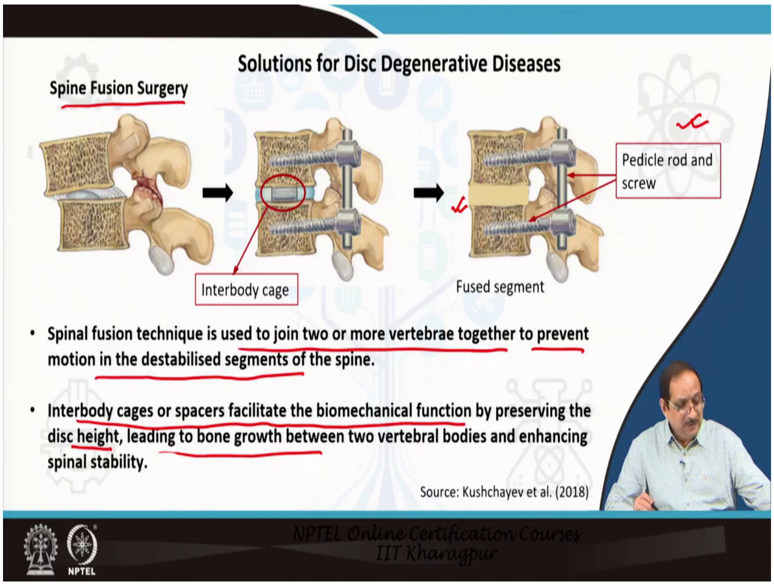
So, all the nodes in the inferior surface of the L5 vertebra are fixed. Now, here we introduce a important technique called the sub modelling technique. Now, suppose we are interested in looking into the stresses and strain considering only functional spinal unit L3-L4. What we have observed is that some artificial constraints are actually applied in these sub-models, the inferior end of the sub-model.

Whereas in the superior end, they apply the forces and moments as applied loading conditions. If we consider the curved structure of the lumbar spine and the effect of forces and moments acting on the vertebrae and the intervertebral discs that are attached to the L3 -L4 FSU segment, the effect of forces and moments acting on the vertebra and the intervertebral disc attached to the L3-L4 FSU segment cannot be ignored.

The elastic behaviour of the whole lumbar spine can be effectively incorporated in the sub-model of the FSU, if we can transfer the nodal displacements at the cut boundaries from the full spine model to this submodel. Therefore, the sub modelling technique helps to effectively incorporate the elastic behaviour of the whole lumbar spine into the functional spinal unit submodel.

A link between the FSU submodel and the full reference model can be established by transferring the nodal displacements at the cut boundaries from the full model of the spine to the submodel, as shown here in these figures. The stress distribution at the cut boundaries of the functional spinal unit submodels was compared with those of the reference solution to assess the validity of this sub modelling technique.

(Refer Slide Time: 21:52)

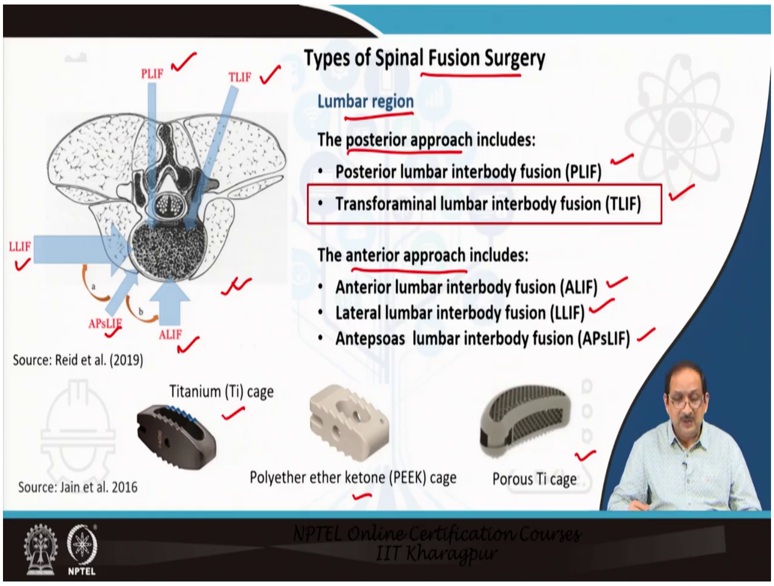


Now, let us discuss some solutions for disc degenerative diseases. Now, spine fusion surgery or spinal fusion surgical technique offers you a solution for disc degenerative diseases.

The spinal fusion technique is used to join two or more vertebra together to prevent motion in the destabilized segments of the spine. As you can see here in the figure, that an interbody cage or spacer is inserted within the two vertebrae in the intervertebral disc space.

So, the interbody cage is a spacer to facilitate the biomechanical function by preserving the disc height leading to bone growth between the vertebral bodies at a later stage and enhancing spinal stability. The pedicle screws and rods help to hold the two vertebrae or hold the two vertebrae in position during the fusion surgery so as to prevent any motion.

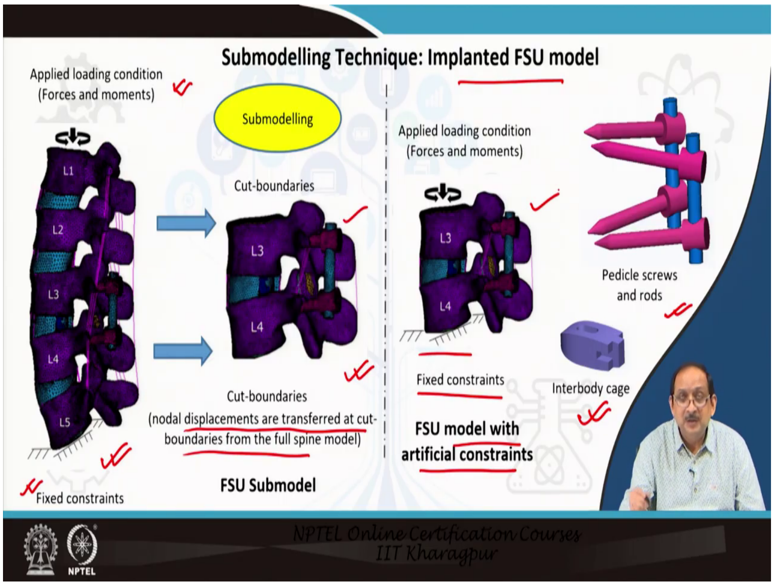
(Refer Slide Time: 23:57)



Let us discuss the types of spinal fusion surgery. So, in the lumbar region, there are two approaches, one is the posterior approach and the other is the anterior approach. So, the posterior approach, as indicated in the figure, consists of two approaches posterior lumbar interbody fusion PLIF and transforaminal lumbar interbody fusion TLIF.

The anterior approach includes anterior lumbar interbody fusion, the lateral lumbar interbody, fusions and the antepsoas lumbar interbody fusion as shown in the figure. Now the interbody cage that is used in this spinal fusion surgery can be made of titanium, polymer, PEEK, and it can also be a porous titanium cage.

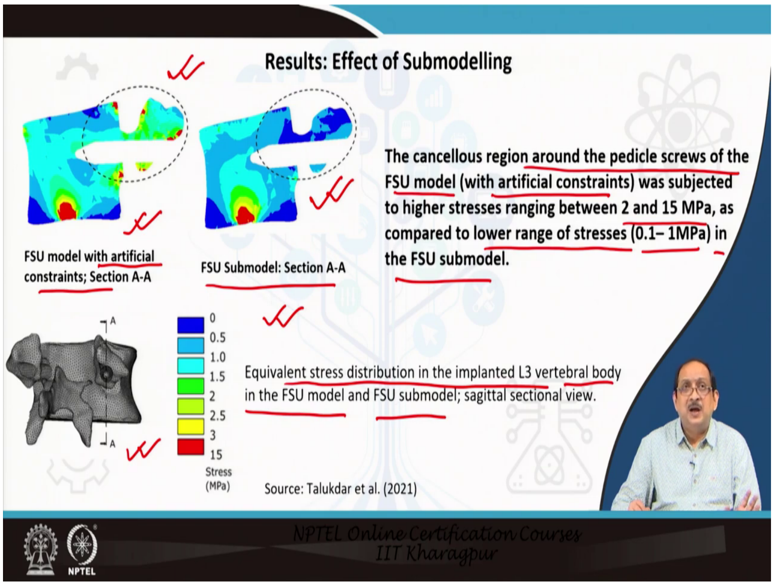
(Refer Slide Time: 25:20)



Now, let us again employ the sub modelling technique for the implanted FSU model. As you can see here, we have the implanted model full model with applied loading conditions, forces and moments and fix constraints at the inferior end of L5. We also have FSU submodel of L3- L4, and the nodal displacements are transferred at the cut boundaries from the full lumbar spine model to this sub-model.

We have actually compared the results corresponding to the sub-model and the results predicted by the model with artificial constraints in the submodel just to investigate the effect of the boundary conditions. Now, this implanted FSU model consists of the interbody cage, which was inserted using the virtuals surgical techniques, and then we also modelled the pedicle screws and rods, as you can see in both cases.

(Refer Slide Time: 27:04)

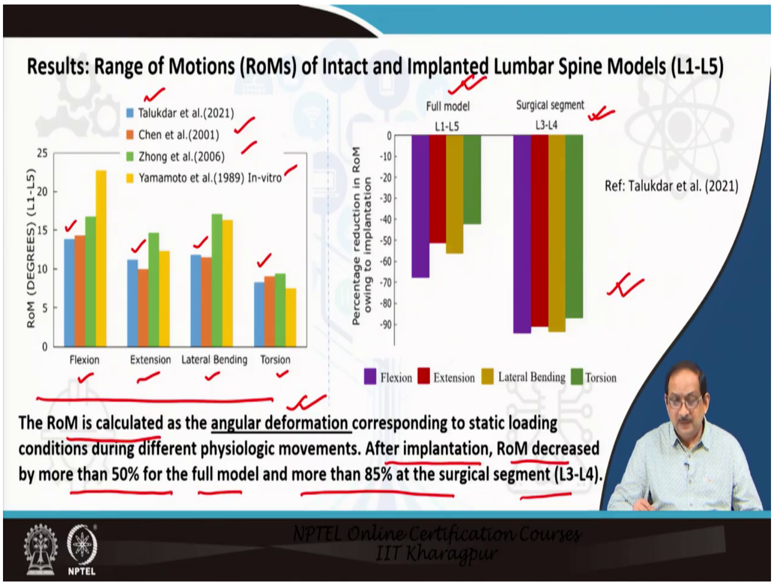


Let us discuss the results on the effect of the sub modelling technique. Now, as you can see here, the evaluation of stresses and strain adjacent to the fixed boundary condition of the small spinal segment appears to be inappropriate and may lead to doubtful results. The artificial constraints generated high stresses, as shown in the encircled region in the figure.

This is for the FSU model with artificial constraints. Now, you can pay attention to the FSU sub-model. As you can see, both the figures are sectional plots of the spinal segment, and the section A-A is shown here in the figure. The equivalent stress distribution in the implanted L3 vertebra only in the FSU model and the FSU submodel is presented and compared.

Now you can clearly see the difference between the equivalent stress distributions. The cancellous bone region around the pedicle screws of the FSU model with artificial constraint, as indicated earlier, was subject to high stresses ranging between 2 to 15 MPa, as compared to the lower range of stress up to its 0.1 to 1 MPa in the FSU submodel. So, in the FSU sub-model, the stresses are considerably lower, as compared to the FSU model with artificial constraints.

(Refer Slide Time: 29:31)

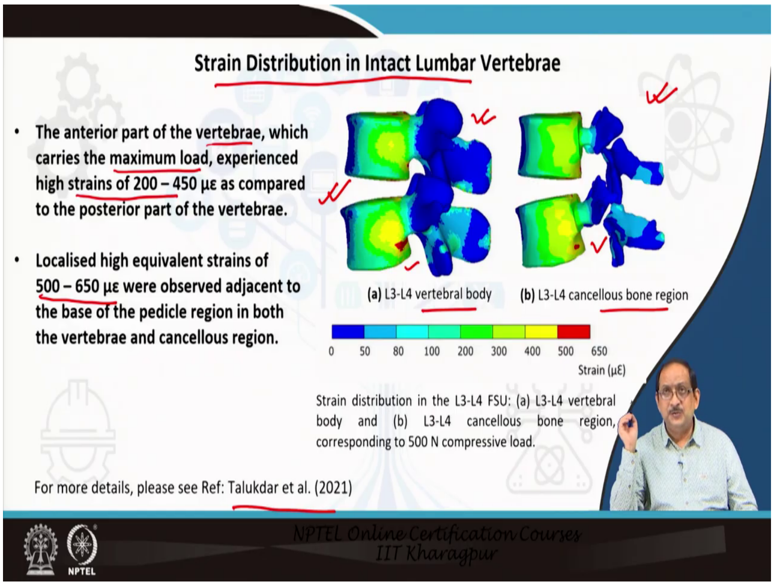


Let us discuss the results predicted by the intact and implanted lumbar spine models, and we will be comparing the predicted results from our study with some earlier published studies. So, the range of motion, calculated as the angular deformation corresponding to static loading conditions during different physiological movements as you can see flexion, extension, lateral bending, and torsion is presented here on the left.

So, the blue bar is the result of our study. Whereas the other colours correspond to published results undertaken earlier. You can see from the figure that the blue bar, which indicates the range of motion, is well comparable and consistent with the results predicted by earlier published studies as indicated here in the figure.

Now, what happens when the lumbar spine is implanted? After implantation, the range of motion is decreased by more than 50 percent for the full model, as you can see here L1 to L5 and more than 85 percent at the surgical segment L3-L4. So, this figure presents the decrease or reduction in ROM after surgery for the full model L1 to L5 and for the surgical segment model L3-L4.

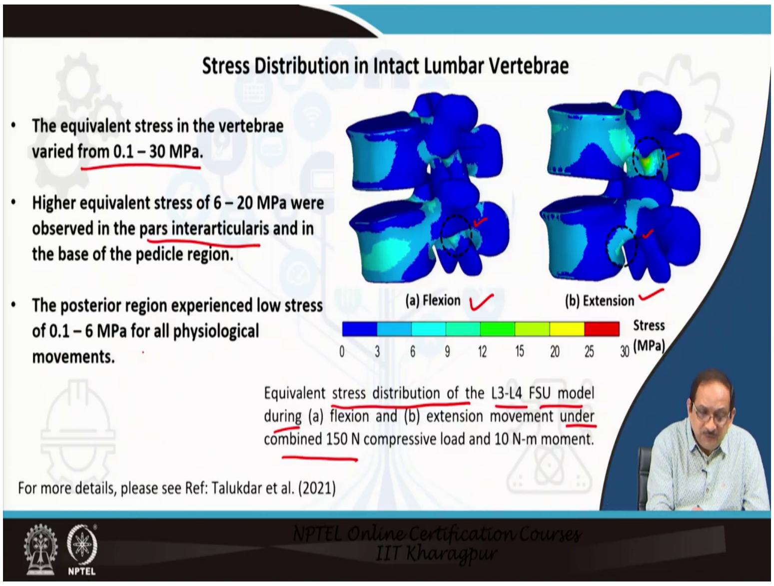
(Refer Slide Time: 32:07)



Now, let us look into the detailed stress and strain distribution. First, we are presenting the strain distribution in the intact lumbar vertebra. So, the anterior part of the vertebra, which carries the maximum load, experienced high strains, 200 to 450 microstrain as compared to the posterior part of the vertebra, which experiences less strain.

Localized high equivalent strains of 500 to 650 microstrain were observed adjacent to the base of the pedicle region as indicated in the figure, in both vertebra and the cancellous bone regions. So, figure a represents the full vertebra and the right figure b represents the strain distribution in the cancellous bone region only.

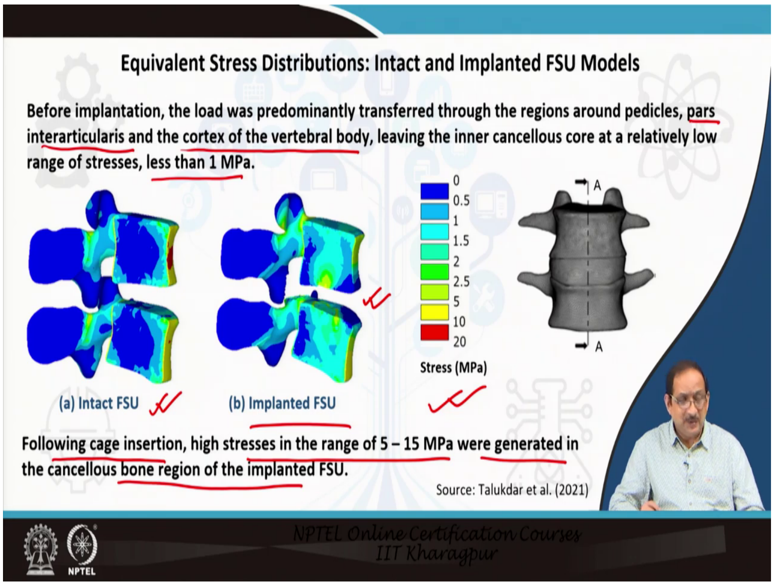
(Refer Slide Time: 33:57)



The stress distribution in the intact lumbar vertebra is presented in this slide. The equivalent stress distribution in the L3-L4 FSU submodel during flexion and extension movement under a combined load of 150 N compressive force and a moment of 10 N-m is presented.

So, the equivalent stresses in the vertebra varied between 0.1 to 30 MPa. High stresses of 6 to 20 MPa were observed in the pars interarticularis and in the base of the pedicle region as shown in the figure. So, these regions, the pars interarticularis and the base of the pedicle region, is marked by black circles. The posterior region experienced low stress, as evident from the figure. So, the stress level is between 0.1 to 6 MPa for all physiological movements.

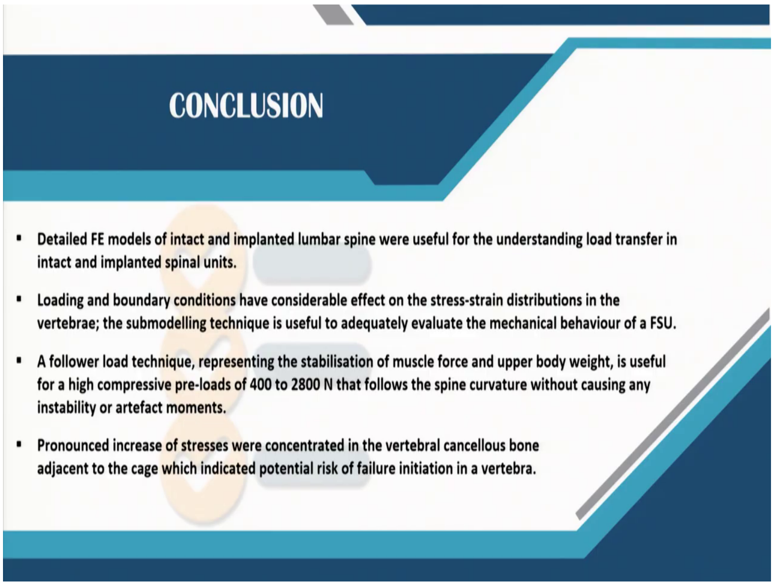
(Refer Slide Time: 35:47)



Let us now compare the intact and implanted FSU models. Before implantation, the load was predominantly transferred through the regions around pedicles that is pars interarticularis and the cortex of the vertebral body, leaving the inner cancellous core at a relatively low level of stress, less than 1 MPa, as indicated here in the figure.

After implantation or following the cage insertion, high stresses in the range of 5 to 15 MPa were generated in the cancellous bone regions of the implanted FSU, as indicated here in the case of the implanted FSU.

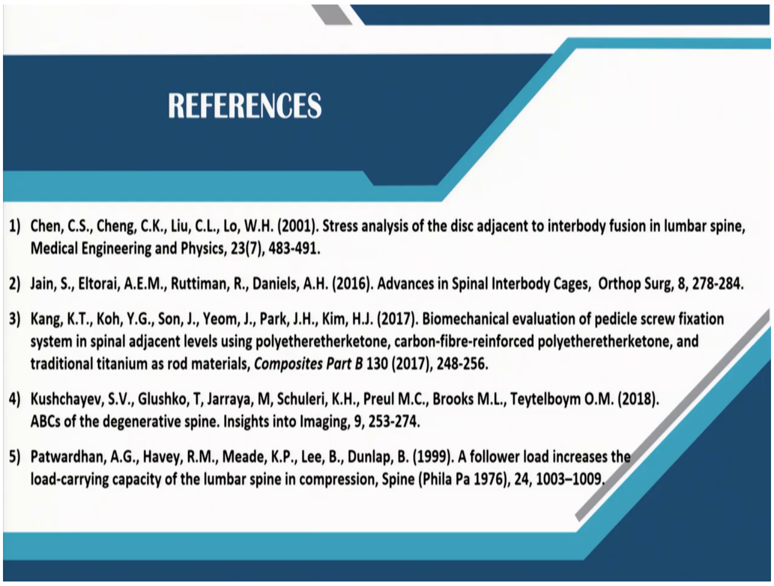
(Refer Slide Time: 37:26)

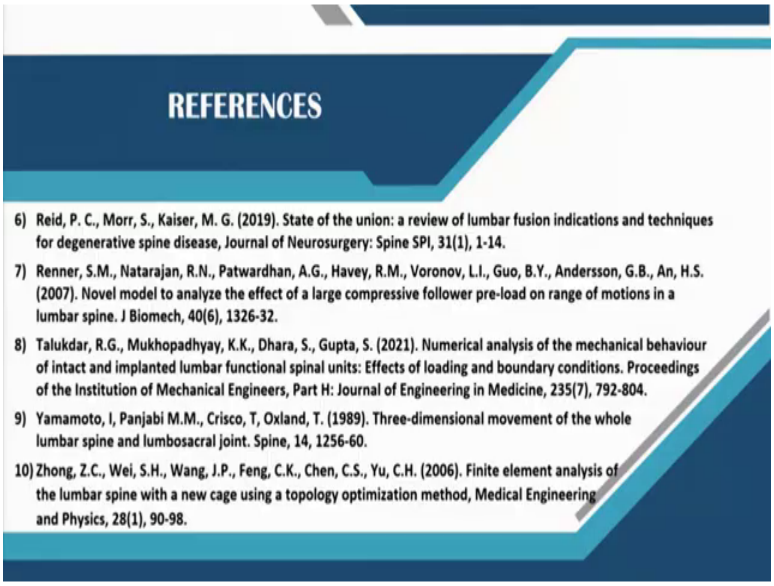


Let us finally come to the conclusions of this lecture. Detailed finite element models of the intact and implanted lumbar spine were useful for understanding load transfer in the intact and implanted spinal units. The loading and boundary conditions have a considerable effect on the stress-strain distribution in the vertebra, and as we had discussed elaborately, the sub modelling technique is useful to adequately evaluate the mechanical behaviour of a functional spinal unit.

A follower load technique representing the stabilization of muscle force and upper body weight is useful for the case of high compressive preloads of 400 to 2800 N, and this technique follows the spine curvature without causing any instability or artefact moments. The pronounced increase of stresses was concentrated in the vertebral cancellous bone adjacent to the cage interbody cage, which indicated a potential risk of fracture initiation in a vertebra.

(Refer Slide Time: 38:51)





The list of references is presented in two slides. Thank you for listening.