Biomechanics of Joints and Orthopaedic Implants
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Lecture No. 28
Anisotropic Nature of Bone

Good afternoon everybody, welcome to the lecture on Anisotropic Nature of Bone.

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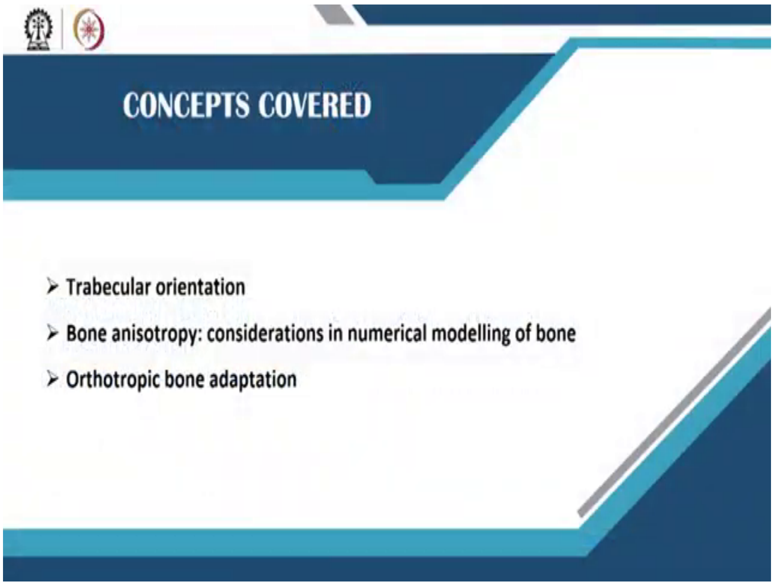

Concepts covered in this lecture are trabecular orientation, bone anisotropy considerations in numerical modeling of bone, and orthotropic bone adaptation.

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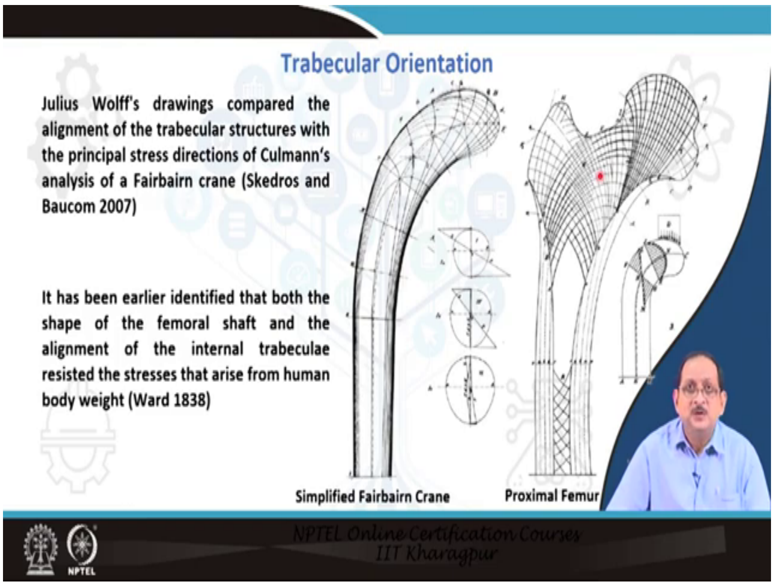

Let us first discuss trabecular orientation. The drawings of Julius Wolf compared the alignment of the trabecular structure with the principal stress directions of Culman's analysis of a Fairbairn crane. In this figure, a simplified solid model of a Fairbairn crane was considered assuming continuum; the figure shows that the principal stress directions owing to the vertically applied load at d, can roughly be compared with those of the proximal femur.

The trabecular orientation or architecture in the proximal femur appears to be somewhat similar to the principal stress directions in the simplified Fairbairn Crane structure. It has been earlier identified that both the shape of the femoral shaft and the alignment of the internal trabeculae resisted the stresses that arise from human body weight during physiological activity.

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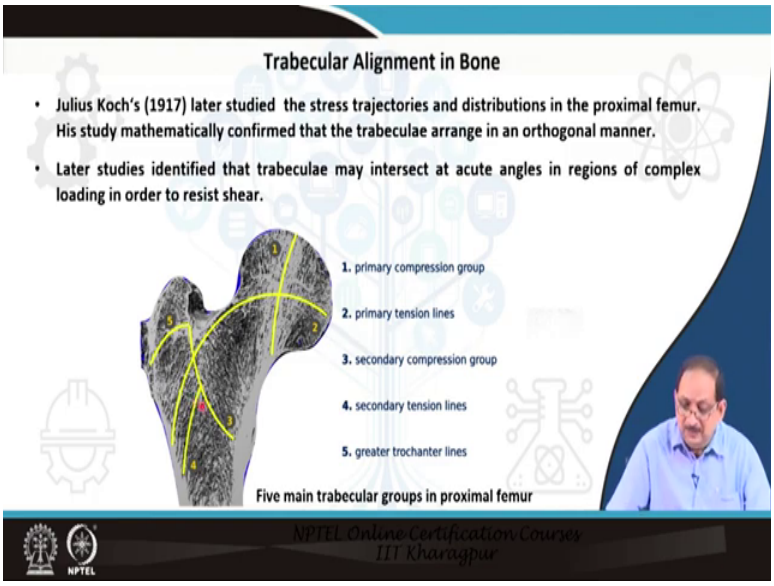

Julius Koch later studied the stress trajectories and distribution in the proximal femur. His study mathematically conformed that the trabeculae arrangement is more or less in an orthogonal manner. Later studies identified that the trabeculae may intersect at acute angles in the regions of complex loading in order to resist shear. The trabeculae in the proximal femur can be classified into five main groups according to their functions, as shown in the figure.

In this figure, the five main trabecular groups in the proximal femur have been plotted. As indicated 1, 2, 3, 4, and 5 are the primary compression groups, primary tension lines, secondary compression group, secondary tension lines, and the number 5 is the greater trochanter lines. So, these are the trabecular groups that mostly intersect in an orthogonal manner, but there are cases, regions where they intersect at an acute angle as well.

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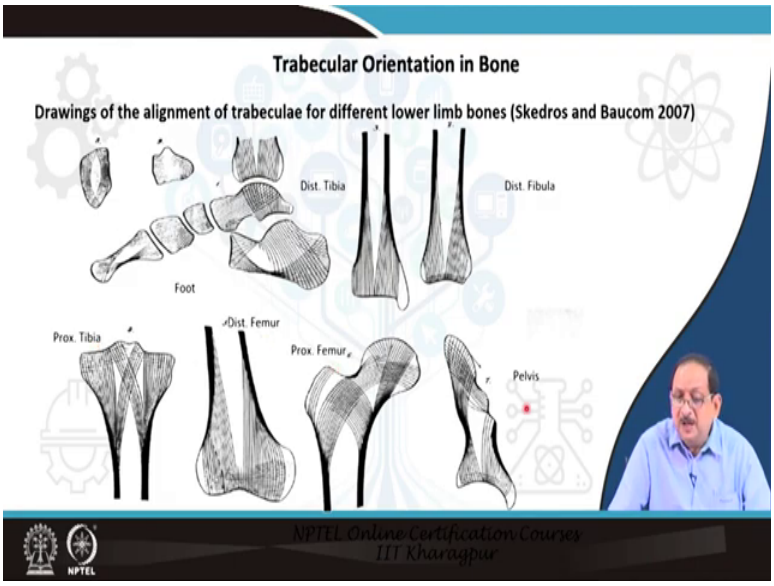

Now, in this slide, the drawings of the alignment of trabeculae for different lower limbs have been presented. So, the trabecular orientation in foot in distal tibia, distal fibula, proximal tibia, distal femur, proximal femur and pelvis has been plotted.

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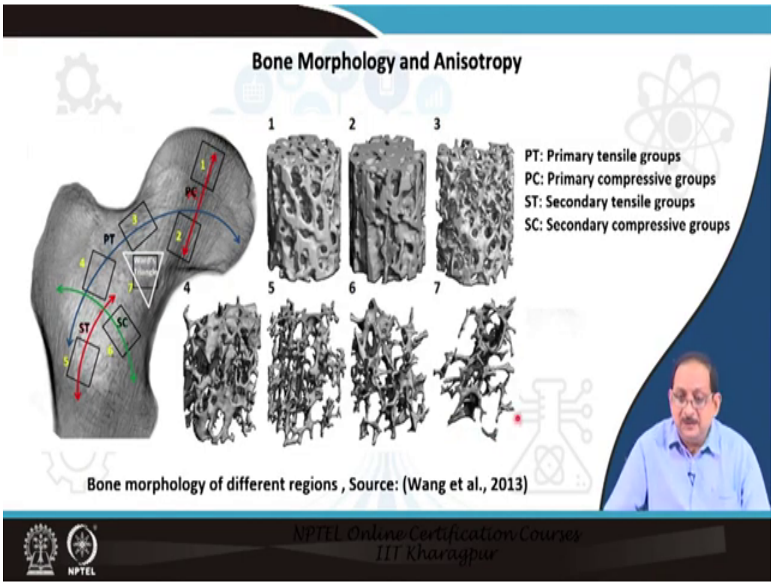

Now, let us discuss about bone morphology and anisotropy. Loading influences bone morphology and hence, the trabecular orientation. The image shows the morphology of bone samples. There are about 7 samples from different areas of the proximal femur. Sample 1 and

2 have similar bone morphology as you can see and these have higher bone density as well. So, these 1 and 2 samples are from the principal compression group area BC whereas, the sample 3 and 4 have similar bone morphology with a lesser amount of bone density and they correspond to the principal tension group.

The samples 5 and 6 in comparison have similar bone morphology with even lesser bone density; these samples correspond to the secondary tension and compression groups in the proximal femur. In between the compressive and tensile groups, there is a triangular-shaped region that is partly dense, that is number 7. This area is known as the Ward's triangle.

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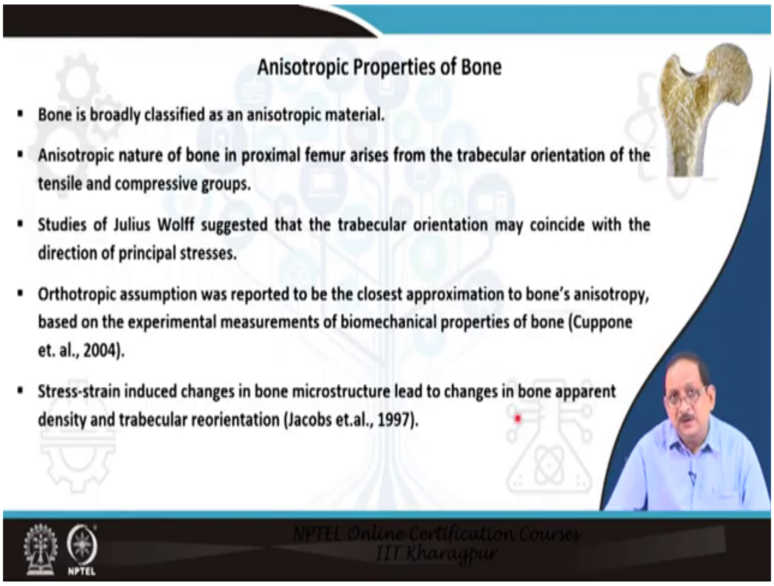

So, let us summarize the anisotropic properties of bone. Bone is broadly classified as anisotropic material. Anisotropic nature of bone in proximal femur arises from the trabecular orientation of the tensile and compressive groups. Studies of Julius Wolf suggested that the trabecular orientation may coincide with the direction of principal stresses.

Orthotropic assumption was reported to be the closest approximation to bone anisotropy based on the experimental measurement of bone mechanical properties. Stress-strain induced changes in bone microstructure lead to changes in bone apparent density and trabecular reorientation.

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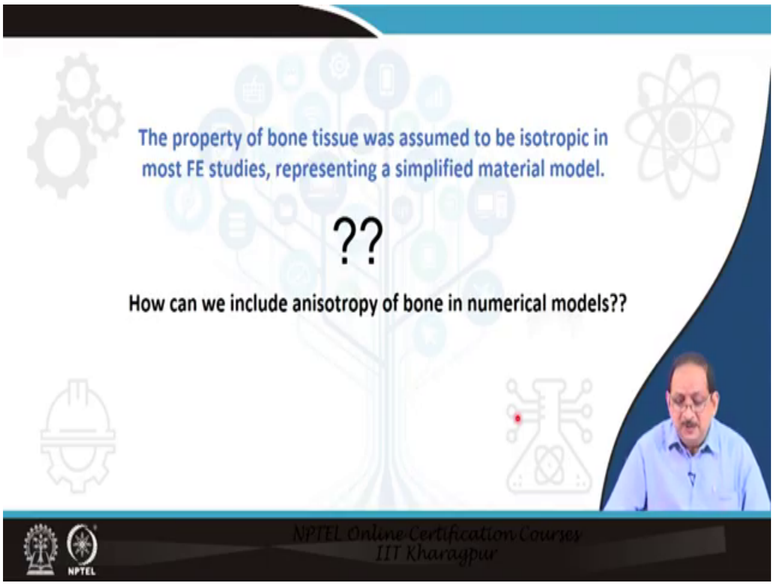

Now, the property of bone tissue was mostly assumed to be isotropic in many finite element studies, representing basically a simplified material model. The main question was, how can we include anisotropy of bone in the numerical models?

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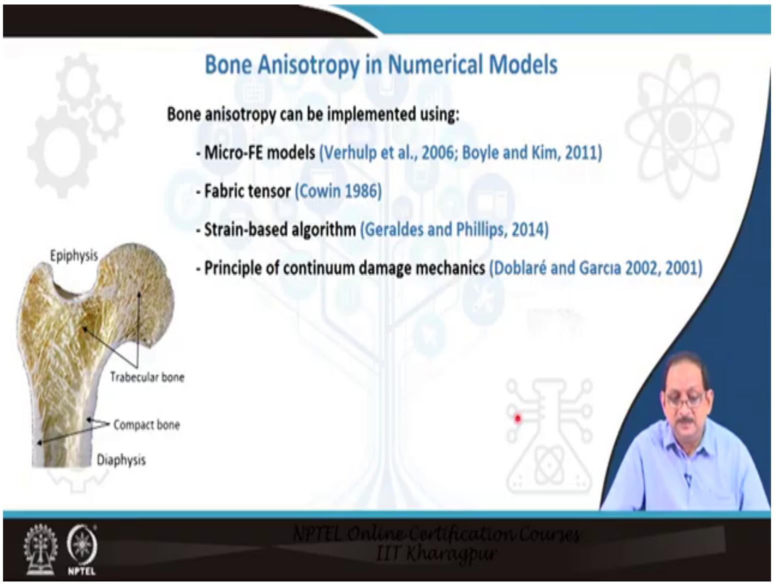

Now, bone anisotropy in numerical models can be implemented using several techniques, which are presented in the following: Micro-FE models, the Fabric tensor method, the Strain-based algorithm, and the Principal of continuum damage mechanics.

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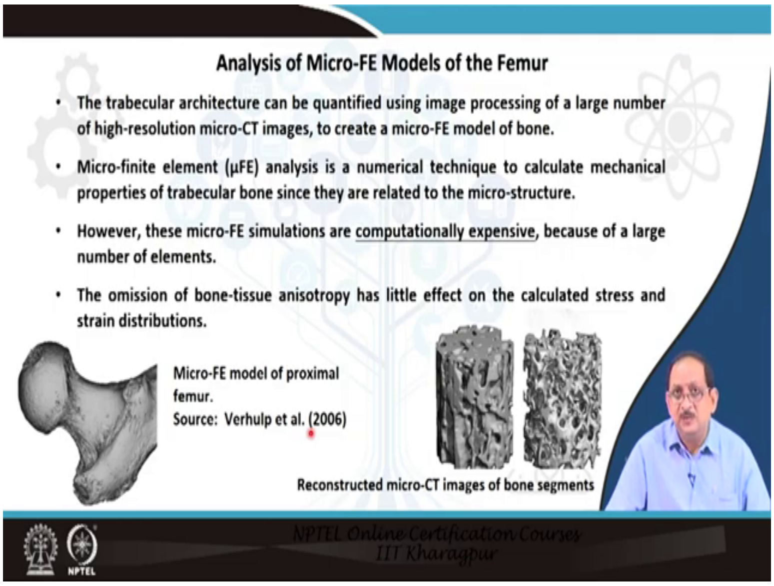

Let us consider the analysis of micro-FE models of the femur. The trabecular architecture can be quantified using image processing of a large number of high resolutions micro-CT images to create a micro-FE model. The reconstructed micro-CT image of bone segments is presented here in the figure. And a micro-FE model of the proximal femur is also presented on the left hand side; this study was done by Verhulp in 2006 published in the journal of biomechanics.

The micro-FE model analysis is a numerical technique to calculate mechanical properties of trabecular bone since they are related to the micro-structure. However, this micro-FE simulation are computationally very expensive because they consist of a large number of elements. The omission of bone-tissue anisotropy has been found to have little effect on the calculated stresses and strain distribution.

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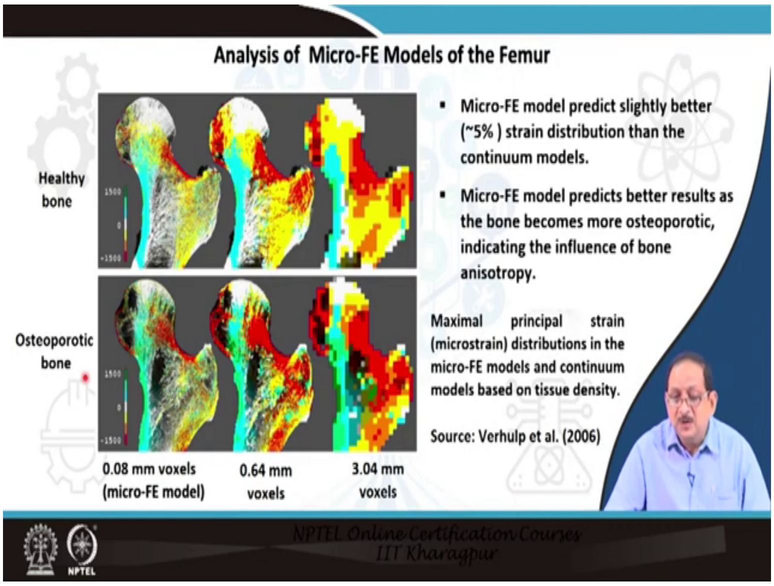

Let us consider more in detail about the study by Verhulp et al. 2006. So, he considered two types of micro-FE models: one from the healthy bone, the other from the osteoporotic bone. So, he had a point 0.08 millimeter voxels micro-FE model. He had the other more closer models, which was microscopic model assuming continuum. One was 0.64 millimeter voxels ,the other was around 3 millimeter voxels size. So, they were comparing the macro-scale continuum model with the micro-FE model constructed from micro-CT scans.

The study observed that the micro-FE model predicted slightly better strain distribution than the continuum model; the difference was around 5 percent as compared to the voxel continuum based model. However, the micro FE model predicts better results as the bone actually becomes more osteoporotic, indicating the profound influence of bone anisotropy in the osteoporotic bone model.

The maximal principal strain distribution in the micro-FE models and continuum-based models was based on tissue density.

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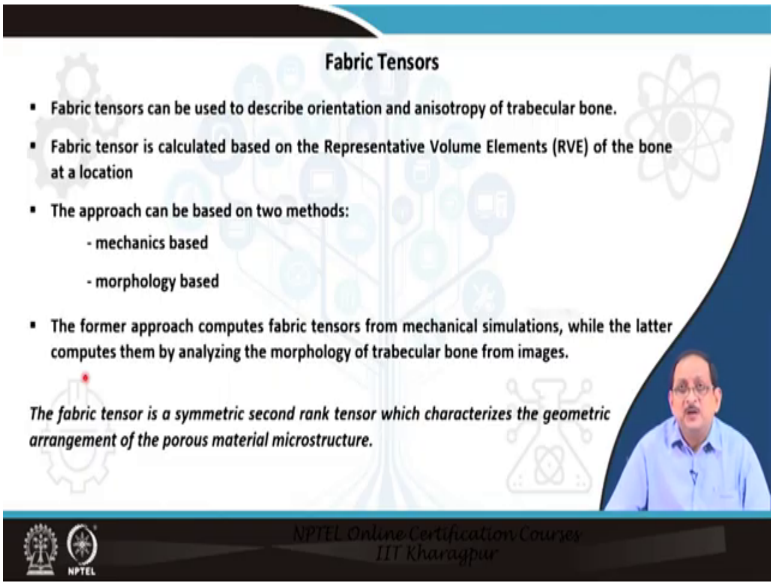

Let us come to another method: Fabric tensor method. The fabric tensors can be used to describe the orientation and anisotropy of trabecular bone. Fabric tensor is calculated based on the representative volume elements of the bone at a particular location. The approaches can be either mechanics-based or morphology-based.

The former approach or the mechanics based approach computes the fabric tensor from mechanical simulations, while the Latter computes it by analyzing the morphology of trabecular bone from high resolution images. The fabric tensor is a systematic second rank tensor which characterizes the geometric arrangement of the pores material micro-structure.

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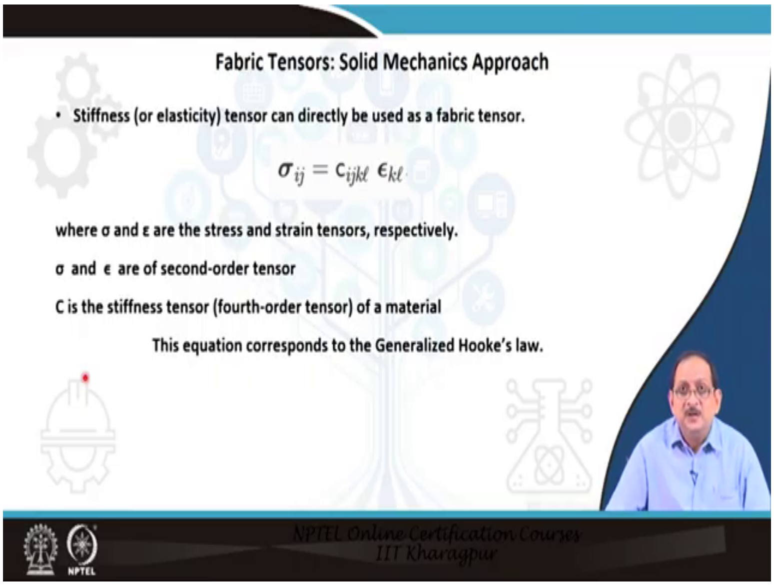

Let us consider the stiffness tensor, which can be directly be used as a fabric tensor.

$\sigma_{ij} = C_{ijkl}\epsilon_{kl}$

In this expression, the sigma and epsilon are the stress and strain tensors, respectively. Both Sigma and Epsilon are second order tensors, and C is the stiffness tensor of fourth order of a material. So, this equation corresponds to the generalized Hooke's law.

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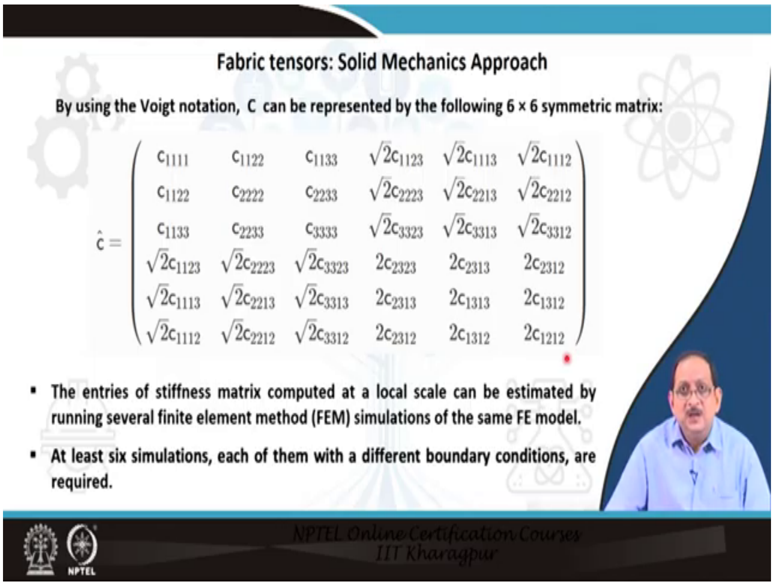

By using the Voigt notation, C can be actually represented by the following 6 x 6 symmetric matrix. The entries of the stiffness matrix computed at a local scale can be estimated by running a finite element method based simulations of the same FE model. At least 6 of such simulations each of them with different boundary conditions are required to calculate the entries of the stiffness matrix.

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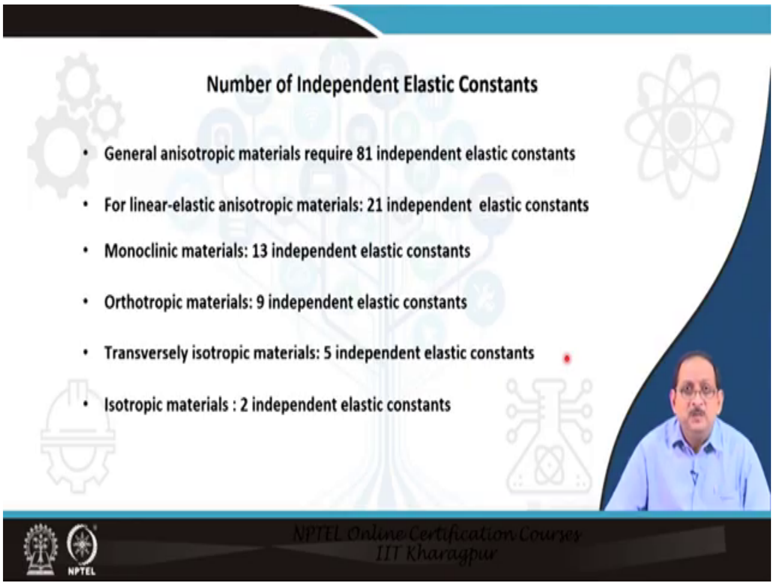

So, we can conclude the number of independent elastic constants for a general anisotropic material, there are 81 independent elastic constants. For linear-elastic anisotropic materials, there are 21 elastic constants. Monoclinic materials have 13 independent elastic constants. Orthotropic materials have 9 independent elastic constants. Transversely isotropic materials needs 5 independent elastic constants, and finally the Isotropic materials needs 2 independent elastic constants.

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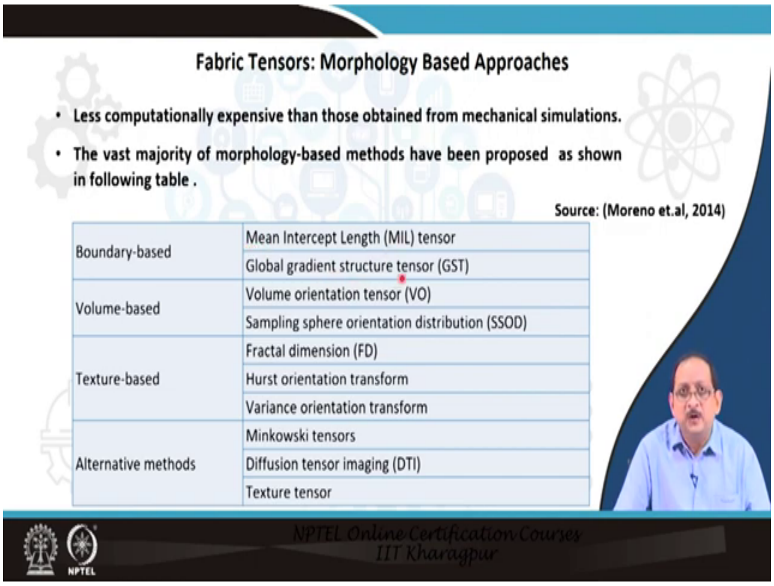

Now, let us move into the fabric tensors based on the morphology approach. The morphology approach is less computationally expensive than those obtained from the mechanical simulations. Let us consider the fabric tensor, which is categorized under the morphology-based approaches. Fabric tensors are less computationally expensive than those obtained from mechanical simulations.

The vast majority of morphology-based methods have been proposed. As shown in the following table, out of which the boundary-based methods considering the mean intercept length tensor or the global gradient structure tensor have been found to be popular.

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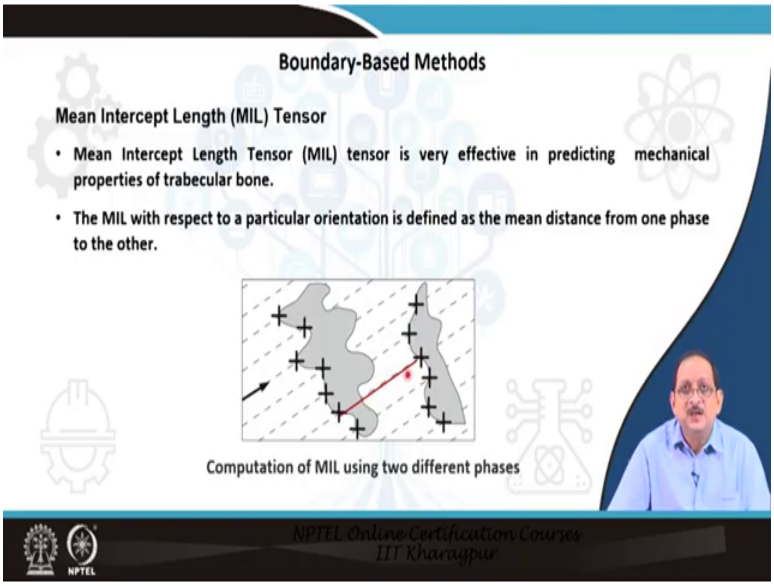

Let us consider the mean intercept length tensor. Mean intercept length tensor is very effective in predicting mechanical properties of trabecular bone. As discussed earlier, bone is a composite material consisting of different phases. The mean intercept length with respect to particular orientation is defined as the mean distance from one phase to the other, as presented in the figure.

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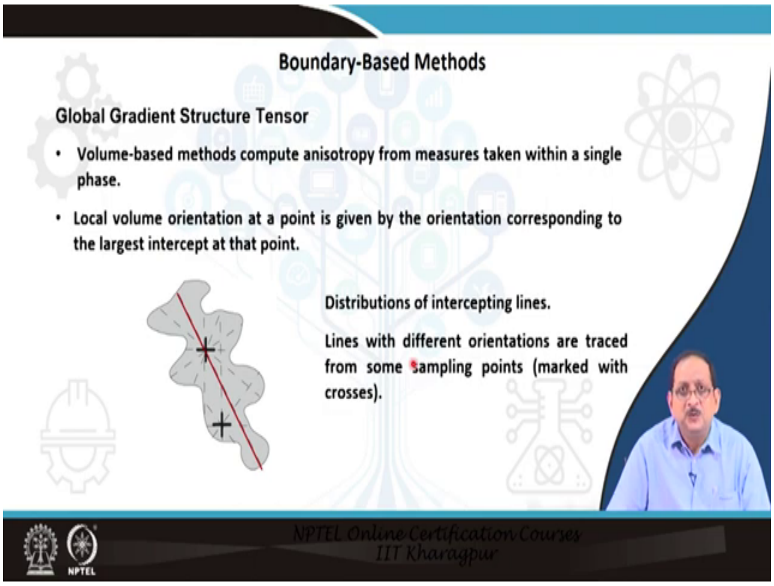

The global gradient structure tensor is another method. It is volume based method that compute anisotropy from measures taken with a single phase, the local volume orientation at a point is given by the orientation corresponding to the largest intercept at that point, as shown in the figure.

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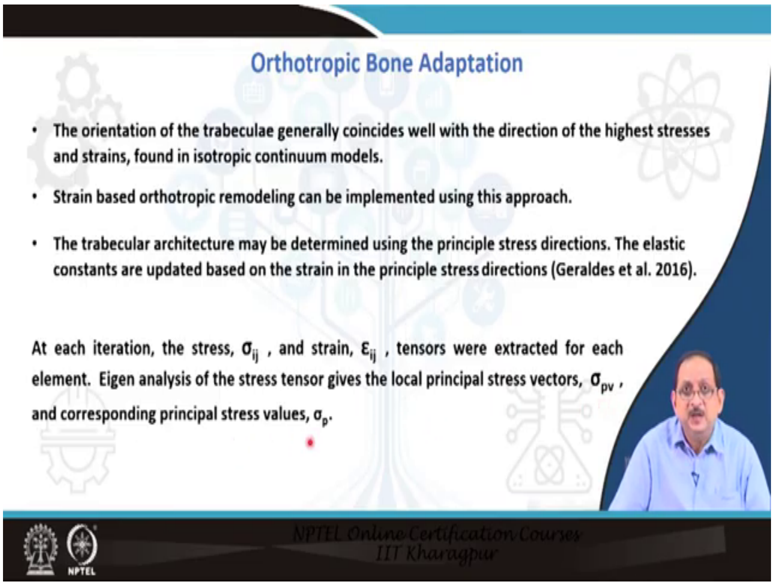

Let us now consider the orthotropic bone adaptation. The orientation of the trabeculae generally coincides well with the direction of the highest stresses and strains, found in isotropic continuum models. Strain based orthotropic remodeling can be implemented using this approach. The trabecular architecture may be determined using the principal stress directions; the elastic constants are updated based on strain in the principal stress directions.

At each iteration, the stress and strain tensors are extracted for each element. Please note it is element-wise extraction so, for an element, the stress and strain tensors are extracted. The Eigen analysis of the stress tensors gives the local principal stress vectors directions σ_{pv} and the corresponding principal stress values, σ_p.

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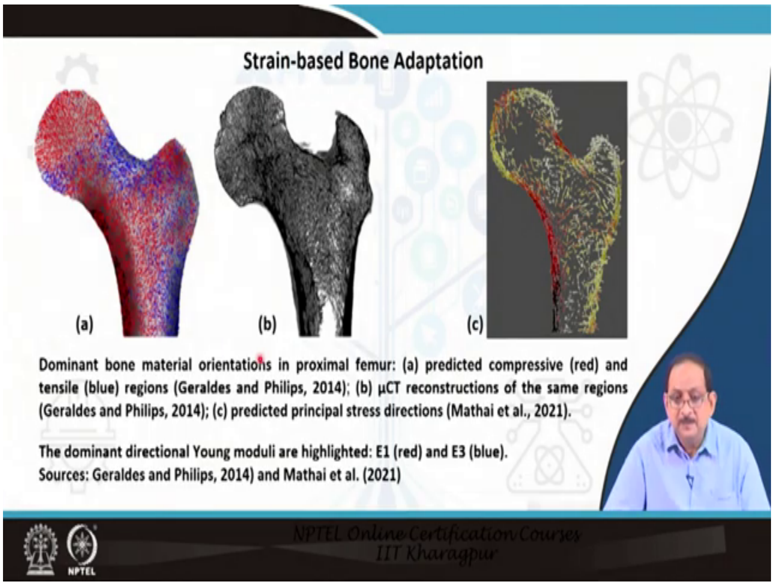

Let us discuss some studies which have been carried out on strain based bone adaptation. In the slide, we can see that the dominant bone material orientation in the proximal femur has been plotted. The first figure a predicted compressive and tensile regions; compressive has the color red and the tensile blue. The second figure is the micro-CT reconstruction of the same regions of the same model. And the third one is the predicted principal stress direction that has been carried out in our laboratories.

So, the dominant directional Young's modules are highlighted in red and blue. In this simulation, the mechanical stimulus is considered as strain along principal directions. The strains are transformed along principal stress directions; the starting configuration, however is the isotropic heterogeneous model on which bone remodeling rule has been applied.

Finally yielding trabecular orientation as a result. However, an intermediate result can be obtained in the form of up gradation of the elastic modulus. Please note that orthotropic bone remodeling will be discussed elaborately later in module 7 in lecture number 7.4, wherein details about theory, formulation, and algorithm development will be presented.

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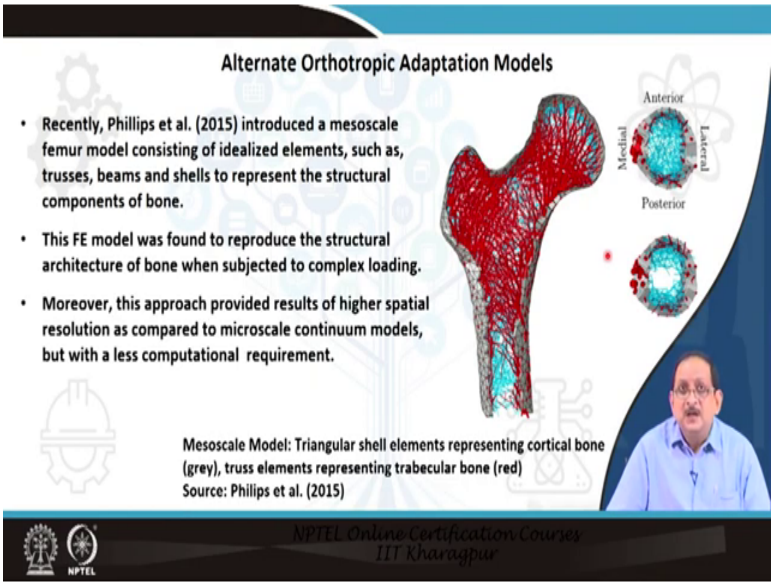

This is another alternate orthotropic adaptation model, very recently investigated by Philips and his group. They introduced a meso scale femur model, consisting of idealized elements such as trusses, beams, shells to represent the structural components of the bone, as shown in the figure.

This FE model was found to reproduce the structural architecture of bone when subject to complex loading conditions. Moreover, this approach provided results of higher special resolution as compared to micro-scale continuum model, but with a less computational requirement.

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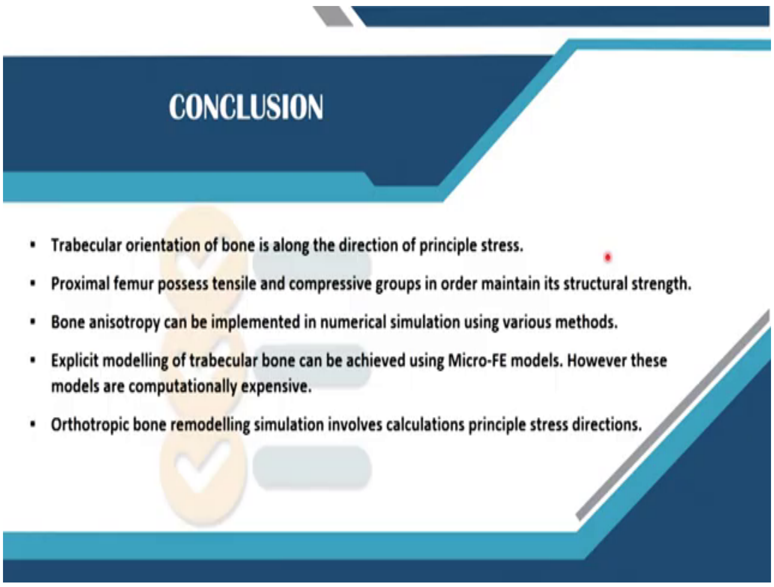

Let us come to the conclusion of this lecture, the trabecular orientation of bone is along the direction of principal stresses. Proximal femur possesses tensile and compressive groups in order to maintain its structural strength. Bone anisotropy can be implemented in the numerical simulation using various methods.

Explicit modeling of trabecular bone can be achieved using micro-FE models; however these models are computationally very expensive. Orthotropic bone remodeling simulation involves the calculation of principal stress directions.

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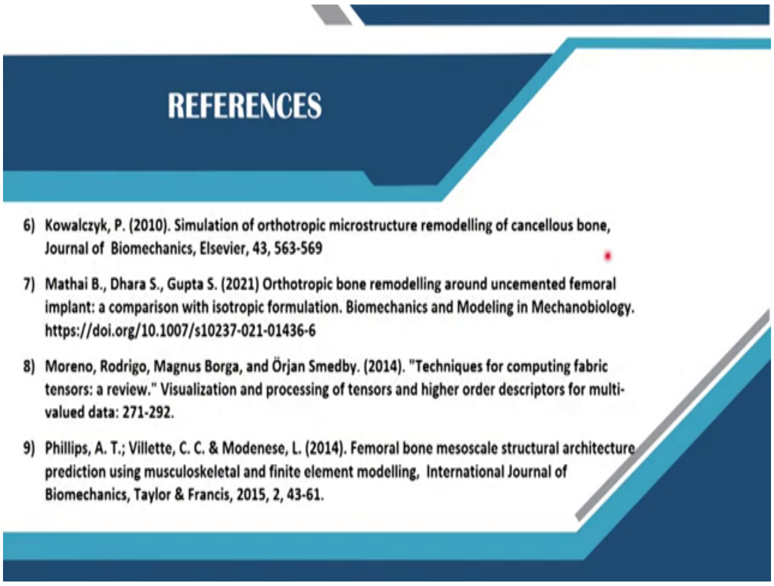

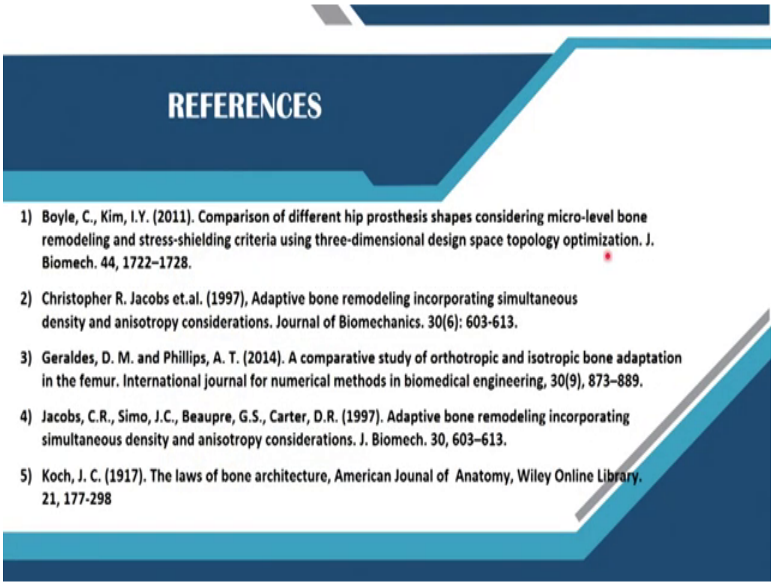

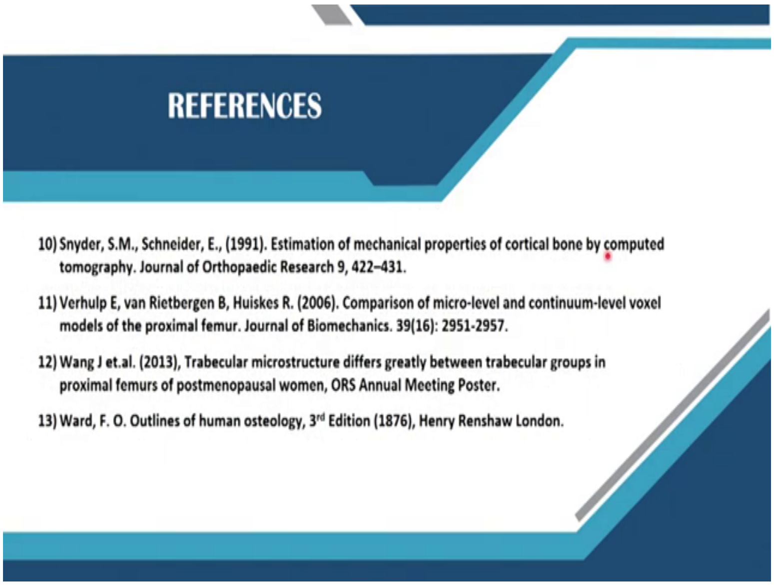

The references, quite a few, are listed here in three slides, and I thank you all for listening.