Biomechanics of Joints and Orthopaedic Implants
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Lecture 30
Introduction to Finite Element Modelling of Bone and Implant

Good morning, everybody. Welcome to the second lecture of module 6.

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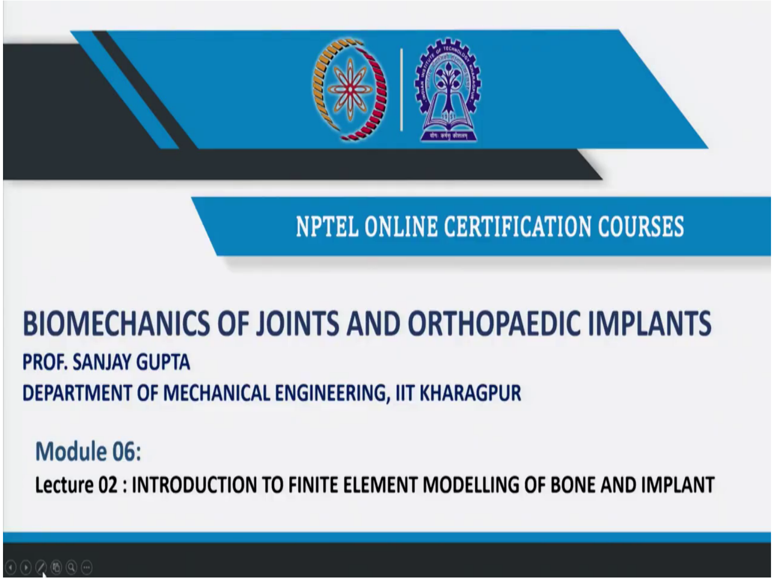

On Introduction to Finite Element Modelling of Bone and Implant.

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In this lecture, we will be discussing Geometric reconstruction and modelling techniques. We will be discussing material property assignment in the finite element model of bone. And we will be discussing applied loading conditions and constraint conditions that is used in the FE model of bone and implant.

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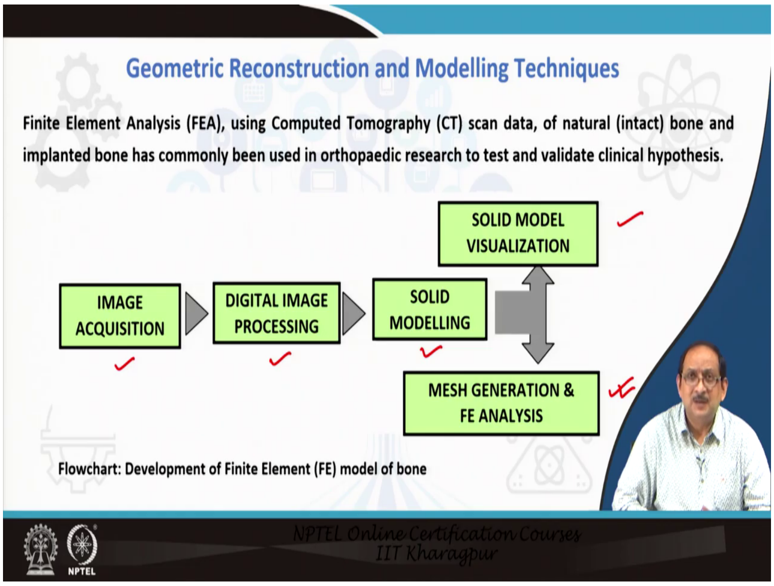

Now, let me start with the geometric reconstruction and the details of the modelling techniques. Finite element analysis using computed tomography scan data, popularly known as CT scan data of natural as we refer to natural intact bone and implanted bone, has been commonly used in orthopaedic research to test and validate the clinical hypothesis. So, finite element analysis has been used in orthopaedic research to test and validate the clinical hypothesis.

So, to do that, we need to develop a good quality finite element model of the bone and implanted bone structures. So, in this flowchart, we summarize the modelling technique. So, we start with CT scan image acquisition. It should be quantitative CT scan QCT images. So, after acquiring the image from the CT scan, we can apply the image processing techniques from which we can actually develop the solid model of bone.

So, this solid model of bone can be used for several purposes for visualization, for a critical appreciation of the reconstructed image in the form of a solid model and most importantly, it is used for creating the finite element model using the mesh generation technique in the finite element modelling.

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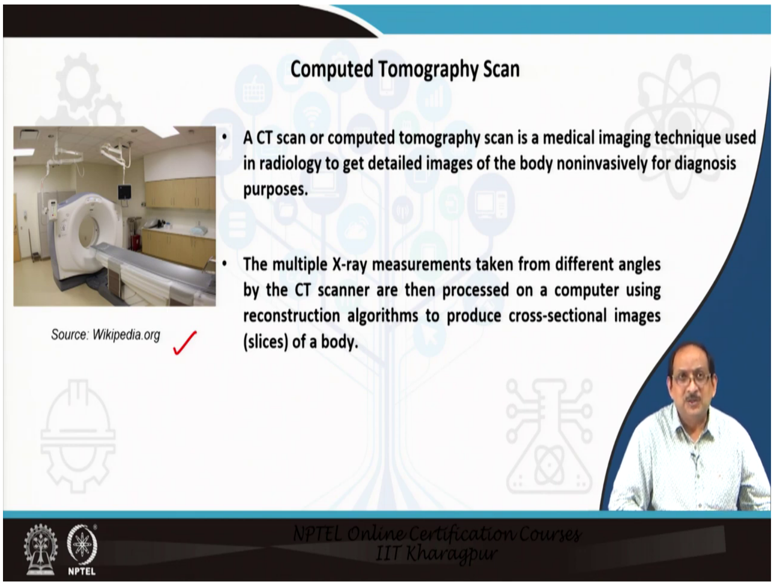

Now, what is a computed tomography scan? The word tomography means section. So, a CT scan or computed tomography scan is a medical imaging technique used in radiology to get detailed images of the body non invasively for the diagnosis purpose. The multiple X-ray measurements taken from different angles by the CT scanners are then processed on a computer using a reconstruction algorithm to produce cross-sectional or slice CT slices of a body. On the left, you can see a typical CT scanner used for image acquisition.

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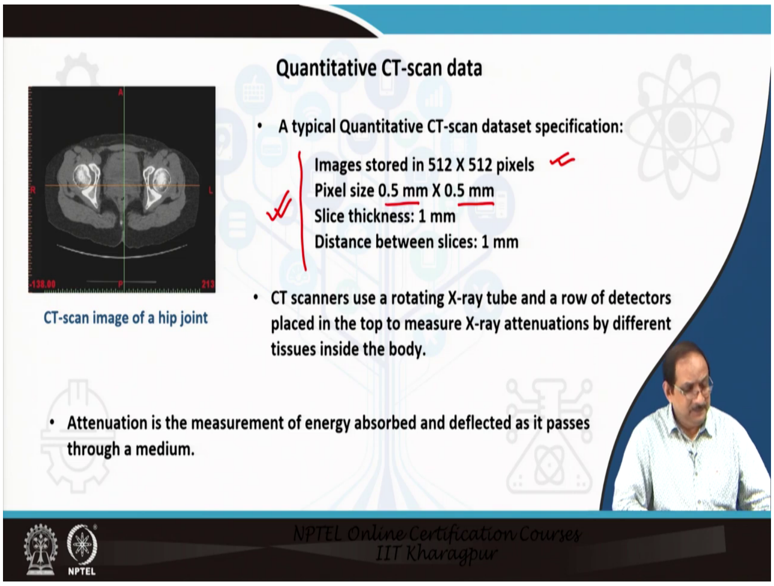

Now, let us talk about quantitative CT scan data. A typical quantitative CT scan data set, specification is mentioned here. Images are generally stored within say 512 x 512 pixels. So, that is the size of a slice. The pixel size can vary, and of course, the image size can also vary. Pixel size here is 0.5 mm x 0.5 mm, slice thickness is an important specification and distance between slice.

Distance between slice is important because that will actually influence the reconstruction quality of or the quality of reconstruction of the solid or finite element models. The less the distance between slices, the better the reconstructed model is because we do not have to interpolate between slices to get more information of the image.

CT scanners use a rotating X-ray tube and a row of detectors placed in the top to measure X-ray attenuations by different tissues inside the body. Now, attenuation is the measurement of energy absorbed and deflected as it passes through a medium.

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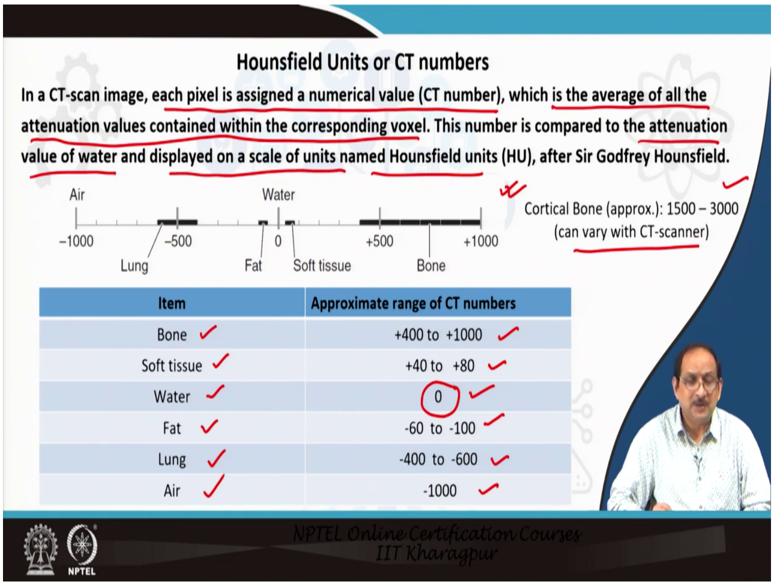

Let us now discuss Hounsfield units or CT numbers. In a CT scan image, each pixel is assigned a numerical value or CT number, the average of all the attenuation values contained within the corresponding voxel. Now, this number is compared to the attenuation value of water and displayed on a scale of units known as the Hounsfield units or HU and it is named after Sir Godfrey Hounsfield.

So, you can generally see the different items like bone, soft tissue, water, fat, lung, air and the corresponding approximate range of CT numbers. Remember that these values can vary from one CT scanner to the other. But generally, water is 0; bone can vary from 400 to 1000, it can cortical bone can go up to 3000 as indicated here, soft tissue 40 to 80, fat is close to water minus 60 to minus 100, lungs is minus 400 to 600 and air just air is minus 1000. Please remember these values can vary from one CT scanner to the other.

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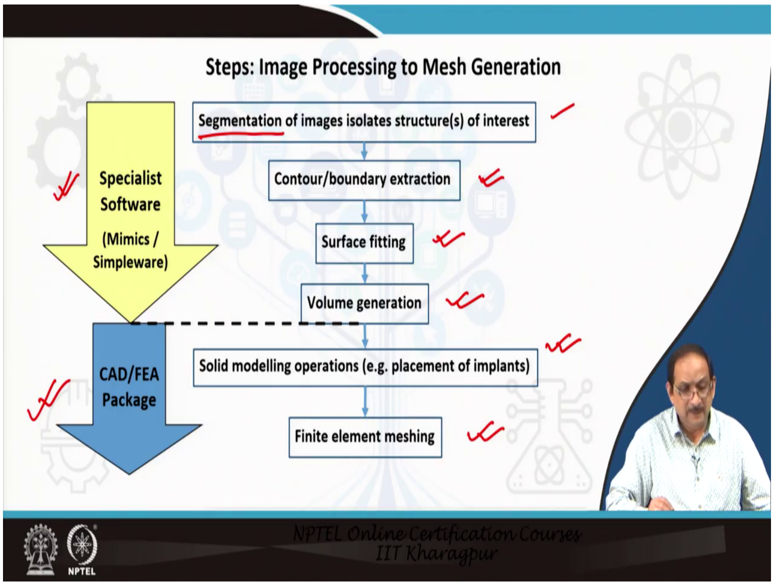

Now, let us talk about the steps from image processing to mesh generation. So, these are the critical steps. The first step is the segmentation of images. So, segmentation of images isolate structures of interest. Then we detect the contours, so contour detection or boundary extraction, then apply a surface fitting and obtain a volume.

Now, this volume is used further for different purposes. Say we if we want to virtually implant. We virtually insert an implant in the solid model of the bone and then we can do Boolean operations and place the implant based on the surgical technique as specified for a particular anatomic site.

We actually undertake a meshing operation to obtain a finite element model. So, the first part, as indicated by the yellow arrow, focuses on image processing and solid Model Generation or volume generation. After that, we undertake the solid modelling operations and finite element Model Generation using meshing.

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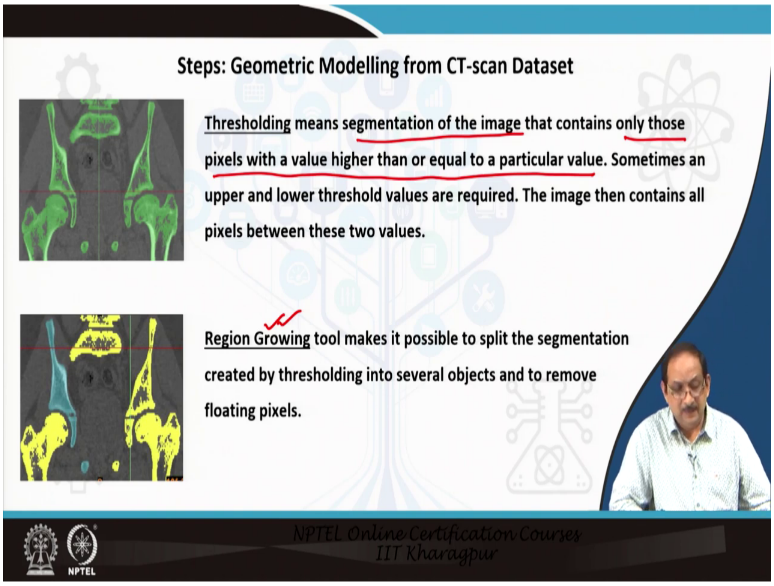

Now, let us discuss a little bit more detail about geometric modelling from CT scan data. So, thresholding is the first operation that we apply on a CT scan data slice. So, thresholding means segmentation of the image containing only those pixels with a value higher than or equal to a particular value. So, it is a threshold value based on which we segment the image.

Sometimes upper and lower threshold values are required. The image contains all pixels between these two values. The next step is a region growing as indicated in the slide, and the region growing tool makes it possible to split the segmentation created by thresholding into several objects and removing floating pixels. So, we are concentrating on the object of interest.

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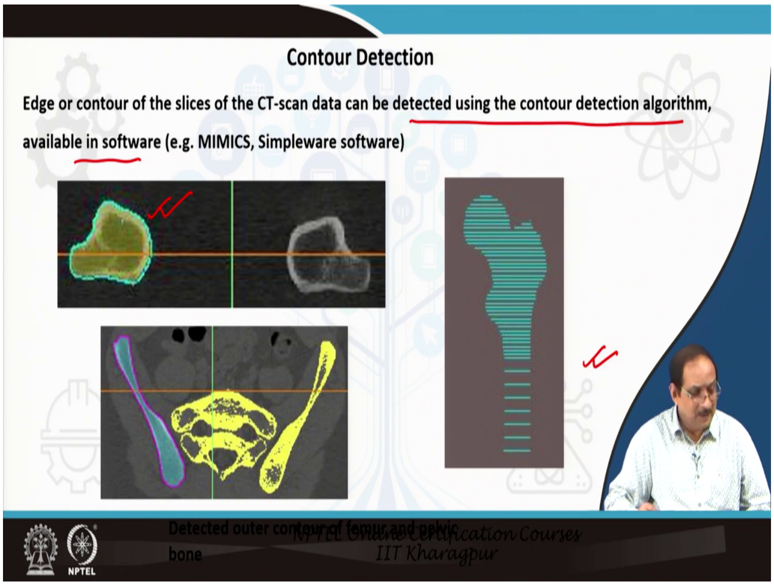

The next important step is age or contour detection within a slice. So, age or contour of the slice of the CT scan data can be detected using the contour detection algorithm available within software which you may be using; it may be MIMICS, Simpleware or any other equivalent software, which can help you to detect the contour as indicated in the slide here. So, you can see that a contour of a femur has been extracted in the slice and subsequently, different slices will give you a set of contour data corresponding to that slice and when you stack these slices containing the contour data, it looks like this.

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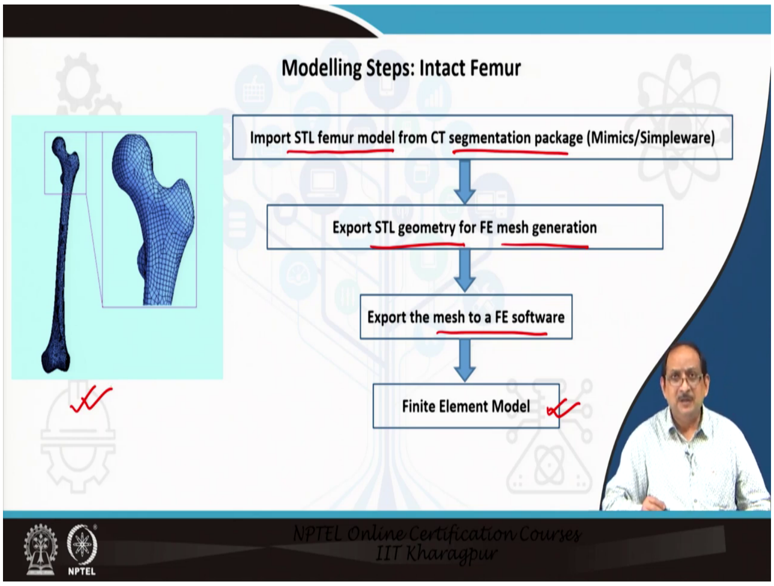

Now, we discuss the modelling steps corresponding to an impact femur for example. Now, we import the STL model of the femur from the segmentation package, and then we export the STL geometry for FE mesh generation. Then, we export this mesh to a finite element software that you may be using.

And then, after checking about the element shapes, whether it is there are distorted elements or elements with excessive curvature, we can rectify that. And finally, we have the finite element model of the bone. For this case, it is the intact femur as indicated in the slide.

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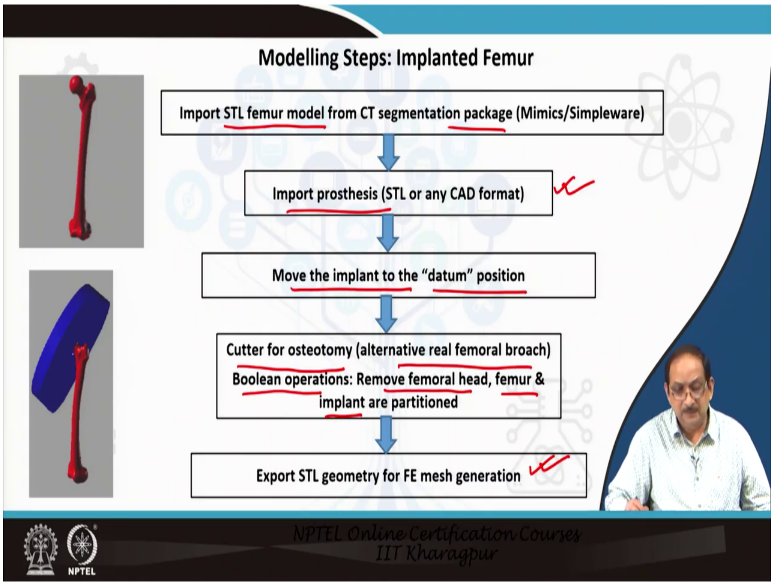

Now, the modelling steps for the implanted femur may be a little bit more complex as compared to the intact femur. So, here also we import the STL femur model from the segmentation on image processing software. We separately import the prosthesis's STL or CAD file and move the prosthesis to the specific position or the datum position as required in the surgical technique.

So, we have to place the implant model virtually within the bone, but a certain excess part of the bone needs to be removed. So, we employ a cutter for osteotomy. So, it is an alternative to a real femoral broach. Now within the computer software or the framework, we can actually apply the Boolean operations by which we can remove the femur head or the femoral head, and we can partition the femur and the implant in this solid model, then we can export the STL geometry of the implanted bone structure for mesh generation and the final evaluation of the FE model of the implant-bone structure.

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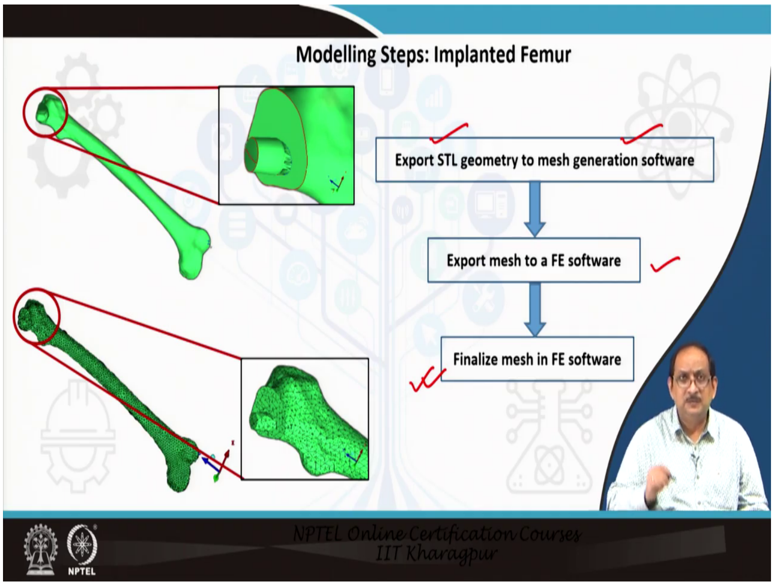

We just discussed it a little bit more in detail. Here you can see exporting the STL geometry for mesh generation. Then, we export the mesh to a finite element software. And here, we evaluate the FE mesh, and if there is some rectification required, we attend to it and finalize the mesh quality in the finite element software and finalize the finite element model of the bone.

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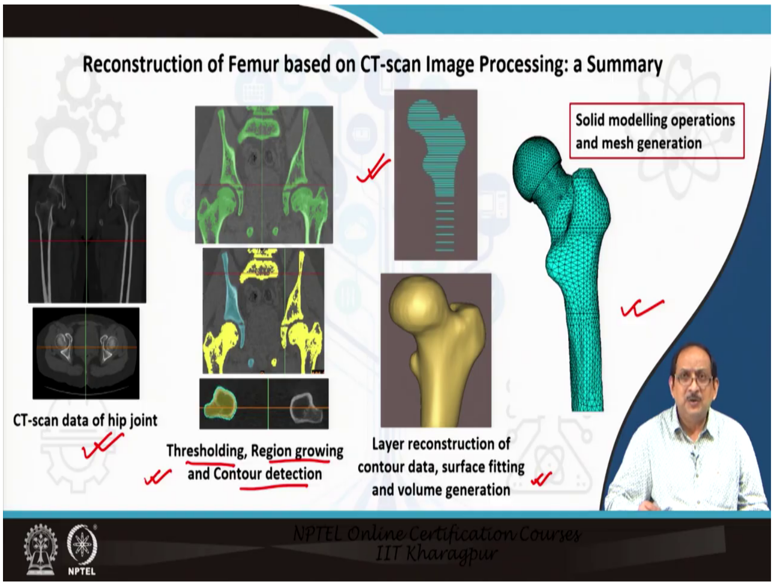

This slide presents a summary of the reconstruction of the femur based on CT scan image processing. As you can see, it started from CT scan data of the hip joint from which we apply the image processing techniques like thresholding, region growing, and contour detection.

We obtain the contours which are stacked here. And using layer reconstruction of contour data, surface fitting and there are after volume generation. We obtain a solid model. From the solid model, we can obtain the finite element model after the mesh generation operation.

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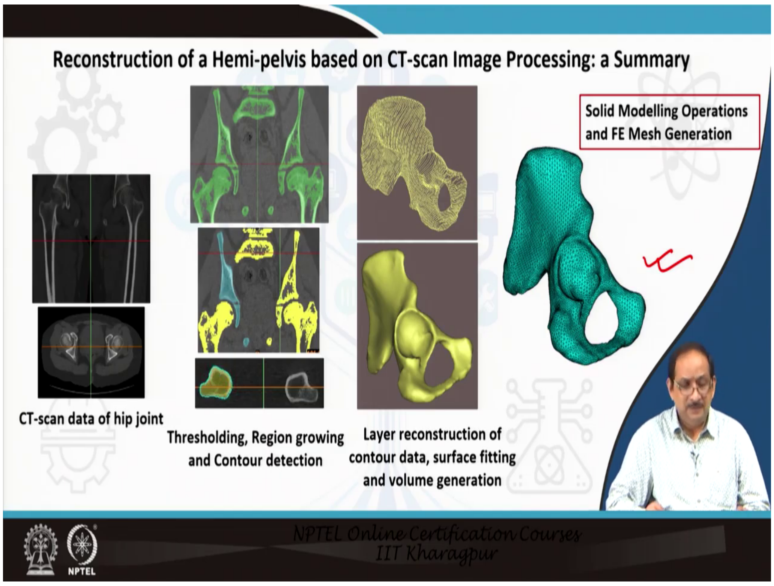

A similar summary can be seen here. So, this is a Hemi-pelvis. So, the earlier slide was on the femur, intact femur. This slide is on the FE model of the Hemi-pelvis that has been generated using an exactly similar procedure.

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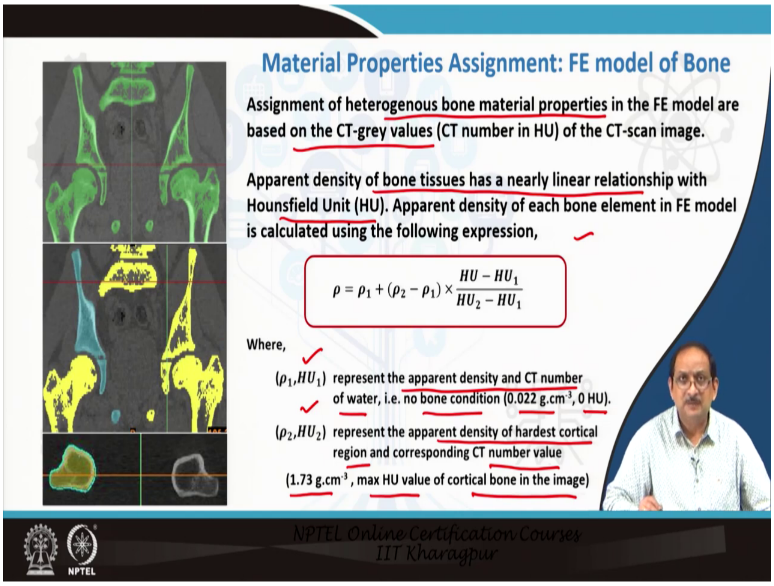

Let us now come to the second topic of this lecture on material property assignment in the FE model of bone and implant-bone structure. The assignment of heterogeneous bone material properties in the FE model is based on the CT grey values or the CT scan data set. This is a crucial step in the development of the finite element model of bone and implanted bone structure.

Now, here we are interacting with the CT scan data set to extract pixel grey values contained within an element and after that, we average all the pixel grey values contained within the element to assign one-pixel grey value for a particular element. And later, we can relate this pixel grey value to the apparent density of bone and further Young's modulus of the bone element.

The apparent density of bone tissue has a nearly linear relationship with the Hounsfield unit. The apparent density of each bone in the FE model is calculated using the following expression. Now, in this expression, there are two important points ρ_1 HU_1 and ρ_2 HU_2. So, the first point represents the apparent density and CT number of water that is no bone condition with apparent density assumed to be 0.022 and obviously the CT number of water as 0.

The second point represents the apparent density of the hardest cortical region corresponding to the CT number obtained from the image as indicated here. So, we can assume the apparent density of cortical bone as 1.73. The other HU value would be the maximum value of the cortical bone in the CT image.

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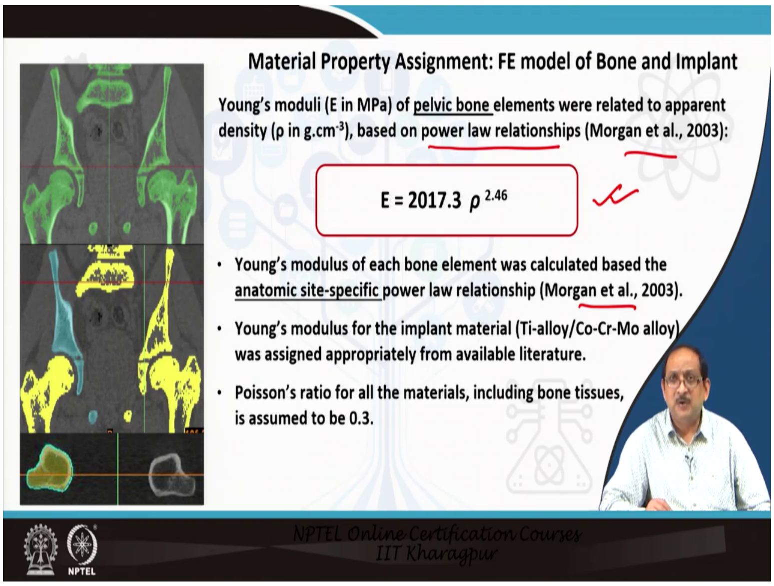

The Young's modulus of pelvic bone elements, specifically this is for the pelvic bone, were related to the apparent density, based on power-law relationship as suggested by Morgan. So, this is a site-specific power-law relationship. It can vary from one bone to the other. So, Young's modulus of each bone element was calculated based on the anatomic site-specific power-law relationship as specified by Morgan.

The Young's modulus of implant material titanium alloy or cobalt chrome molybdenum alloy can be assigned appropriately from available standard data available in the literature. So, the poisons ratio of all the elements, including bone tissue, is assumed to be 0.3.

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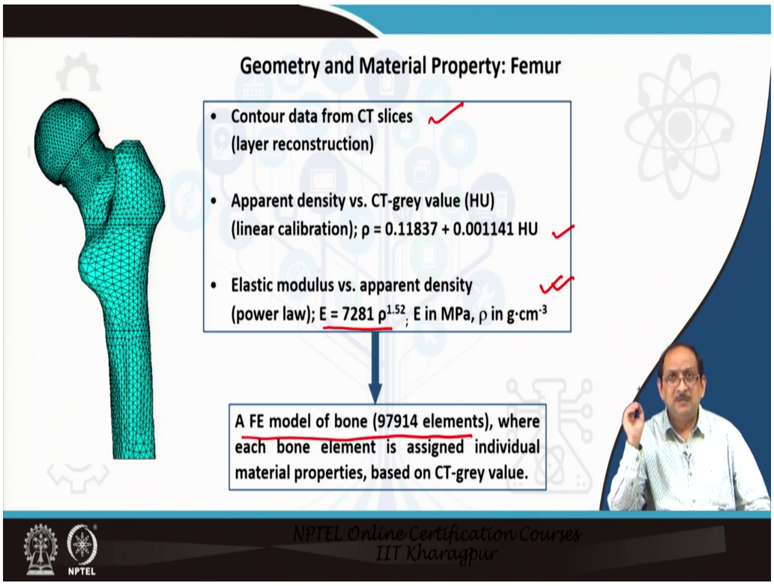

Now, let us present to you a summary of the geometry and material property of an intact femur. So, we start from contour data of CT slices, using layer reconstruction method was called we develop the finite element model, and from finite element model, we apply the linear calibration of apparent density with respect to the CT-grey value.

Then we can obtain the young's modulus of the bone element using the power-law relationship. So, here please note that the relationship between Young's modulus and apparent density is different from the pelvic bone relationship. So, we finally obtain a finite element model of around 100,000 elements where each bone element is assigned individual material properties based on CT-grey value.

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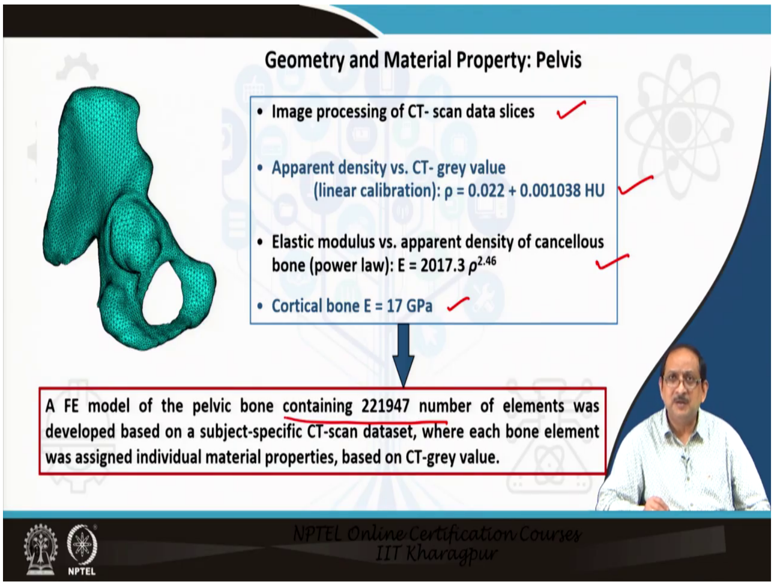

Now, this slide summarizes the geometry and material property, and finally, the development of the FE model of a pelvis. So, it starts from image processing on the CT slice. And then, using the linear relationship between apparent density and CT-grey value and power-law relationship between apparent density and Young's modulus, we can actually obtain a heterogeneous model of bone.

If we are segmenting cortical and cancellous bone regions, the cortical bone can be assigned a material property of around 17 GPa. So, the FE model of the pelvic bone containing about 200,000 elements was developed based on subject-specific CT scan data set, where each bone element was assigned individual material properties based on CT-grey values.

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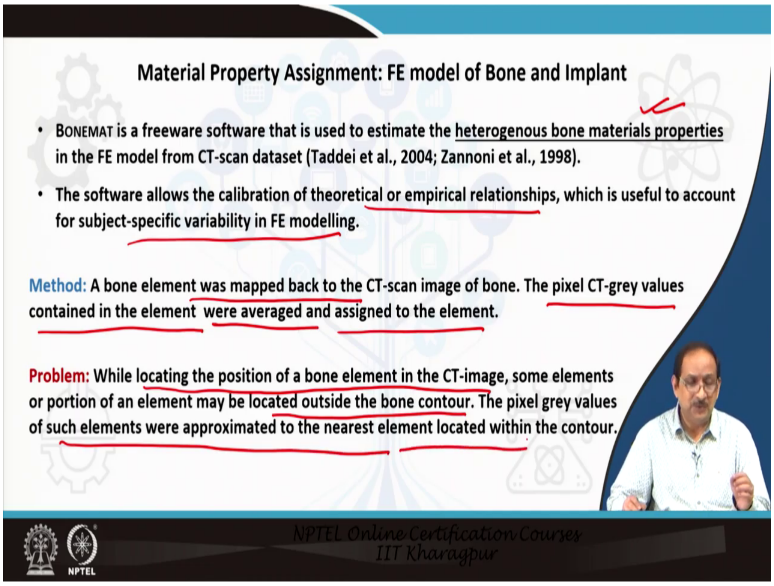

Now, BONEMAT is a freeware software that is used to estimate heterogeneous bone material properties in a finite element model from CT scan data. Now, this is a freeware software that can be used in combination with finite element software, for example, ANSYS, and we have used it successfully in allocating bone material properties. The software allows the calibration of theoretical or empirical relationships, which is helpful in account for subject-specific variability in the FE model.

Now, basically, what it does is a bone element is mapped back to the CT-scan image of the bone. The pixel CT-grey values contained within the element can be averaged and assigned one-pixel grey value to that particular element. But we actually face some problems, some practical problems associated with material property assignment.

While locating the position of a bone element in the CT-image, some elements or portion of an element may be located outside the bone contour in the CT-image. So, this leads to some error in extracting CT-grey values. So, the pixel grey values of such elements were approximated to the nearest element located within the contour.

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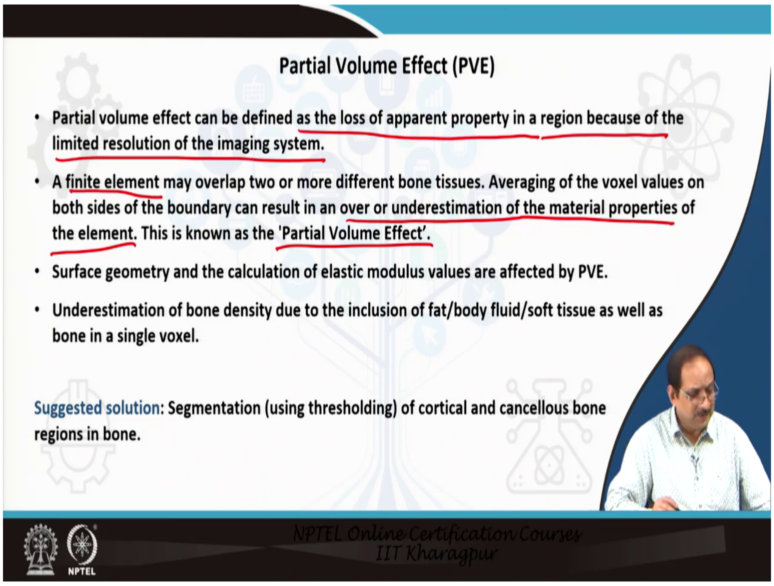

This problem, generally known as the partial volume effect, can be defined as the loss of apparent property in a region because of the limited resolution of the imaging system. A finite element may overlap two or more different bone tissues averaging the voxel values on both sides of the boundary, which can result in an overestimation or underestimation of the material properties of the element.

Now, surface geometry and the calculation of elastic models are affected by the partial volume effect and underestimation of bone density due to the inclusion of fat body fluid or soft tissue and bone in a single rock cell. So, the suggested solution is segmentation using thresholding of cortical and cancellous bone region is a way forward to tackle this partial volume effect.

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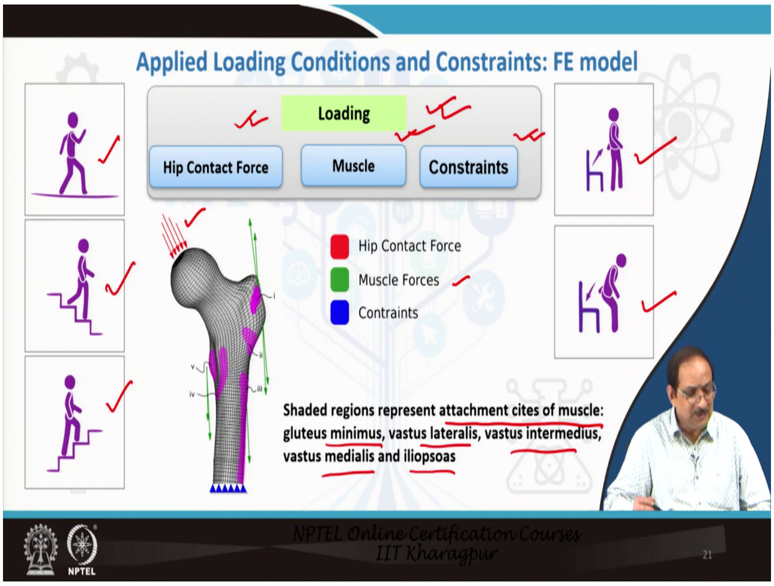

Now, let us come to this lecture's third and final topic on applied boundary conditions and constraints in the FE model. So, we need to load the FE model. So, here we consider the femur, hip contact force, muscle force and constraints as indicated in the slide is presented here.

So, the hip contact force is applied at the femoral head, as you can see, and the muscle forces are applied at attachment sites of muscle. So, in this image, we are showing the attachment cites of some of the muscles like gluteus minimus, vastus, lateralis, vastus, medialis, iliopsoas and vastus intermedius.

Now, the applied loading condition may consist of several load cases and these load cases correspond to different activities it may also be one activity; you may have several load cases representing one activity. You can also have several load cases representing various activities like walking, stair down, stair up, sitting up from a chair, and sitting down on a chair. So, the more the number of load cases, the more are the results predicted regarding stress distribution during various daily activities.

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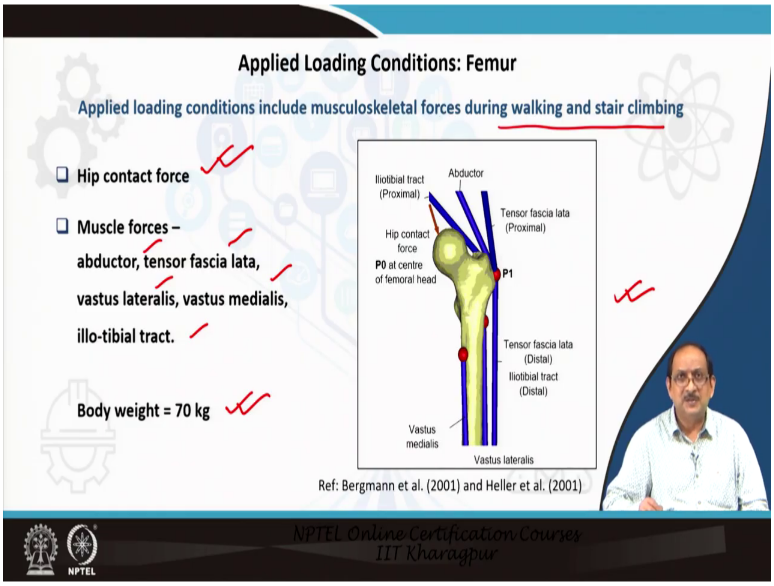

Here we present the applied loading conditions that include musculoskeletal forces during walking and stair climbing only. So, we have used data for our model. So, we have hip contact force and muscle forces like abductor, tensor fasciae lata, vastus lateralis, vastus medialis, illo-tibial tract and these quantitative values of forces will be dependent on the patient body weight.

So, I have referred to this figure from Bergmann and Heller, we have discussed a lot about muscle-skeletal forces earlier, and you can see the location of these force vectors in the natural femur as indicated in the figure presented in the slide.

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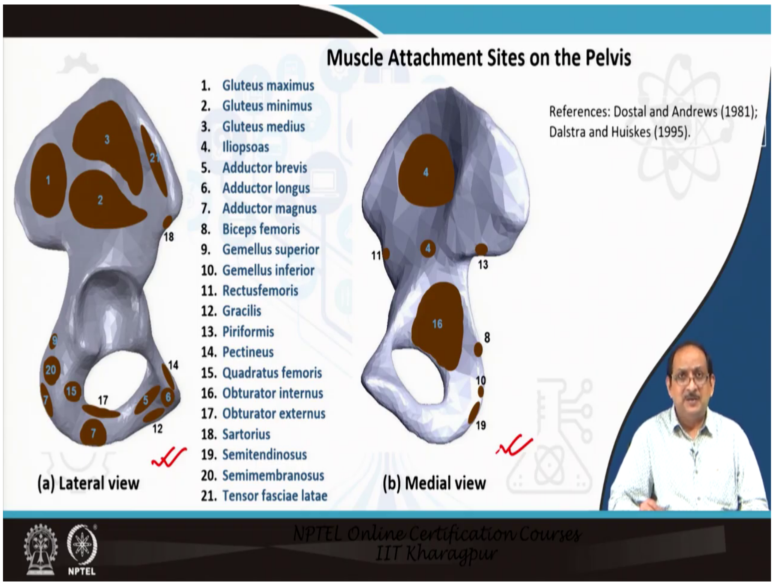

So, the muscle attachment sites of the pelvis is indicated here; there are about 21 muscles presented in lateral view and medial view. The attachment sites of the pelvis solid model that we had created.

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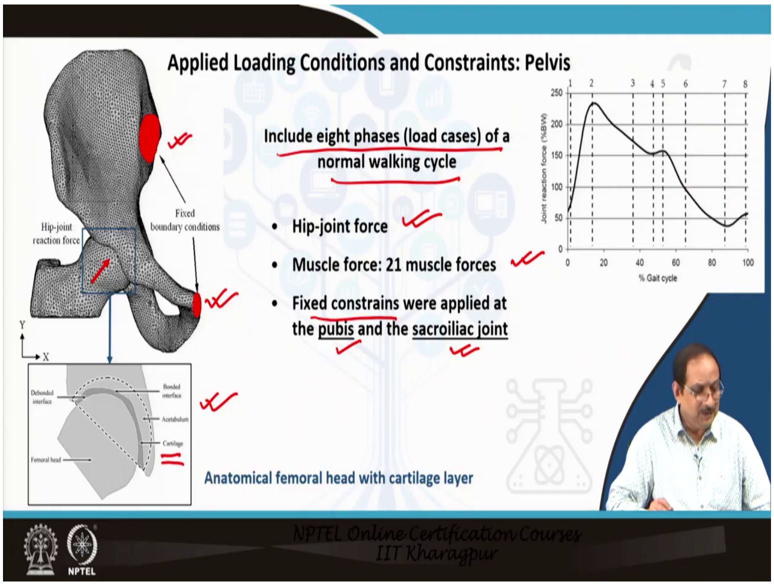

Now, applied loading conditions and constraints for the pelvis, this model was created by us. So, you can see that this applied loading condition included eight phases, load cases of a normal walking cycle. So, we have a set of data corresponding to hip joint force, 21 muscle forces for each load case. And please pay attention here that about the fixed constraints applied at the pubis and the sacroiliac joint in the finite element model.

So, these constraint conditions correspond to physiologic constraint conditions existing in real bone. As you can see in the model, the hip joint reaction force is applied through the femoral head and includes a layer of cartilage between the acetabulum and the femoral head. So, this ensures that there is no concentrated force applied directly on a node on the acetabular cavity; instead, it is applied through the femoral head and the cartilage on the acetabular cavity. This method of application of the hip joint force is closer to the actual condition in the hip joint.

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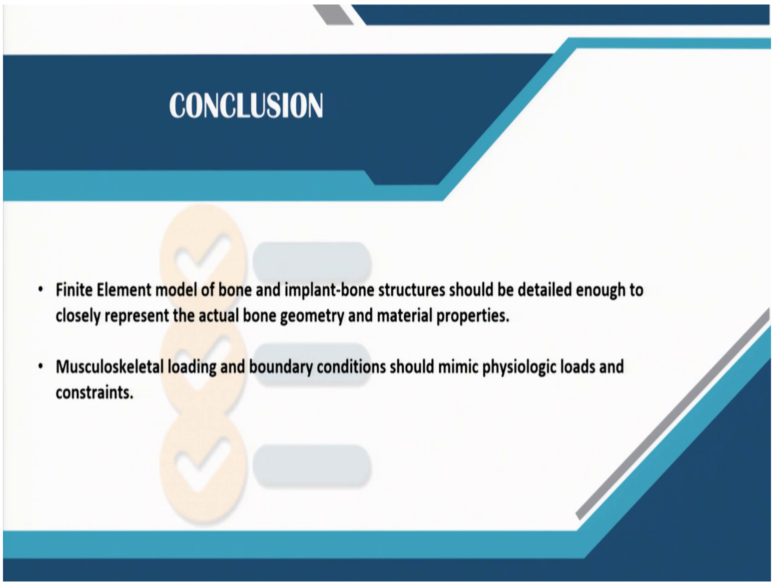

Let us conclude this lecture. The finite element model of bone and implanted bone structures should be detailed enough to represent the actual bone geometry closely, and material property distribution, musculoskeletal loading and boundary conditions should mimic physiologic loads and constraints existing in the actual condition.

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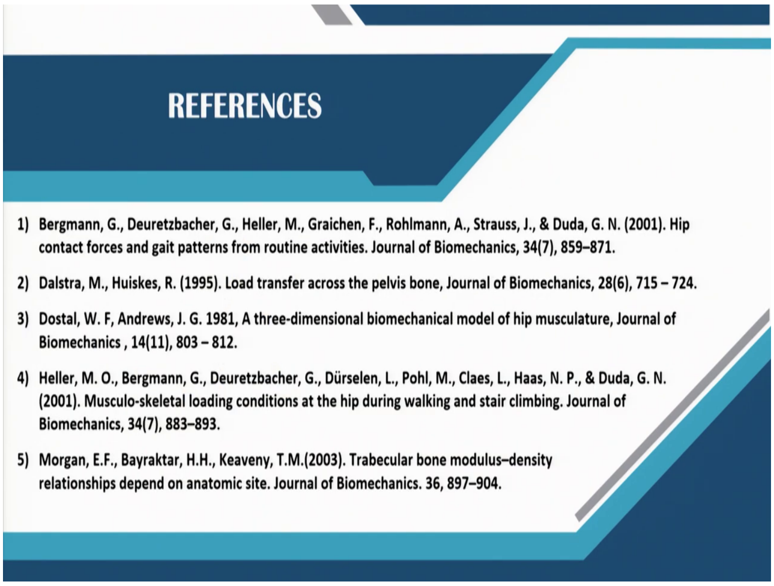

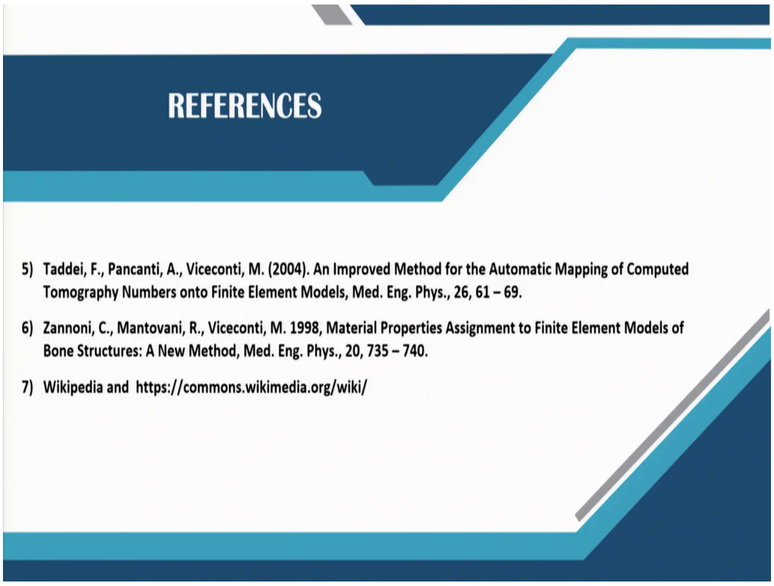

The list of references are presented here in two slides based on which the lecture has been prepared. Thank you for listening.