Biomechanics of Joints and Orthopaedic Implants
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Lecture 29
Implant Classification and Failure Mechanism

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

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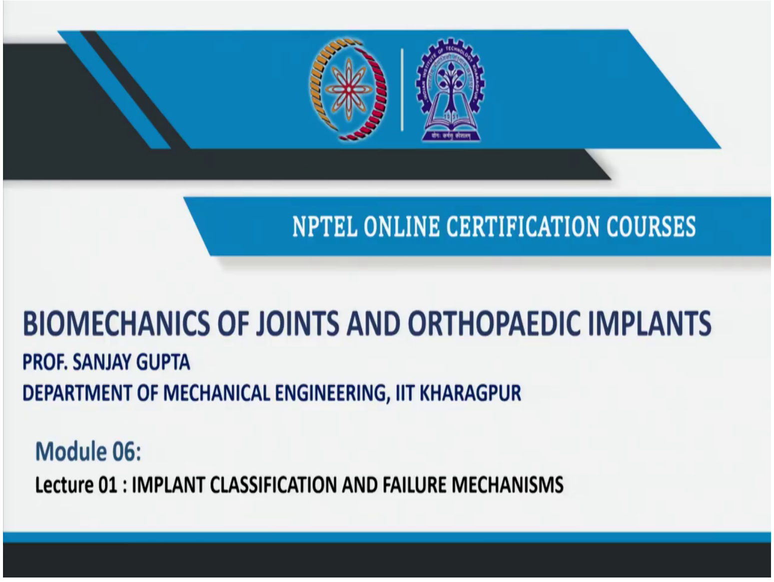

On Implant Classification and Failure Mechanisms.

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In this lecture, we will be discussing the classification of implants in total joint replacements with special emphasis on hip replacements. After that, we will discuss implant failure mechanisms.

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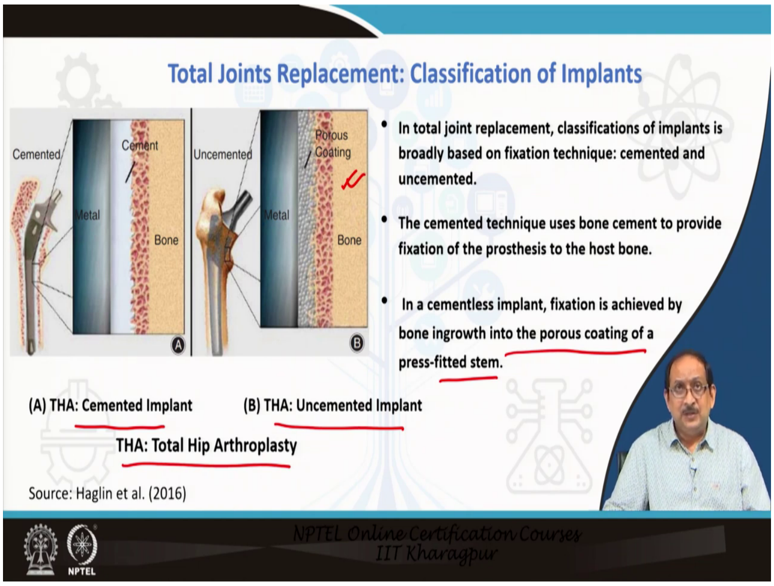

Now, during a joint replacement surgery, for instance, hip replacement, the implant is fixed to the host bone with or without cement. Now, in cemented type, as you can see here from the figure, acrylic bone cement helps the implant be fixed within the femur. So, this is a figure corresponding to total hip arthroplasty.

Whereas, in case of uncemented type, the biological fixation is achieved between the porous coating of the implant surface and the host bone through bone in growth. In a cementless implant, fixation is achieved by bone ingrowth into the porous coating of the press-fitted stem as indicated in the figure.

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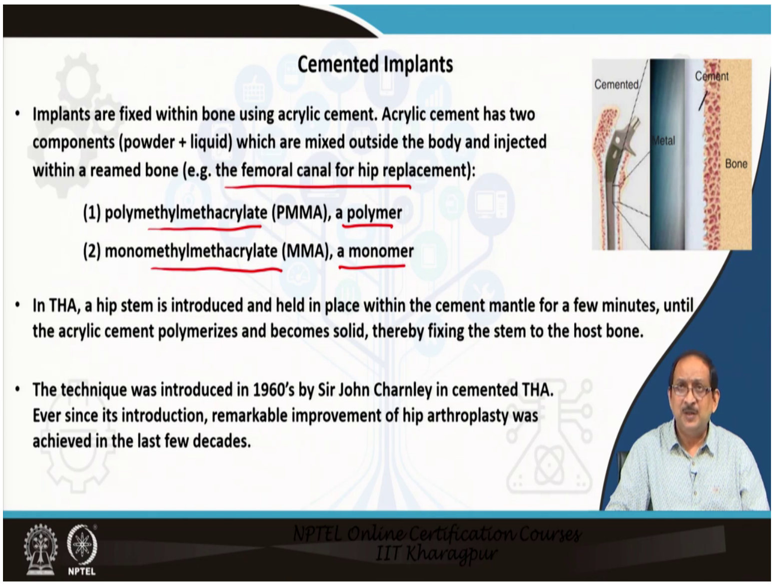

The implants are fixed within bone using acrylic cement in the case of cemented implants. The acrylic cement has two components: powder and the liquid, mixed outside the body and injected within a reamed bone or a cavity in the bone, for example, the femoral canal for hip replacements. Now, acrylic cement consists of a polymer, polymethylmethacrylate (PMMA) and a monomer (the liquid) monomethylmethacrylate (MMA).

In total hip arthroplasty, a hip stem is introduced and held in place within the cement mantle for a few minutes until the acrylic cement polymerizes and becomes solid, thereby fixing the stem to the host bone. This technique was introduced in the 1960s by Sir John Charnley in cemented total hip arthroplasty. Ever since its introduction, a remarkable improvement of hip arthroplasty was achieved in the last few decades.

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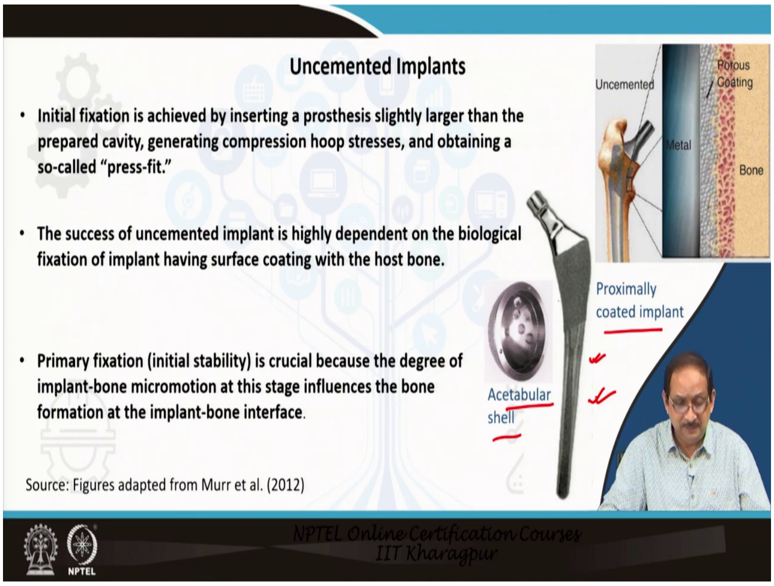

Now, let us discuss the initial fixation of uncemented implants. The initial fixation is achieved by inserting a prosthesis slightly larger than the prepared cavity, generating compression hoop stresses and obtaining the so-called press fit. The success of an uncemented implant is highly dependent on the biological fixation of the implant. The primary fixation or initial stability is crucial because the degree of implant-bone micromotion influences bone formation at the implant-bone interface.

Now, let us focus our attention on the figure presented here; we have a proximally coated hip stem and a porous-coated acetabular shell. Now component coating can be full or partial. In this case, it is a partial coated hip stem complete coating that presents a larger surface area for fixation, but this may reduce loading of the proximal bone. The proximal coating transfers the load through the femoral metaphysis but provides a smaller area for stable fixation.

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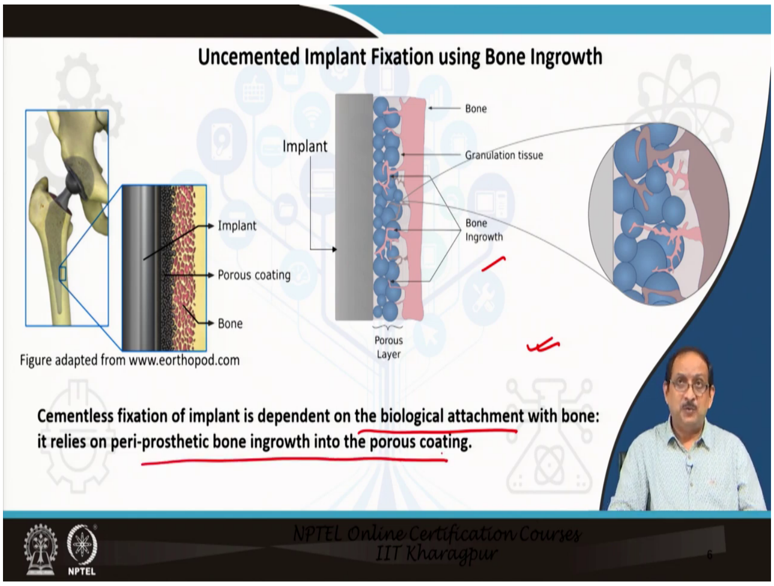

The implant is usually provided with a porous coating to enable implant fixation using bone in growth in the case of uncemented implants. As you can see in the slide, bone grows into the porous structure and creates a mechanical interlocking, thus helping to secure the fixation of the implant within the host bone. Cementless fixation of implant is, therefore, highly dependent on the biological attachment with bone, and it relies on peri-prosthetic bone ingrowth into the porous coating.

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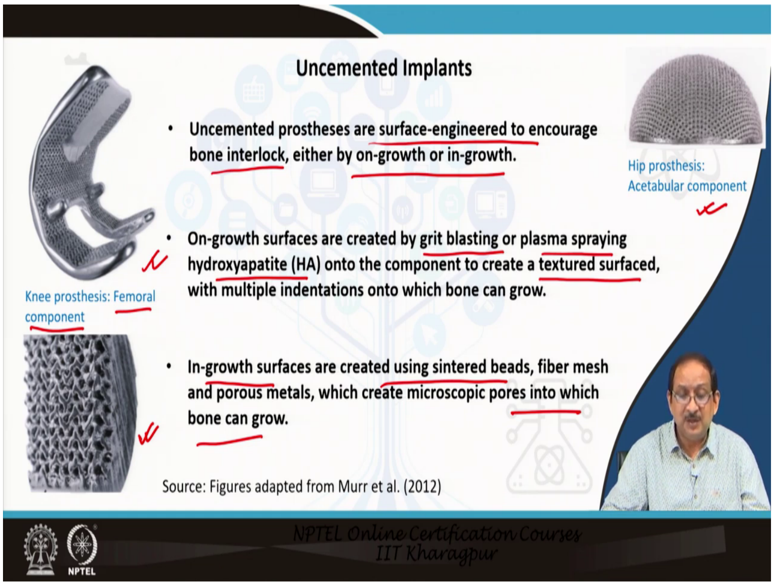

Now, let us discuss more the uncemented implants. The uncemented implants are surface engineered to encourage bone interlock either by ongrowth or by ingrowth. Ongrowth surfaces are created by grit blasting or plasma spraying hydroxyapatite onto the component to create a textured surface with multiple indentations onto which bone can grow.

Ingrowth surfaces are created using sintered bids, which create microscopic pores into which bone can grow. The potential for improved bonding thus stability through coating prosthesis with bioactive material such as hydroxyapatite and tricalcium phosphate has attracted increasing interest towards uncemented fixation. The figure presented here shows a knee prosthesis of the femoral component of a knee prosthesis and an enlarged view of the porous coating on this femoral knee component.

On the right, you can see a hip prosthesis, the acetabular component and porous coated acetabular component of the hip prosthesis are presented in this slide. In total hip arthroplasty, there is a tendency to use uncemented femoral stems in younger patients due to higher reported rates of loosening of cemented stems or cemented hip stems in the long term follow up studies. Now, I will show you a short video on hip implants cemented and uncemented total hip arthroplasty and total knee arthroplasty. Enjoy the video.

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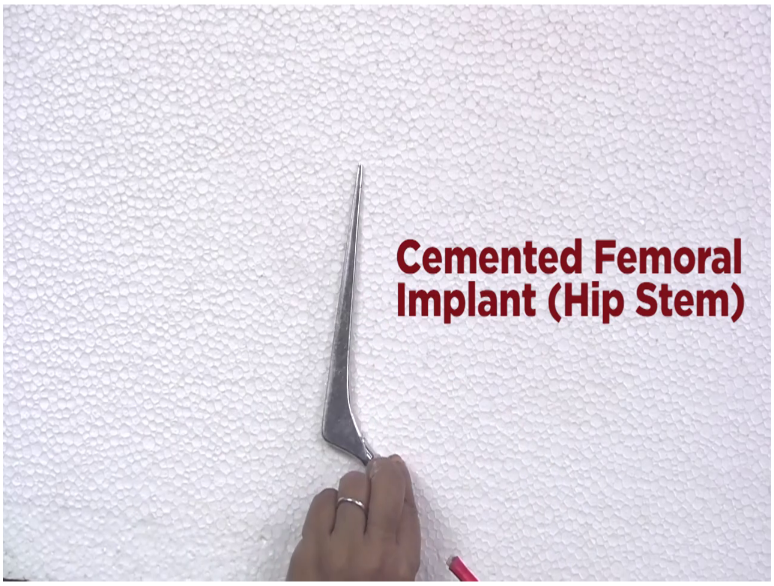

Let me present to you a hip implant. This is a cemented hip implant or femoral implant which is used for hip replacement. I am rotating the implant so that you can see the femoral hip stem that is used for cemented hip replacement. Please note that this cemented femoral implant has a very polished surface on all sides. It has a very polished surface on all sides.

Let me present to you an uncemented hip stem with a rough texture and a porous coating on the proximal part of the hip stem compared to the polished surface that we had for the cemented hips stem shown earlier. Let me turn it around to see the prosthesis fully. This stem has a rough texture, a coated texture that helps biological fixation with bone.

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Total Hip Arthroplasty


Total Hip Arthroplasty


Total Hip Arthroplasty

Let me present to you a reconstructed femur with a hip implant, as you can see clearly. So, now, I will this is the femur head, the artificial femur head, and I will take off in parts and here you can see the rimmed canal within the femur into which the prosthesis is placed. Now, please have a look at the prosthesis. This is an uncemented hip stem with texture on the surface to facilitate bone ingrowth. It has a porous coating on the surface of the implant that is supposed to promote bone ingrowth. Now, I will assemble these modular parts and insert them in place within the resected femur.

Now, I present to you a pelvic bone with the acetabular component implanted within it. You can see in different views the reconstructed pelvic bone with the hemispherical acetabular component implanted within it. So, the femoral component and the acetabular component articulate with each other and thereby produces and thereby, the hip joint is reconstructed to offer a normal range of motions.

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Let me present to you a model of the total knee replacement. So, if you are looking from the front, you can see the patella. Now I will be rotating the replaced knee, and you can see the femoral component, the black one on the top and the tibial component inserted within the tibia.

Now, I am moving towards the posterior view, where you can clearly see the tibial and femoral components. In the posterior view, you can clearly see the black femoral and tibial components inserted below within the tibia in total knee replacement. On the sides, the collateral ligament is holding the bone, as can be seen in the model.

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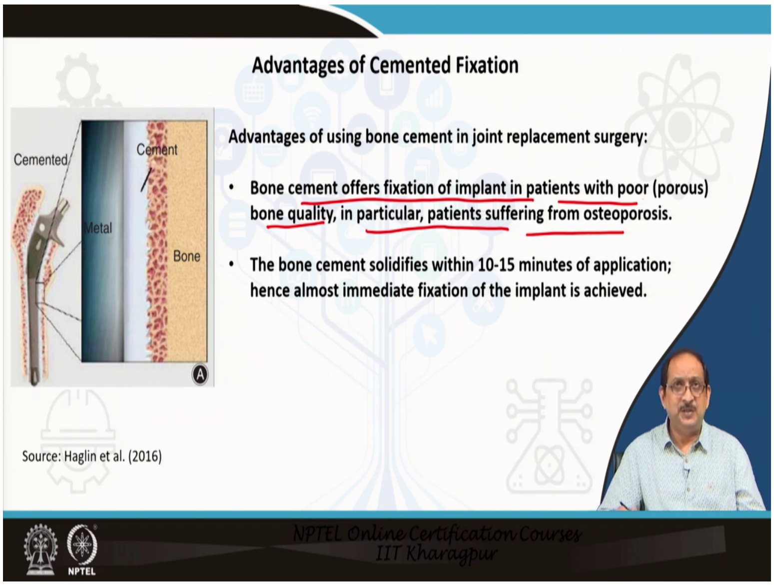

Now, let us discuss some advantages of the cemented fixation. Bone cement offers implant fixation in patients with poor bone quality, which means that bone is very porous. Therefore, bone cement offers fixation of the implant in patients who have osteoporosis. The bone cement solidifies within 10 to 15 minutes of application. Hence, almost immediate fixation of the implant is achieved.

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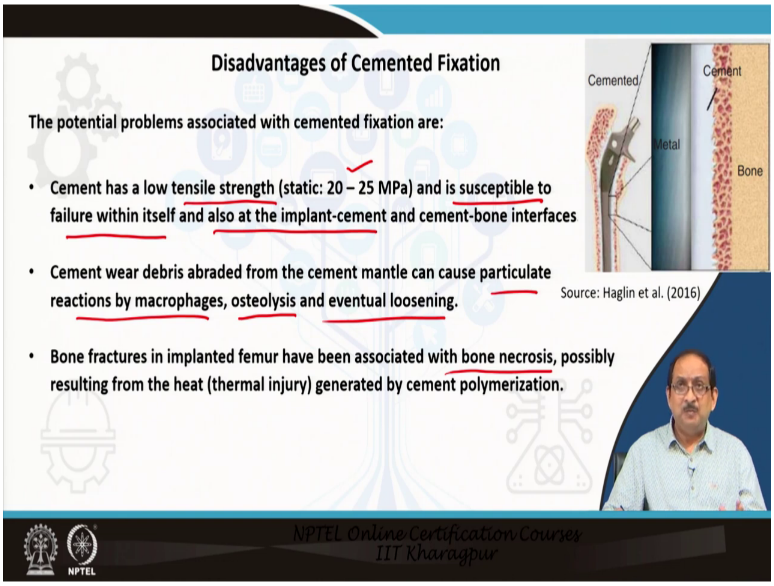

Now, some serious issues are threatening the long-term efficacy of the bone cement. The potential problems associated with cemented fixation are as follows: cement is strong in compression but weak in tension. It is the most likely material where the crack is initiated.

Now, bone cement has a low tensile strength, reported static strength is around 20 to 25 MPa whereas, the static strength for some millions of cycles can come down to 8 to 10 MPa.

Now bone cement is susceptible to failure within itself and at the implant cement and cement bone interfaces. Moreover, the implant cement and cement bone interfaces are the weakest links in the implant-bone structure leading to interface debonding.

Cement wear debris abraded from the cement mantle can cause particulate reactions by macrophages, osteolysis and eventual loosening. Now, what is osteolysis? Osteolysis is defined as progressive destruction. It is the process of progressive destruction of Periprosthetic bone tissue.

The other potential problem with cement fixation is bone fractures in implanted femur reported to be associated with bone necrosis, possibly resulting from the heat generated by cement polymerization. Therefore, there is a potential threat of thermal injury to the bone layer adjacent to the cement layer due to cement polymerization. Now, what is bone necrosis? Necrosis is the death of bone tissue due to a lack of blood supply.

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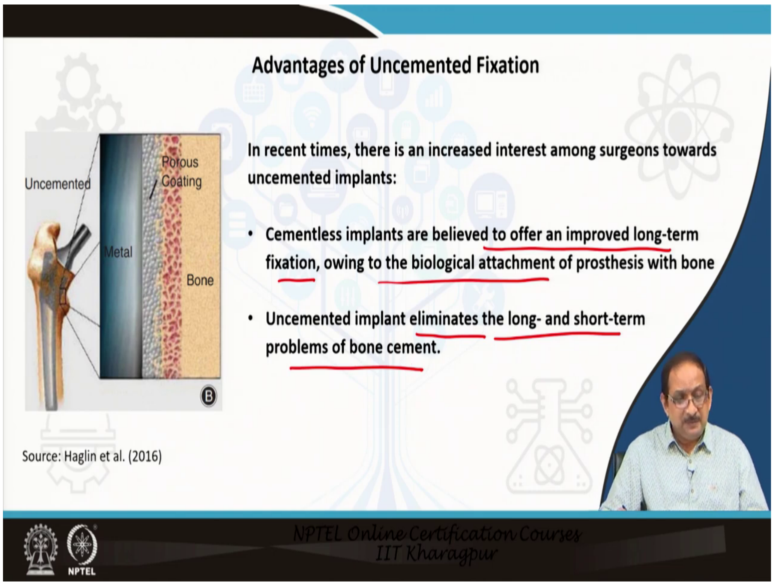

Now, let us come to the advantages of the uncemented fixation. In recent times, there has been an increased interest among surgeons towards uncemented implants. The cementless implants are believed to offer an improved long-term fixation, owing to the biological attachment of the prosthesis with the bone. The uncemented implant eliminates the long- and short-term problems of bone cement.

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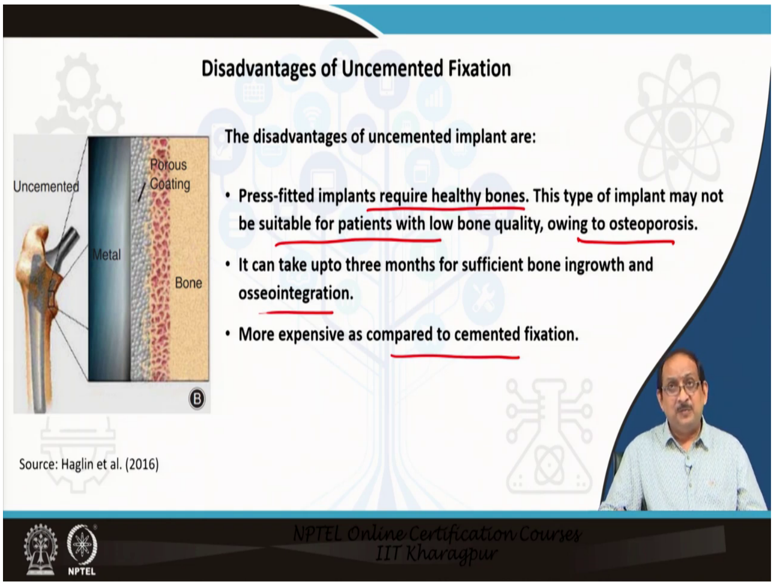

Let us now discuss the disadvantages of the uncemented implants. Press fitted implants require healthy bone. So, the initial fixation of the uncemented implants requires healthy bone. This type of implant may not be suitable for patients with poor bone quality owing to osteoporosis. It can take up to three months for sufficient bone ingrowth and osseointegration. Now osseointegration means implant integration of fixation with the surrounding bone. Uncemented implants are more expensive as compared to the cemented type of implants.

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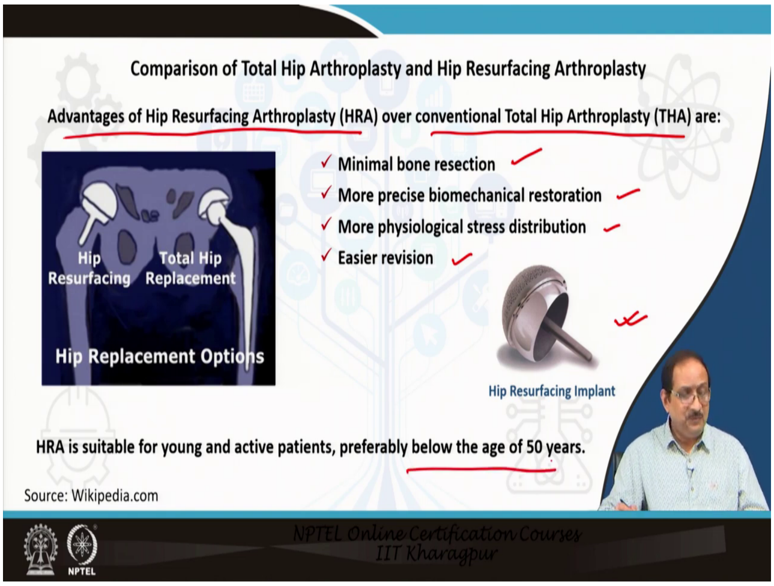

Let us now discuss about total hip arthroplasty and hip resurfacing arthroplasty. We had discussed briefly earlier in the module one, but let me now present to you the advantages of hip resurfacing arthroplasty over the conventional total hip arthroplasty. So as you might know, hip resurfacing is a surgical procedure that involves surface replacement or replacement of the joint's articular surfaces. So you can see a typical hip resurfacing implant presented in the slide, which replaces the surfaces of the femur bone and the acetabular bone.

The total joint replacement is far more invasive. So, the hip resurfacing arthroplasty has the advantage of minimal bone resection and more precise biomechanical restoration. So, hip resurfacing arthroplasty is reported to be suitable for young and active patients, preferably below the age of 50 years.

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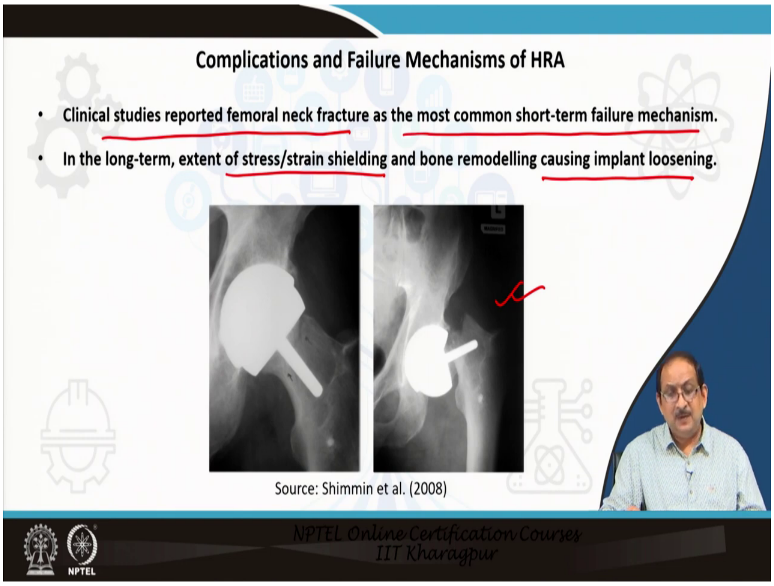

However, there are some unique set of complications in the case of hip resurfacing, arthroplasty. Now clinical studies reported femoral neck fracture after surgery as the most common short term failure mechanism. This is indicated here in the slide. In the long term, the extent of stress-strain shielding and adverse bone remodeling leading to bone resorption, periprosthetic bone resorption, eventually causing implant loosening, have also been reported.

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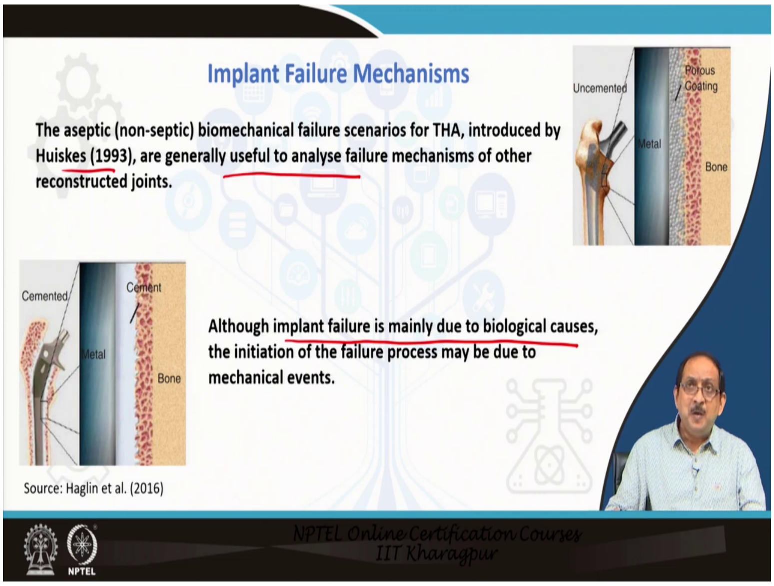

Let us now discuss the second topic that is the implant failure mechanisms, in detail. Now, aseptic biomechanical failure scenarios or mechanisms for total hip arthroplasty was summarized by Huiskes in his publication in 1993. But these failure scenarios are generally helpful to analyze failure in other reconstructed joints. Although implant failure is mainly due to biological causes, the initiation of the failure process may be due to mechanical events.

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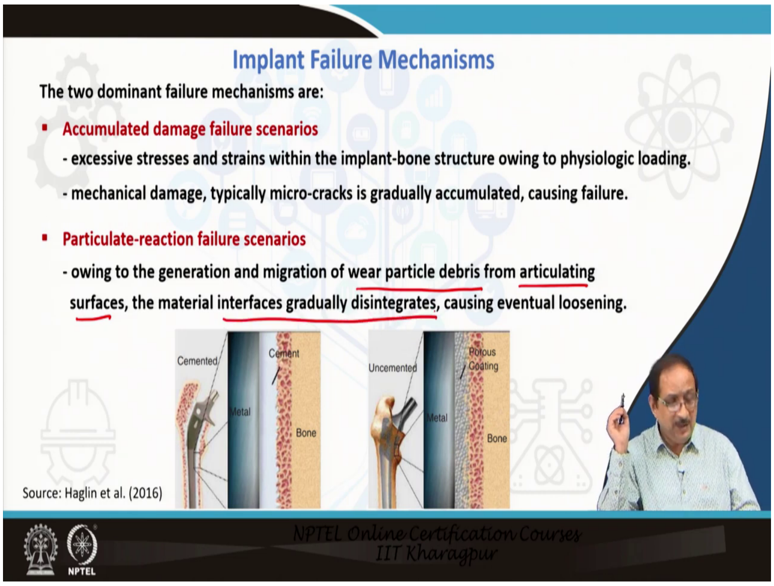

Now, there are two dominant failure mechanisms, as indicated by Huiskes. The first and foremost is the accumulated damage failure scenario. Wherein excessive stresses and strain within the implant-bone structure owing to physiological loading are generated. Mechanical damage: microcrack is gradually accumulated within the implant-bone structure, eventually causing failure.

The other important failure scenario is the particulate reaction failure scenario. Due to the generation and migration of wear particle debris from articulating surfaces, the material interfaces gradually disintegrate, causing eventual loosening.

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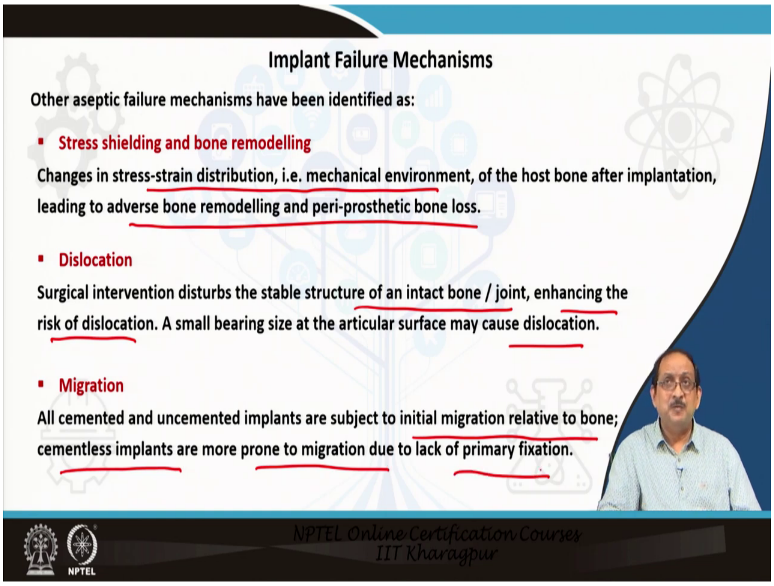

Other aseptic failure mechanisms can also be identified as follows. Stress shielding and bone remodeling is an imminent failure mechanism. Now, changes in stress-strain distribution lead to adverse bone remodeling and periprosthetic bone loss. So, it is mainly due to the alteration of stress-strain distribution or the mechanical environment within the host bone after implantation compared to the natural situation.

Surgical intervention disturbs the stable structure of an intact bone or joint, enhancing the risk of dislocation. So, a small bearing size at the articular surface may cause dislocation, which is one of the failure mechanisms. Now, all cemented and uncemented implants are subject to initial migration relative to the bone. However, cementless implants are more prone to migration due to a lack of primary fixation.

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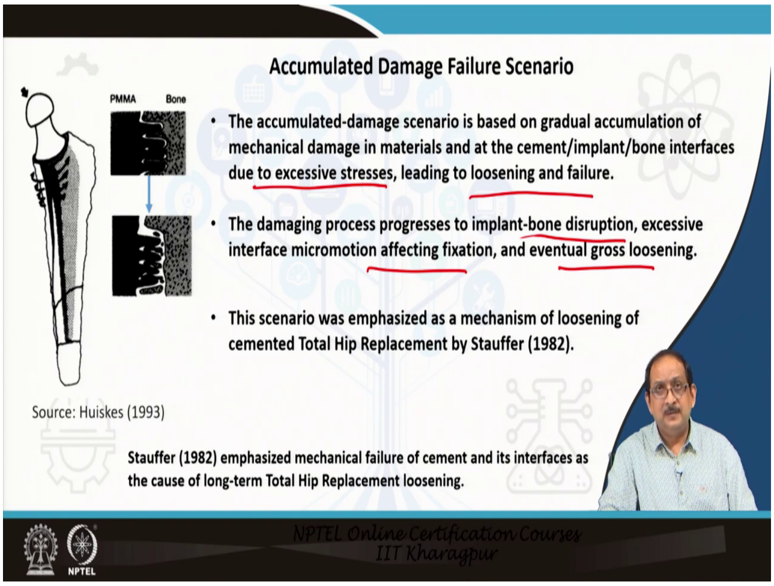

Now, let us discuss the accumulated damage failure scenario. The accumulated damage failure scenario is based on the gradual accumulation of mechanical damage in materials and at the cement-implant or bone interfaces due to excessive stresses, leading to loosening and failure of the implanted joint. The damaging process progresses to implant bone disruption, excessive interface micromotion affecting fixation and eventual gross loosening.

This scenario was emphasized as a mechanism of loosening of cemented total hip replacement by Stauffer in 1982. The strength of the stem cement bond in cemented THR is relatively low. Hence, the failure of this connection over time is not unlikely. Once this stem cement interface is debonded, the cement's stresses can dramatically increase, enhancing the probability of damage accumulation, cement failure, cement bone interface loosening, and eventual gross loosening.

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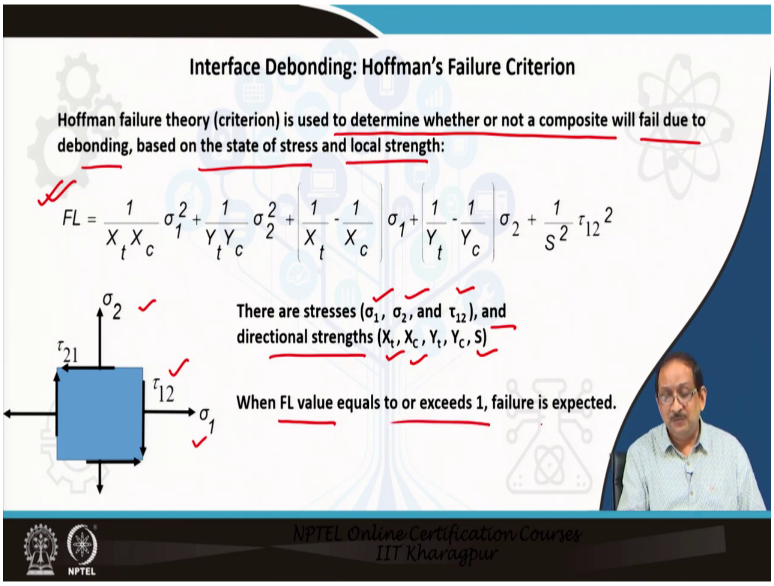

Let us now discuss interface failure. Now, Hoffman's failure criteria is a well-known failure criterion used to determine whether or not a composite will fail due to debonding, based on the state of stress and the local strength. Now, Hoffman's failure criteria is stated here in the slide.

And this criteria combines the stresses sigma one, sigma two, and tau one, two as indicated here in the slide. And the directional strengths, tension, compression, shear. So, here we have directional strength in x and y directions and S is the shear strength. Now, if you put the values in this failure criterion, a value of FL can be calculated if the FL value equals to or exceeds 1, failure is expected.

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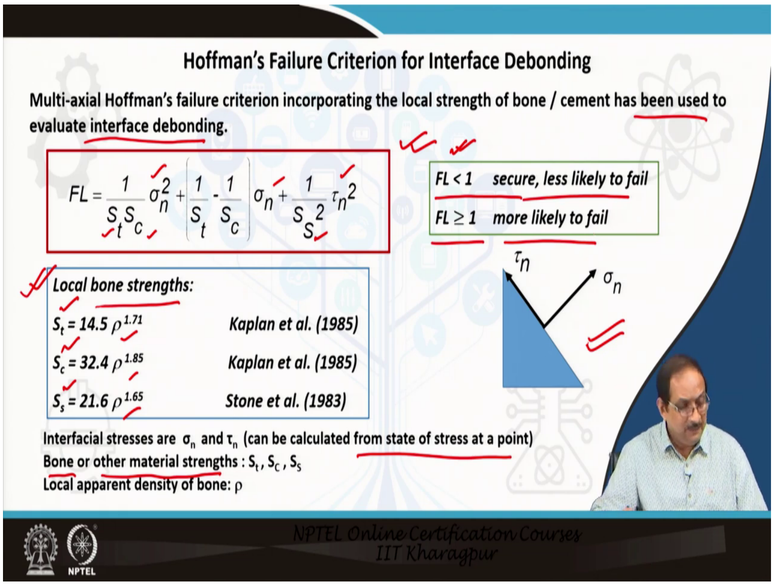

So, Hoffman's failure criteria was very useful in evaluating interface debonding in implant-bone structures. The multi-axial Hoffman's failure criteria incorporating the local bone strength or the cement strength has been used to evaluate interface debonding.

So, the slightly modified Hoffman's failure criteria that is used generally for inter, for evaluating interface debonding is expressed in this slide. Now, this criteria incorporates the interface stresses, the multi-axial interface stresses in the form of normal and shear stresses that can be calculated from state of stress at a point, it also incorporates at the same time the local strengths of bone or other materials in the implant-bone structure.

So, if it is a bone interface, then the changing value of the bone strengths due to change in apparent density of bone is already incorporated in this multi-axial Hoffman's failure criteria. Now, the local bone strength as a function of bone apparent density rho is presented here the relationship between the tensile strength, compressive strength, and the sheer strength of bone can be calculated from the apparent local density of bone.

Now, as stated earlier, the FL value can be calculated based on the normal and shear stress at the interface and the tensile, compressive and shear strength of the interface at any point. If the FL value is less than 1, then the interface is secure and less likely to fail. If the FL is equal to or greater than 1, the interface is more likely to fail.

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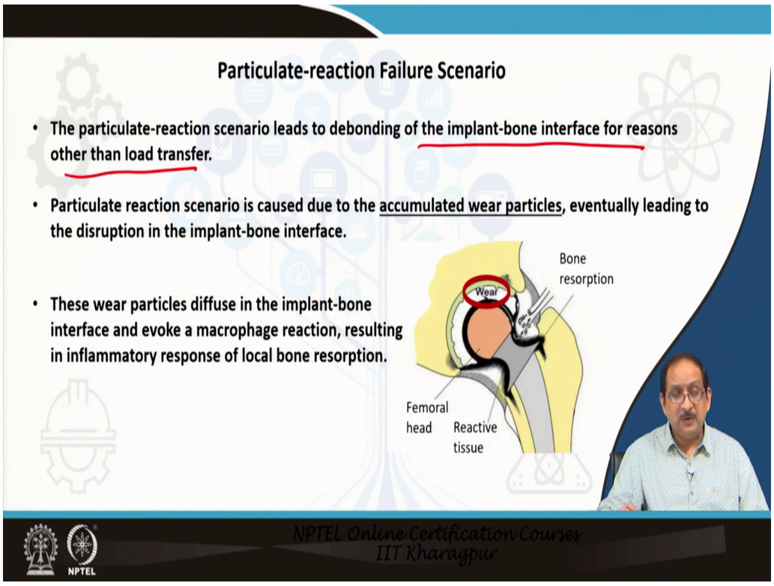

Let us now discuss the particulate reaction failure scenarios. The particulate reaction scenarios lead to debonding of the implant-bone interface for reasons other than load transfer. The particulate reaction scenario is caused due to accumulated wear particles, eventually leading to the disruption of eventually leading to the disruption in the implant-bone interface.

The process weakens the sorry these wear particles diffuse in the implant-bone interface and evoke a macrophage reaction resulting in an inflammatory response of local bone resorption. The process weakens the implant-bone interface and might lead to potential implant migration and gross loosening of the component.

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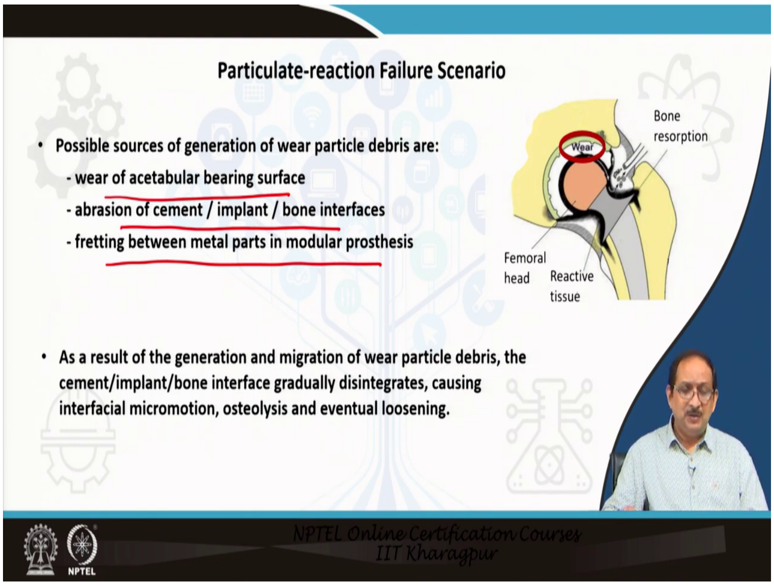

Possible sources of wear particle debris generation are wear of acetabular bearing surface, abrasion of cement, implant or bone interfaces, and fretting between metal parts in a modular prosthesis. Now, where is the loss of material from the surface of a material? This process is generally progressive in nature.

In comparison, abrasion is one of the actions which can cause wear. It is caused by the mechanical process of rubbing the surfaces against some other material. As a result of generation and migration of wear particle debris, the cement implant or bone interfaces gradually disintegrate, causing interfacial micro motion, osteolysis, and eventual loosening.

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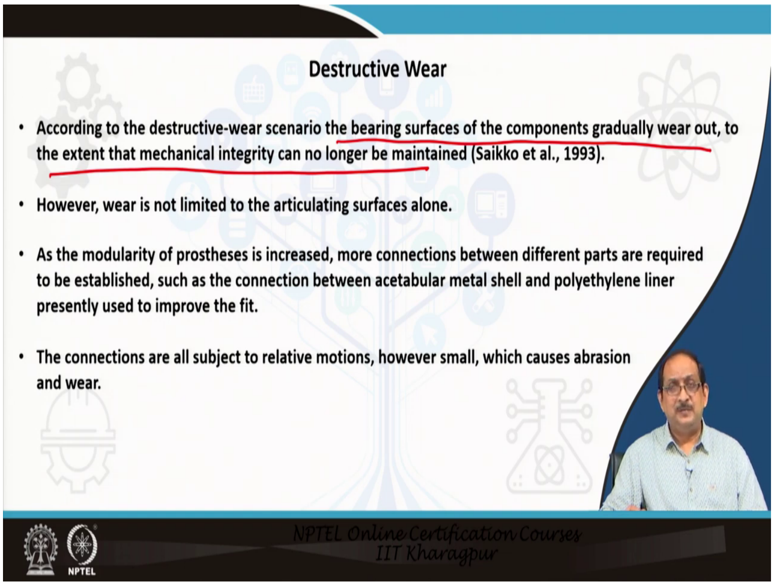

According to the destructive wear scenario, the bearing surface of the components gradually wear out to the extent that mechanical integrity can no longer be maintained. However, wear is not limited to the articulating surfaces alone. As the modularity of the prosthesis is increased, more connections between different parts of the implants are required to be established, such as the connection between acetabular metallic shell and the polyethene liner presently used to improve the fit. The connections are all subject to relative motions; however small they may be, it can actually cause abrasion and wear.

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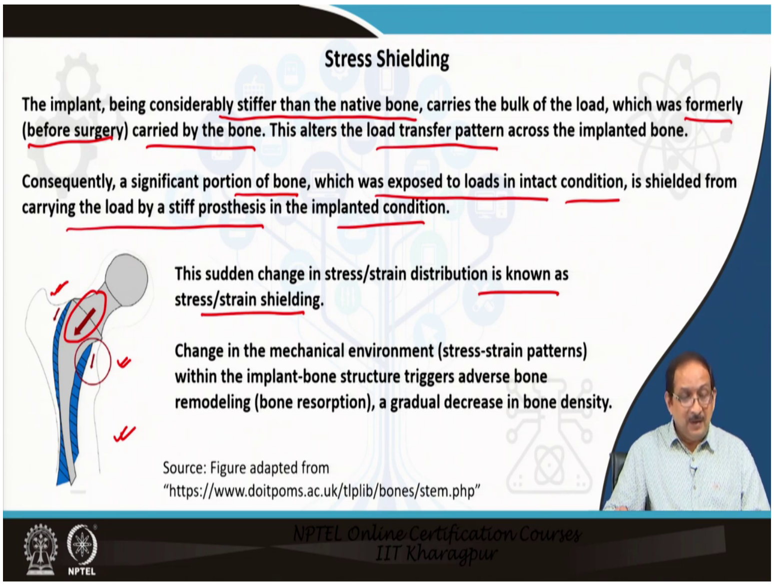

Now, let us discuss about stress shielding and bone remodeling. The implant being considerably stiffer than the native bone carries the bulk of the load, which was formerly before surgery was carried by the bone. So, this alters the load transfer pattern across the implanted bone structure. Consequently, a significant portion of bone exposed to loads in the intact condition is shielded from carrying the load by the stiff prosthesis in the implanted state.

So, this is well exhibited in the figure presented here in the slide. The implant is actually carrying the bulk of the load indicated by a thick, large arrow. Whereas the underlying bone below the implant's surface and near to the surface of the implants on both sides actually carries significantly less bone than the natural situation.

This sudden change in stress-strain distribution is known as stress-strain shielding. Changing mechanical environment stress strain patterns within the implant with bone structure triggers adverse bone remodeling that is bone resorption, a gradual chain that is a gradual decrease in bone density.

Now, the long term bone adaptation phenomenon is known as bone remodeling, and adverse bone remodeling reduces the support to the implant, eventually leading to loosening and failure. Moreover, such prolonged bone resorption also poses a challenge during the revision surgery.

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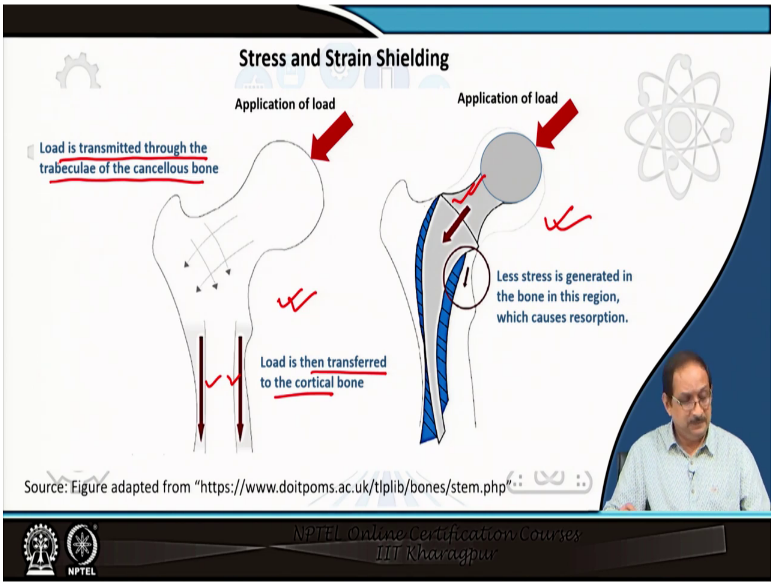

Stress and strain shielding is now explained with the help of two figures in this slide. An equilibrium condition of stresses and strain due to average daily activities prevail in the case of natural or intact bone. Now, the load transfer is presented here in the slide on the left. So, the load is transmitted or transferred through the trabeculae of the cancellous bone present in the proximal part of the femur. The load is then transferred to the cortical bone as indicated from the proximal part of the femur towards the diaphysis of the femur.

Now, what happens after surgery? After surgery, the implant carries the bulk of the load as indicated in the figure here, which was formerly transferred by the bone itself. This shields the bone from carrying the mechanical load evoking abrupt changes in the mechanical environment, eventually triggering bone resorption and osteolysis; as defined earlier, osteolysis is the process of progressive destruction of Periprosthetic bone tissue.

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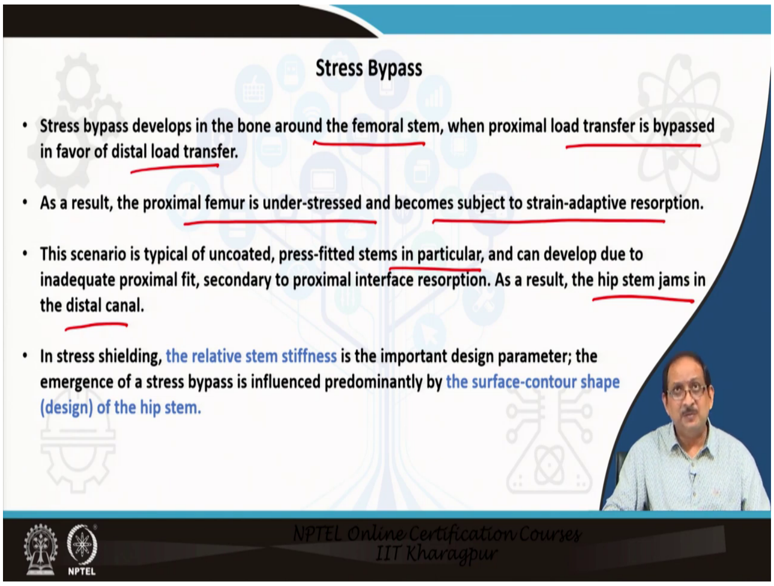

Now, stress bypass develops in the bone around the femoral stem, when proximal load transfer is bypassed in favor of distal load transfer. So, in this case, the proximal load transfer is bypassed in favour of distal load transfer. As a result, the proximal femur is under stressed and becomes subject to strain adaptive bone remodeling and resorption.

This scenario is typical of uncoated press-fitted stems in particular and can develop due to inadequate proximal fit, secondary to proximal interface resorption. As a result, the hip stem and jams in the distal canal. The inadequate proximal fit could be either due to over reaming of the bone or under-sizing of the cement or due to gradual subsidence of the stem.

Many of these cementless hips are likely to subside and jam distally, promoting stress bypass. In stress shielding, the relative stem stiffness is the critical design parameter. The emergence of stress bypass is influenced predominantly by the surface contour shape or the design of the hip stem.

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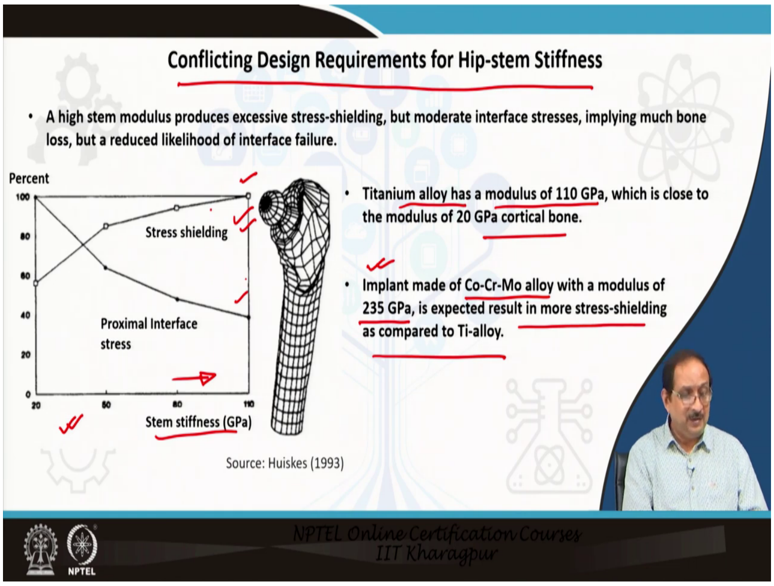

So, we arrive at conflicting design requirements for hip stem stiffness. The hip stem modules have important consequences in stress shielding and interface failure mechanisms. A high stem modulus produces excessive stress shielding, but moderate interface stresses, implying much more bone loss or resorption but a reduced likelihood of interface failure.

Now, titanium alloy has Young's modulus of 110 GPa, and it is rather close to the cortical bone if we compare it with cobalt-chromium molybdenum alloy, which has a modulus of 235 Giga Pascal. Now, implants made of cobalt-chromium molybdenum alloy are expected to result in more stress shielding and adverse bone remodeling than the titanium alloy.

Now, if a stem is stiff, it transfers more load distally and less proximally and it takes larger share of load away from the proximal femur. If it is flexible stem the opposite occurs. If cement is present on the proximal side, the flexible stem evoke less stress shielding in the bone but more interface stresses.

Thus, excessive bone resorption is more likely to occur around stiffer stem as indicated in the figure here. But proximal interface failure is more likely to occur around flexible stem. But proximal interface failure is more like to occur around flexible stems, which is indicated in the figure with an increase in stem stiffness; the chances of stress shielding and bone resorption increase as indicated by the curve, but results in a reduced likelihood of interface failure.

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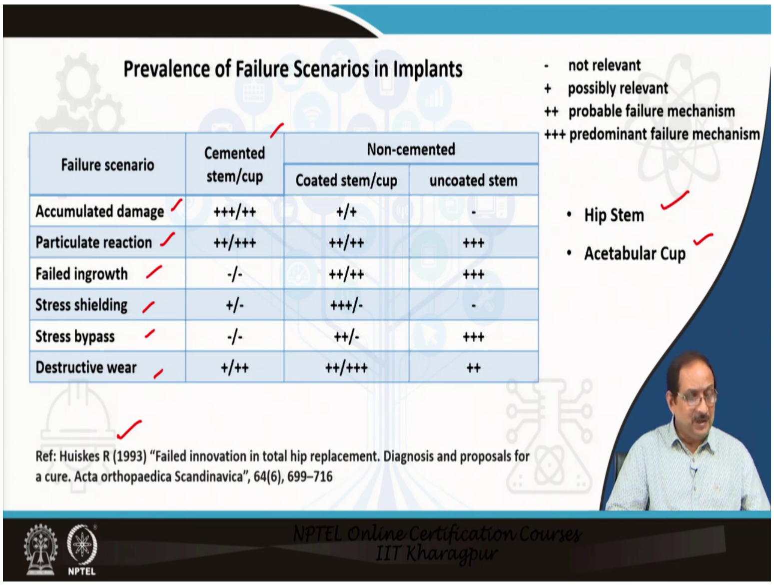

The relevance of the failure scenarios discussed in this lecture is now summarized in this slide for cemented and uncemented or non-cemented hip implants. So, it is mentioned for the hip stem as well as an acetabular component or acetabular cup. So, on the left-hand side of the table, we have the different failure scenarios and corresponding to cemented stem or acetabular cup; the relevance of these failure scenarios are presented individually.

It may be observed that most of the failure scenarios are generic once potential failure mechanisms for cemented and uncemented implants, some prevailed in cemented hip replacements and some in uncemented hip replacements, some are seen more often in the femur and some in the acetabulum as presented by Professor Rick Huiskes in his publication in 1993.

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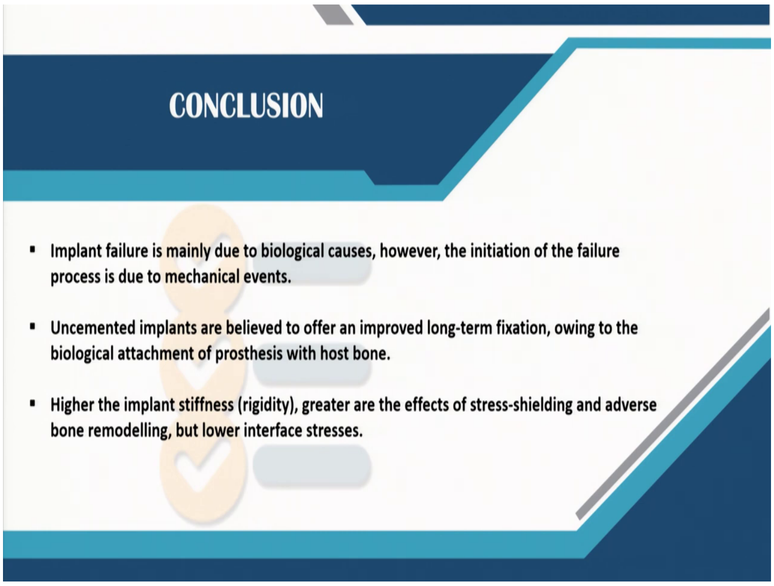

Let me come to the conclusions of this lecture. Implant failure is mainly due to biological causes. However, the initiation of the failure process is due to mechanical events. Uncemented implants are believed to offer an improved long-term fixation owing to the biological attachment of the prosthesis with the host bone: higher the implant stiffness or the rigidity of the implant. Greater are the effects of stress shielding and adverse bone remodeling, but lower interface stresses.

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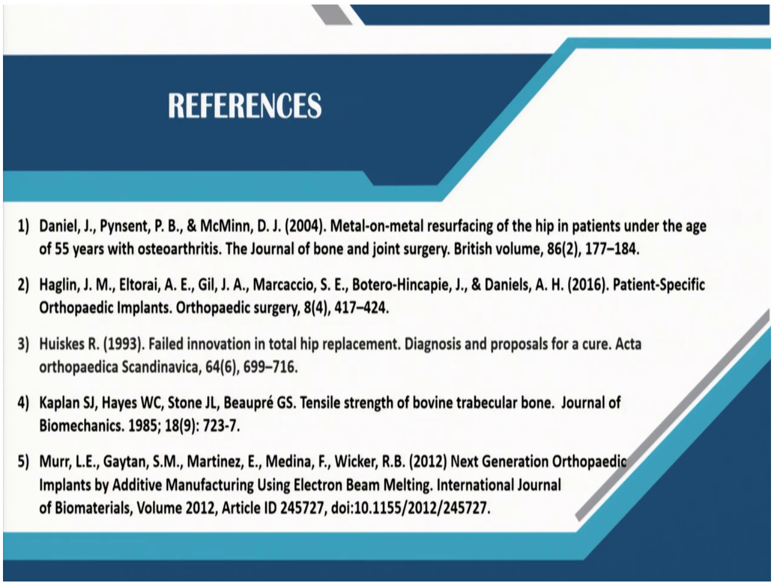

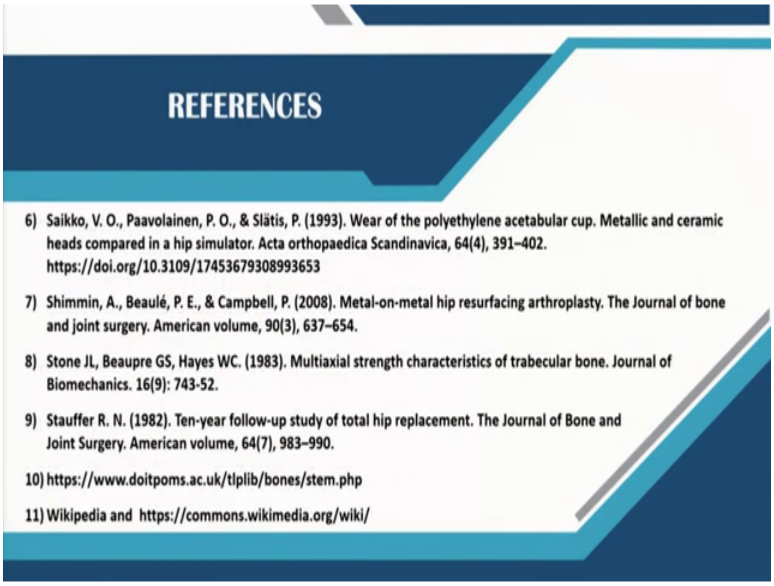

The references are indicated in two slides based on which the lecture has been prepared. Thank you for listening.