Biomechanics of Joints and Orthopaedic Implants
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Lecture 42
Bone Ingrowth Around Porous-Coated Femoral Implant

Good morning everybody. Welcome to the 4th lecture in module 8 on Bone Ingrowth Around Porous Coated Femoral Implant.

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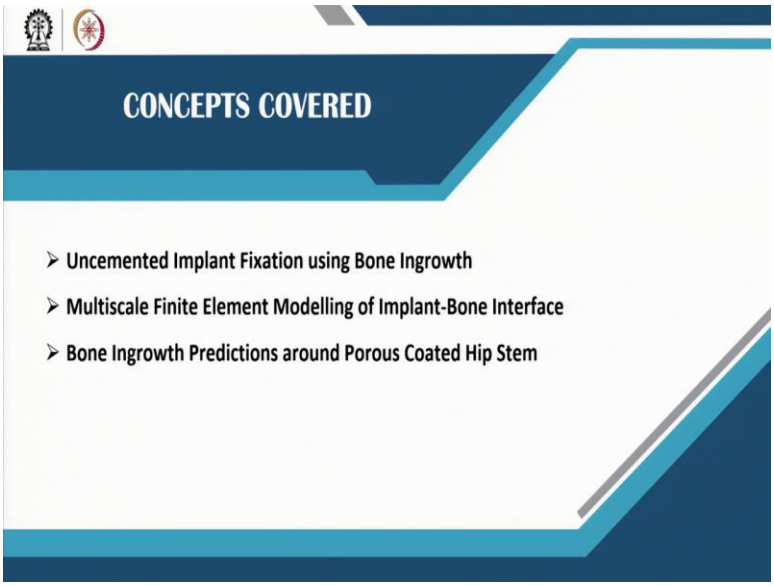

In this lecture, we will be discussing uncemented implant fixation using bone in growth. The second topic is multiscale finite element modelling of implant-bone interface. And the third topic is bone ingrowth predictions around the porous-coated hip stem.

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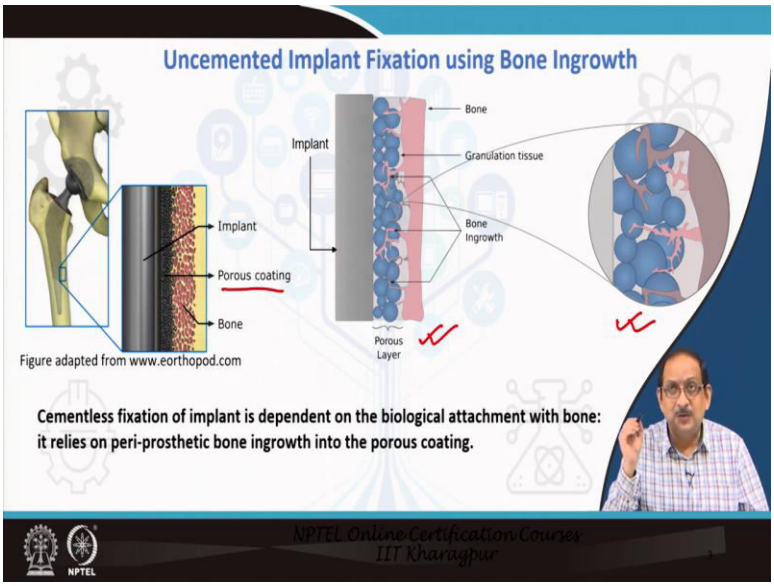

Now, let us consider the uncemented implant fixation using bone ingrowth. The figures presented in the slide summarize the uncemented implant fixation. As you can see here, the implant is usually a product provided with a porous coating to enable implant fixation using bone ingrowth. Now, the cementless fixation of the implant is dependent on the biological attachment with the host bone.

It relies on periprosthetic bone ingrowth into the porous coating as indicated in the figures presented in the slide. Bone actually grows into the porous structure and creates a mechanical interlocking, thereby helping the implant secure fixation with the host bone.

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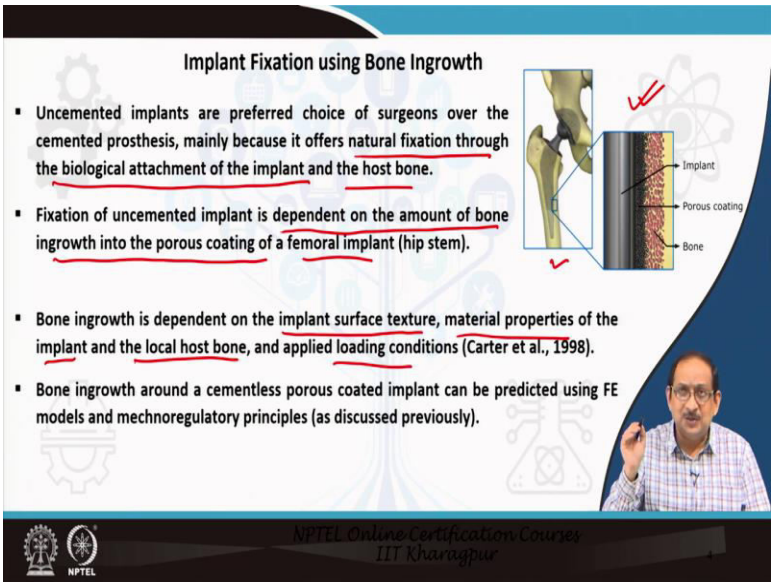

Let us discuss a little bit more about implant fixation using bone ingrowth. Uncemented implants are the preferred choice of surgeons over cemented implants in the recent past. Mainly because it offers natural fixation through the biological attachment of the implant and the host bone, as seen here in the figure. Now, fixation of the uncemented implant is dependent on the amount of bone ingrowth into the porous coating of a femoral implant.

Say for example, a hip stem as indicated in the figure here. Now, bone ingrowth depends on various factors such as implant surface check texture, material properties of the implant, the local host bone, and the applied loading conditions. Which generates or influences the mechanical environment within the implant-bone structure. Now, bone ingrowth around the cementless porous-coated implant can be predicted using Fe models. And the mechanoregulatory principles as discussed earlier.

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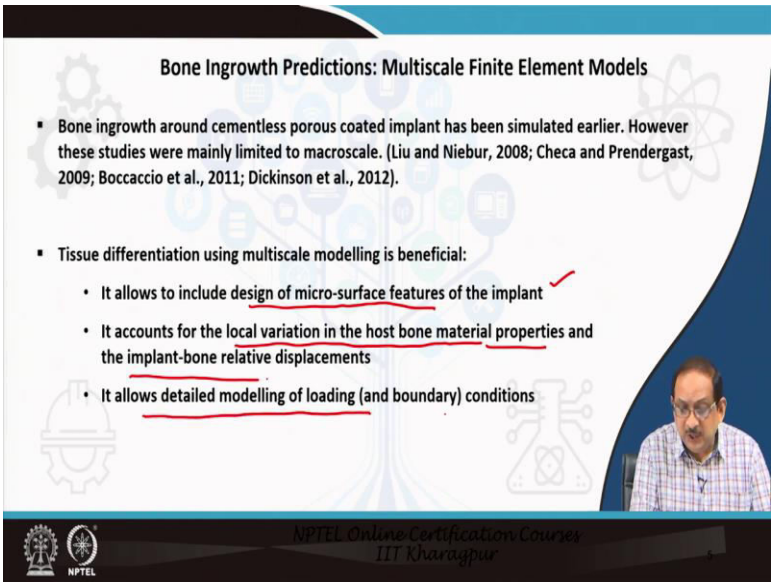

Let us discuss the numerical predictions of bone ingrowth using multiscale finite element models. Now, bone ingrowth around the cementless porous-coated implant has been simulated earlier. However, these studies were mainly limited to macro-scale models. Over the last two decades, several studies have been carried out on numerical simulation of bone ingrowth using finite element models.

Every simulation can predict the spatial distribution of periprosthetic tissue differentiation around porous-coated implants. The tissue differentiation using multiscale modelling is beneficial in many ways it allows to include the design of micro surface features of the implant. It accounts for local variation in the host bone material properties and the implant-bone relative displacements. It allows detailed modelling of the loading and boundary conditions.

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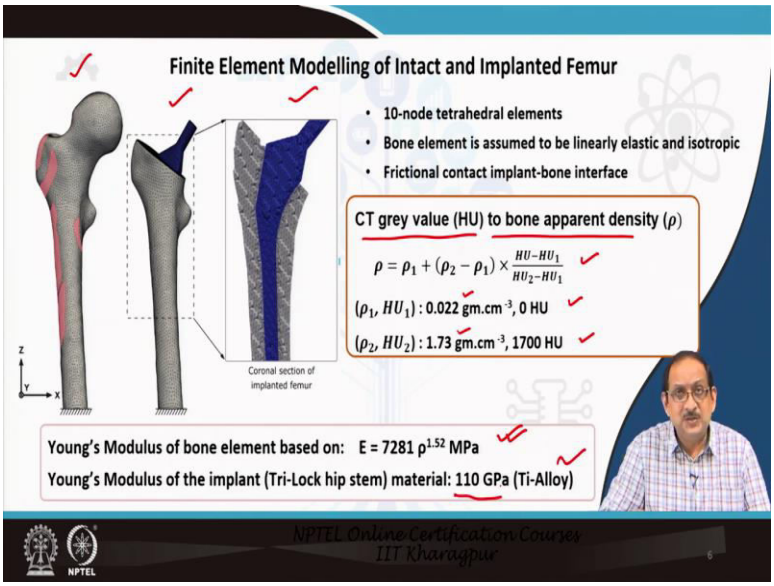

Now, we have undertaken finite element modelling of the intact and implanted femur, which will be eventually used for numerical simulation of bone ingrowth and tissue differentiation to predict the spatial distribution of tissue differentiation around a porous-coated implant. So, for this purpose, we have generated an FE model of an intact femur as indicated in the figure based on the CT scan data set of a subject.

The same femur was virtually implanted with a trial of the hip stem as you can see in the figure and in the inset where a coronal section of the implanted femur has been presented, you can see the implant virtually inside, virtually placed inside the femur bone, the resected femur bone. Now, the model requires a detailed description of the bone material properties we have discussed in the earlier module how the material property distribution of bone can be extracted from CT scan data.

So, here the CT grey value in HU Hounsfield unit to apparent bone density was calibrated for each and every bone element of the finite element model using the relationship as presented in the slide for this femur. Now, here you can see that there are two conditions based on which the linear relationship has been established. So, the first condition corresponds to the one condition that is no bone condition where the apparent density of bone is almost nearly equal to 0, corresponding to a 0 HU.

The second condition corresponds to the cortical bone, where the apparent density is 1.73 grams per centimetre cube. And the corresponding CT grey value is 1700 HU. So, based on these two data points, we can establish the relationship between the CT grey value and the apparent dense bone apparent density and allocate each bone element of the finite element model of the natural femur as well as the implanted femur.

The we can allocate the apparent bone density. From apparent bone density, we can find out the Young's modulus of each bone element using the power-law relationship between E and ρ as mentioned here in the slide. The Youngs modulus of the implant, which is a trial of hip stem, is made of titanium alloy. So, the E modulus is taken as one 110 GPa.

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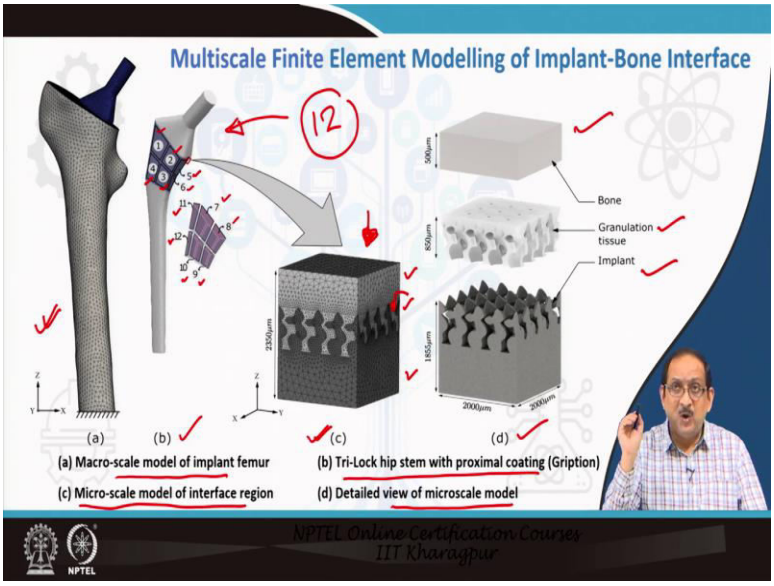

Let us now discuss more in detail the multiscale finite element modelling of the implant-bone interface. So, we started with a macro-scale model of the implanted femur as indicated by a figure a in this slide. And we have the implant has certain regions of interest we define this region of, regions of interest to monitor the spatial distribution of tissue differentiation around the porous-coated implant.

So, you can see that the regions of interest like 1, 2, 3, 4 are indicated on the anterior side of the implant, the 5 and 6 are towards the medial side, 7, 8 move towards the superior, 9, 10 inferior and towards the lateral side we have 11 and 12. So, there are 12 regions of interest in the macro

scale Fe model. Now, multiscale Fe modelling involves separate models of the implanted femur, which can be macroscale and implant-bone interface which is essentially a microscale model.

The hip stem generally includes a porous coating to allow bone ingrowth. As I have discussed, the region is split up into different regions of interest, corresponding to figure (b) of the trial of the hip stem with proximal coating. Now, in this case, the coating has a name which is known as gription coating. And as you can see here in figure (c) the cross-section of the coating is visible.

The microscale model of the implant-bone structure involves a separate region corresponding to bone granulation tissue and implant. Here in figure c also you can see that the granulation tissue is within the inter bead spacing of the coating.

So, figure (c) is basically the microscale model of the implant-bone interface with different regions. And a detailed view of the microscale model is presented in figure (d) with the dimensions. And the different regions like bone granulation tissue and implant as discussed earlier. The displacement boundary conditions are transferred from the macro scale model to the micro scale model, which we will discuss a little later.

The lateral sides of the microscale model are assumed to have periodic boundary conditions for the structural analysis. The microscale model's top region is applied with displacement boundary conditions that correspond to the implant-bone relative displacements. A total number of 12 micro scale models corresponding to these regions as you can see here were used in the FE simulation of the tissue ingrowth in these regions of interest 1 to 12.

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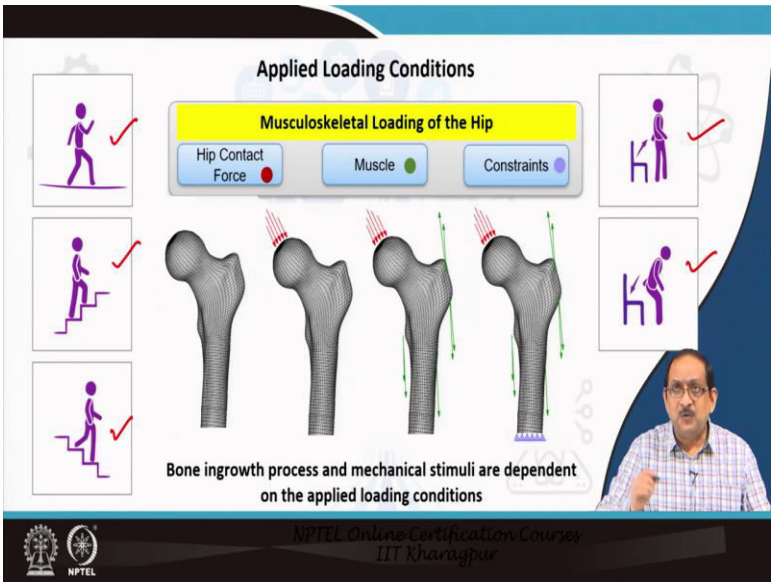

Now, let us figure out the applied loading conditions used for the macroscale model as you already know that the bone ingrowth process and the mechanical stimuli are dependent on the applied loading conditions. The musculoskeletal loading of the hip corresponding to various activities were considered in this study. So, the hip joint reaction force or hip contact force as you can see in the figure, was included in the musculoskeletal model as loading conditions.

We have the muscle forces as well and constraints were prescribed at the distal end of the proximal FE model of the femur bone. The musculoskeletal model of forces correspond to various activities, which are everyday daily activities like walking, stair up, stair down, sitting up from a chair, and sitting down on a chair. So, we have a variety of activities, and each activity has a set of musculoskeletal forces which are used as applied loading conditions for the FE model.

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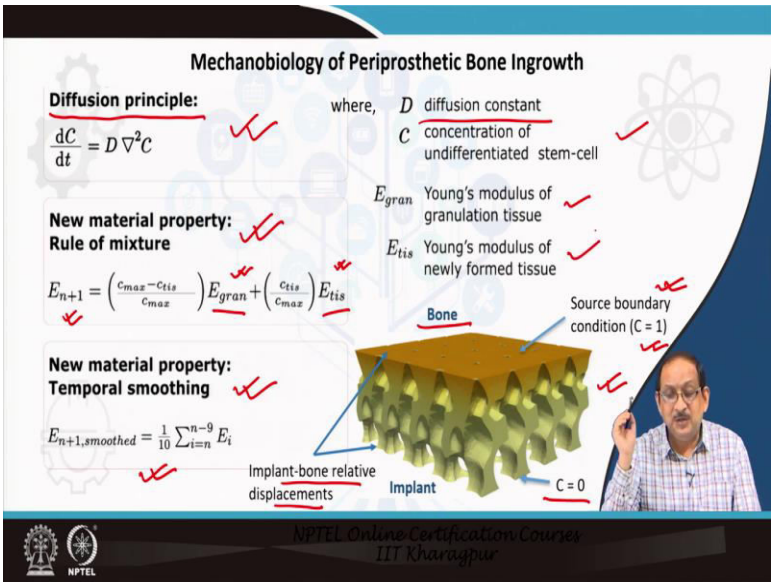

Now, let us look into the mechanobiology of the periprosthetic bone ingrowth which we have discussed earlier in detail. But this slide summarizes the whole process of the mechanobiology based simulation of periprosthetic bone ingrowth. The bone ingrowth simulation is based on the diffusion principle, and the phenomenological model discussed earlier. In the diffusion analysis, the top surface of the granulation tissue so, we will be considering the evolution of the granulation tissue layer.

So, the granulation tissue is plotted here. And the top surface of the granulation tissue is assumed to be the source of mesenchymal stem cells. So, granulation tissue is generally rich with mesenchymal stem cells, and the simulation actually can progress with the source boundary condition, which specifies the concentration of MSC equal to 1. So, concentration the maximum concentration is 1, and we assume that the top surface has the maximum MSC concentration.

Whereas at the bottom surface, which is the implant surface, the concentration of the MSEs is 0. So, we assumed that the MSEs move or migrate from the bone towards the implant. The lateral sides of the microscale model is assumed to have periodic boundary conditions, which means the same boundary conditions on the lateral sides. The new tissue types in the inter bead spacing region can be predicted using mechano regulatory principle.

But before that, we need also to mention that we have to parallelly run a structural analysis. And this structural analysis requires the prescription of boundary conditions in the form of implant-

bone relative displacement. So, the structural model's top and bottom surface will actually consist of implant-bone relative displacements. And the lateral surfaces will be prescribed with periodic boundary conditions extracted from the macroscale model.

So, we need to run two different simulations, one is the diffusion analysis, and the other is structural analysis. We can apply the mechanoregulatory principle, which will eventually translate into new tissue type formations. So, following the mechanoregulatory principle and the method of simulation which we had discussed in detail earlier in the lectures in this module.

We can find out the updated Young's modulus applying the rule of mixtures, this was discussed earlier. So, this rule of mixtures involves Young's modulus of the granulation tissue and Young's modulus of the current tissue, and it gets updated with each iteration; we can also apply the method of temporal smoothing to avoid numerical instabilities. So, in this process using the diffusion principle, you can see the D refers to diffusion constant.

C refers to the concentration of undifferentiated mesenchymal stem cells. $E_{granulation\ tissue}$ is Young's modulus of the granulation tissue, and E_{tissue} is Young's modulus of the newly formed tissue.

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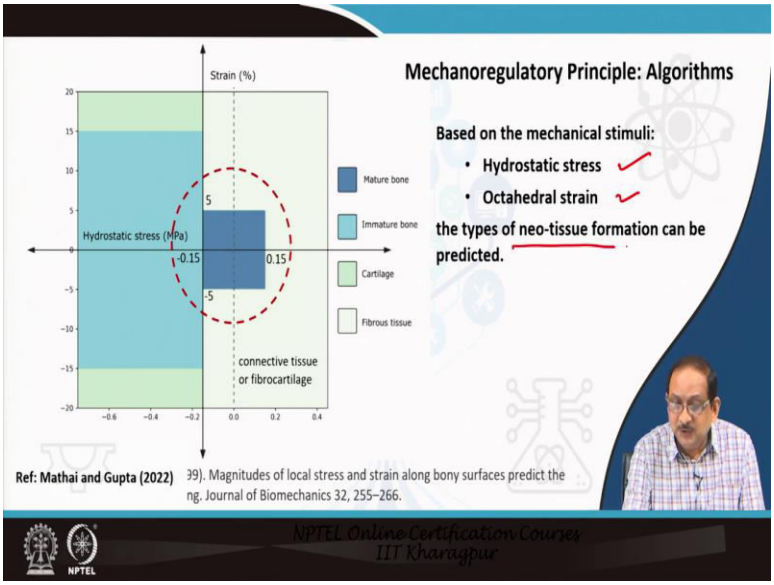

This study uses the mechanical rotary algorithm of Claes and Heigele, which we have discussed earlier, to predict tissue growth in the inter bead spacing, which is assumed to be initially filled with granulation tissue. So, here the mechanical stimuli is based on hydrostatic stress and

octahedral shear strain. So, based on these mechanical stimuli, the type of neo tissue formation can be predicted.

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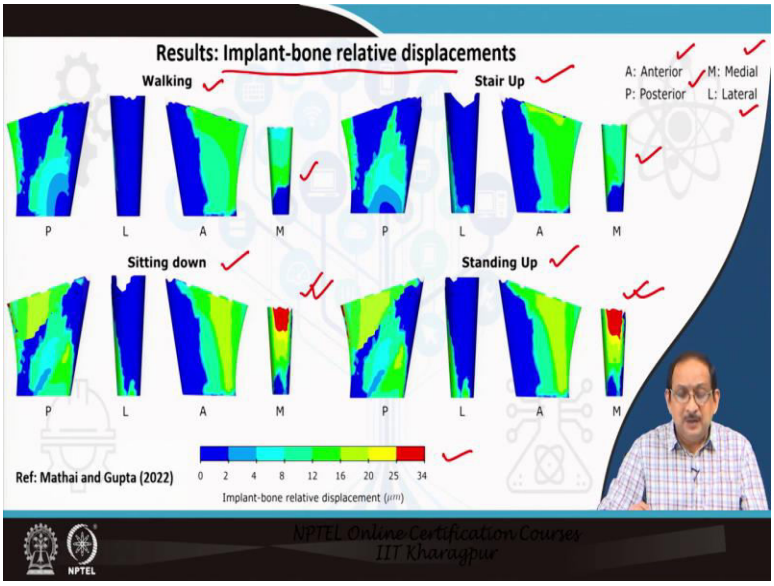

Let us discuss intermediate results coming out of the structural FE simulation. From the structural FE simulation. We can obtain implant-bone relative displacements corresponding to different activities like walking, stair up, sitting down on a chair, and standing up from a chair. The implant-bone relative displacement in the proximal part of the implant corresponding to each of these activities are presented here.

And you can see in different views like anterior, posterior, medial and lateral, the implant-bone relative displacement generally varies between 0 to 34 microns as indicated in the figure. So, you may observe that the implant-bone relative displacement is relatively higher in the medial portion of the hip stem, as shown in the slide. The average value of the implant-bone relative displacement was calculated for each region of interest.

The average value was further used for bone ingrowth simulation at the microscale level analysis corresponding to each region of interest. So, as you know that we are dealing with 12 microscale models corresponding to 12 regions of interest. The lateral sides of the microscale model were assumed to have periodic boundary conditions. For the structural analysis, the top region of the microscale model is prescribed with displacement boundary conditions.

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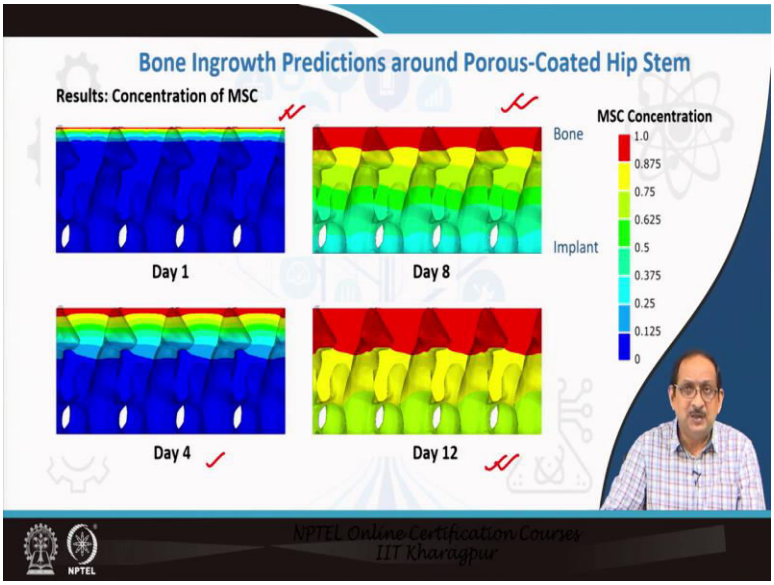

Let me present the first results of the bone ingrowth predictions around the porous coated trial of hip stem. So, here in this slide, we present the mesenchymal stem cell concentration over time and how it is changing from day 1 to day 12. So, the source of the MSC is at the top, where there is the bone region. So, the granulation top layer of the granulation tissue is rich with mesenchymal stem cells.

And you can see that in 3 days, from day 1 to day 4, the mesenchymal stem cells have progressed towards the implant. Now, on day 8, you can see the mesenchymal stem cells' concentration has further increased. And finally, on day 12, we reached an equilibrium state of MSC concentration.

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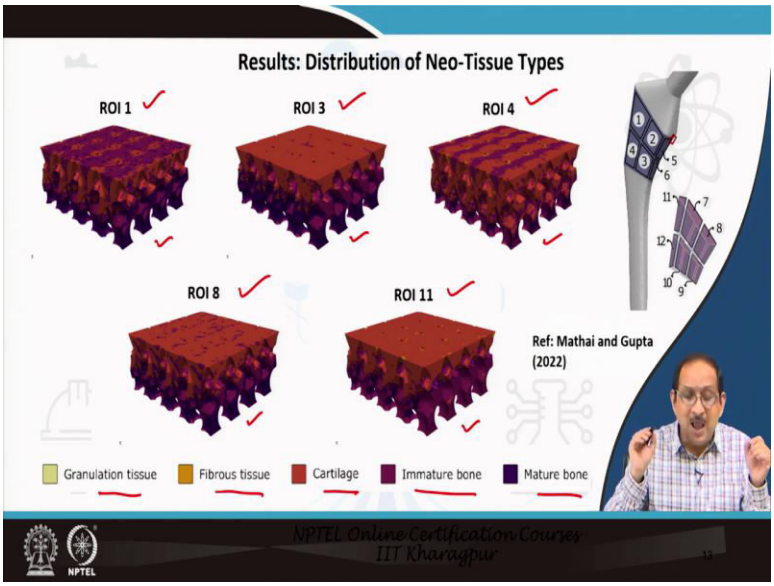

Let us now, look into the distribution of the neo tissue types that are formed from the granulation tissue. So, as you can see, we have presented results of 5 regions. Region 1, region 3, region 4, region 8, and region 11. The color codes refer to granulation tissue, fibrous tissue, cartilage, immature bone, and mature bone. But this figure presents the spatial distribution of the bone ingrowth predictions in selected 5 ROIs.

And this is the state of the spatial distribution after equilibrium is attained in bone ingrowth simulation. Now, you may notice that the bone tissue layer tends to form near the bottom surface of the implant surface, which is commonly known as contact osteogenesis. We must remember that the implant-bone relative displacement and the host bone material property are different for different regions. And the amount of bone ingrowth predominantly depends on the implant-bone relative displacements and the host bone material property in each region.

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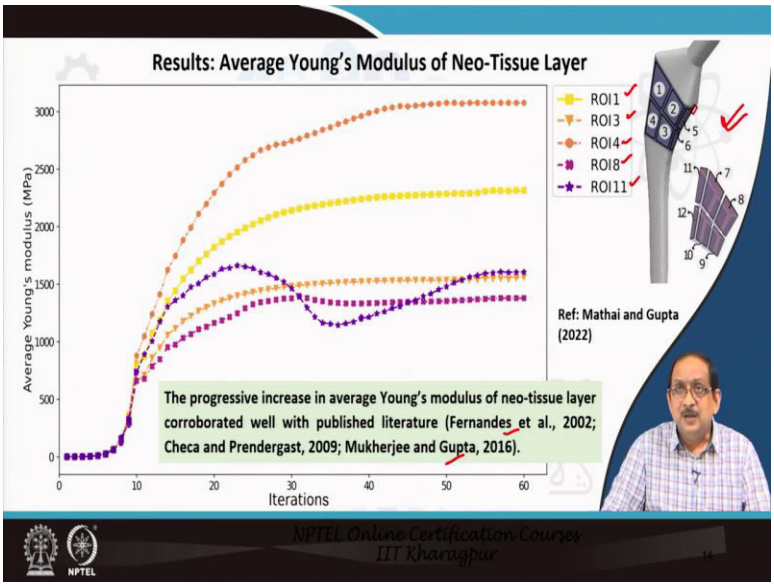

The time-dependent variation of the average Young's modulus of the neo tissue layer in different regions of interest is presented in this slide. So, we have shown for the region of interest 1, 3, 4, 8, and 11 corresponding to the regions of interest in the proximal hip stem. As you can see from the figure, the average value of the Young's modulus in these 5 regions of the intermediate spacing was found to increase with the time that is, with iterations.

It indicates the maturation of bone tissue in the inter bead region or inter bead spacing of the implant. It may be mentioned herewith that there are variations in implant-bone relative displacements and host bone material property in different regions of interest. It has been observed that the implant-bone relative displacement and the host bone material property influence the stiffness of the neo tissue layer in the intermediate spacing.

The progressive increase of the average Young's modulus of the neo tissue layer collaborated well with published literature. So, some of them are cited here. the detail of the citation is mentioned in the reference list. The progressive increase in the average Young's modulus of the neo tissue layer has been observed, corroborating well with published literature mentioned in this lecture. This also serves as an indirect validation of the numerical simulation of bone ingrowth.

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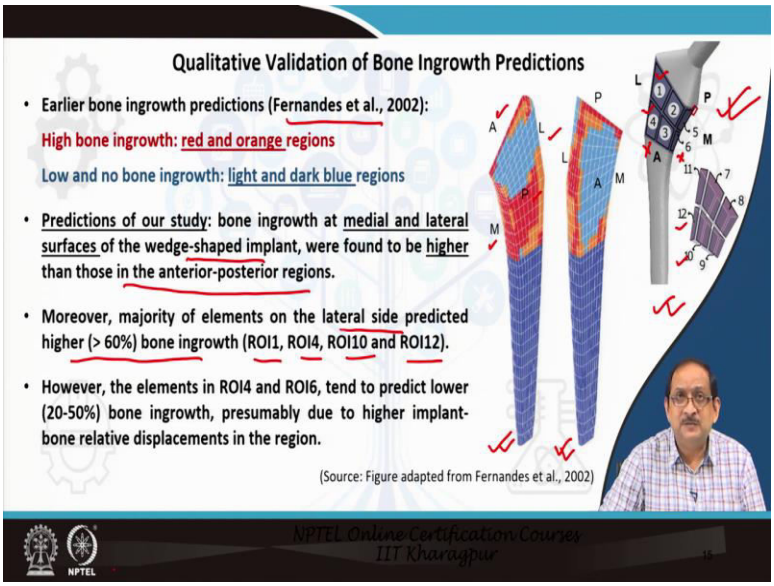

Quantitative and qualitative validation is required to trust the numerically predicted results. Hence, we have compared the results predicted by our study with those of Fernandez group published in 2002. Now, in his study, he predicted the bone ingrowth predictions around a hip stem which is presented here in two views in the slide as you can see here. Now, the directions are marked here medial, lateral, anterior, and posterior and these are also marked on the other view of the hips stem.

As you can see from the results of Fernandes, that high bone ingrowth was predicted in the red and orange zones in the figure as presented in the figure. Whereas low and no bone ingrowth was predicted in the light and dark blue regions, as shown in the figure presented in the slide. Now, predictions of our study are now discussed with those of Fernandez.

From our study, we observed that bone ingrowth at the medial and lateral surfaces of the wedge-shaped implant, as seen here in this slide, was higher than in the anterior- posterior region. So, bone ingrowth at the medial and lateral surfaces was higher than the anterior-posterior regions. Moreover, the majority of the elements on the lateral side predicted higher bone ingrowth, more than 60 percent in areas 1, 4, 10, and 12, corresponding to the figure here. So, ROI 1, 4, 10, and 12.

So, the majority of the elements in these areas predicted higher bone ingrowth greater than 60 percent. However, the elements in region of interest 4 and 6, 4 and 6 tend to predict lower bone

ingrowth 20 to 50 percent presumably due to higher implant bone relative displacements in the region.

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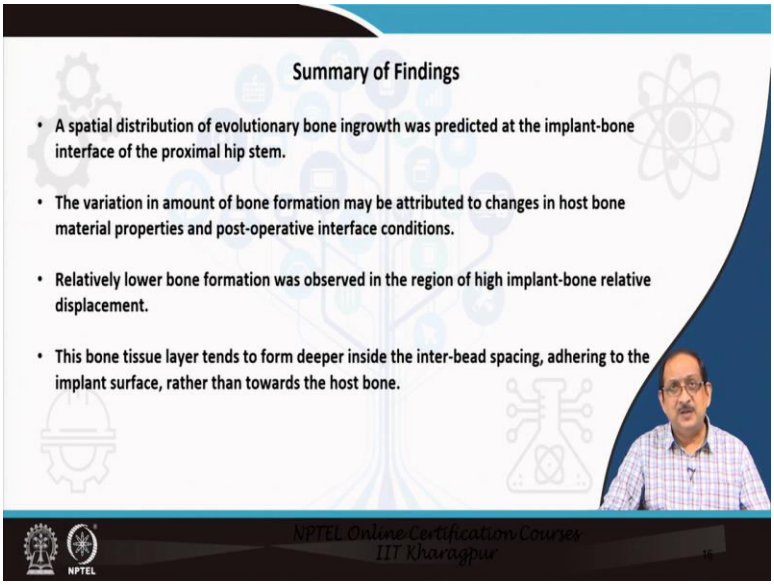

Let us now summarize the findings of this study a spatial distribution of the evolutionary bone ingrowth was predicted at the implant-bone interface of the proximal hip stem. The variation in the amount of bone formation may be attributed to changes in host bone material properties and post-operative interface conditions. Relatively lower bone formation was observed in the region of high implant-bone relative displacement. This bone tissue layer forms deeper inside the inter bead spacing adhering to the implant surface rather than towards the host bone.

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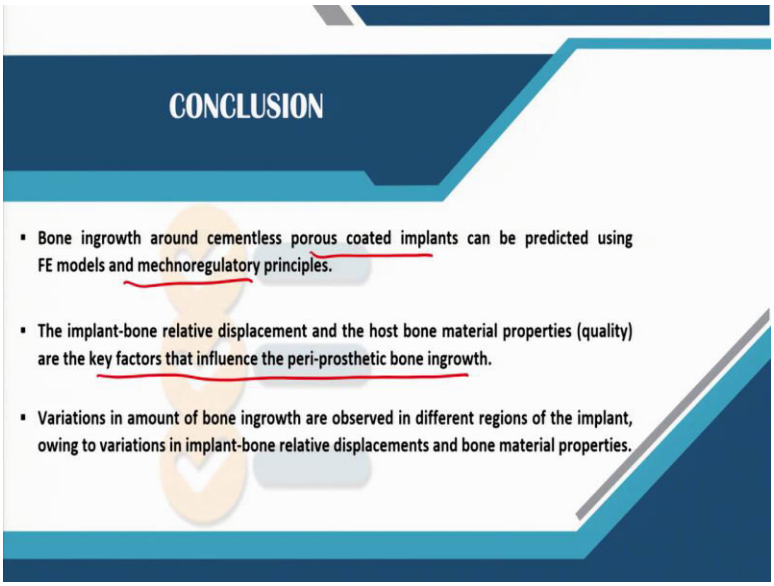

Let me now come to the conclusions of this lecture. Bone ingrowth around cementless porous-coated implants can be predicted using finite element modelling and mechanoregulatory principle. The key factors that influence the periprosthetic bone ingrowth are the implant bone relative displacement and the host bone material properties. Variations in the amount of bone ingrowth are observed in different regions of the implant owing to variations in implant-bone relative displacements and bone material properties.

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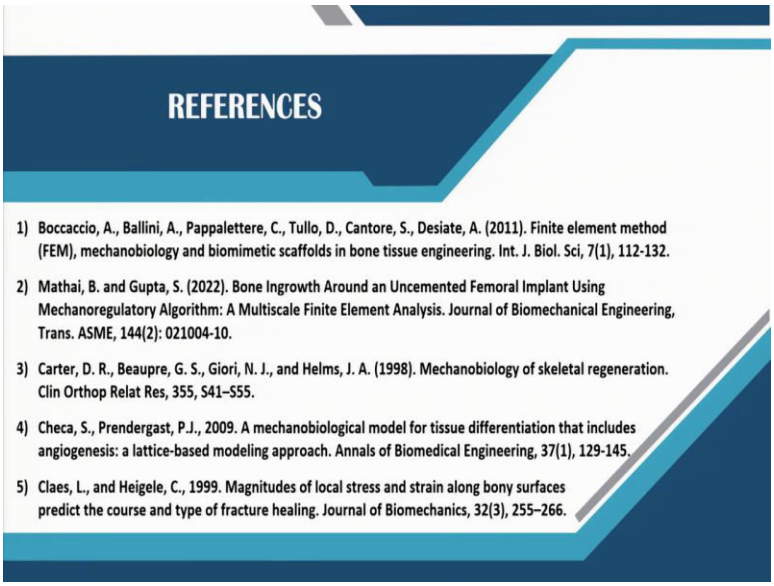

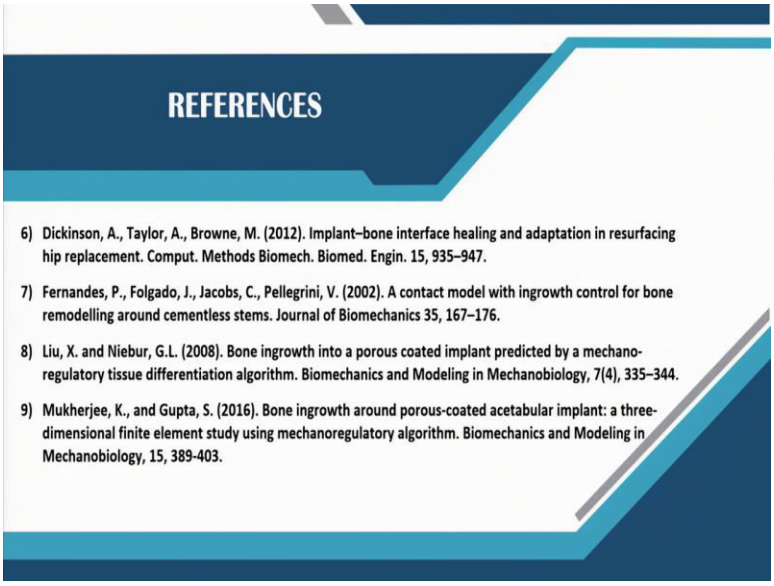

The list of references are presented in two slides. Based on which the lecture has been prepared. Thank you for listening.