Friction and Wear of Materials: Principles and Case Studies

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Lecture - 13
Overview: Bioceramics and Biocomposites

Okay welcome back to NPTEL lectures again. So in this particular lecture, I will introduce you to the broad field of bioceramics and biocomposites.

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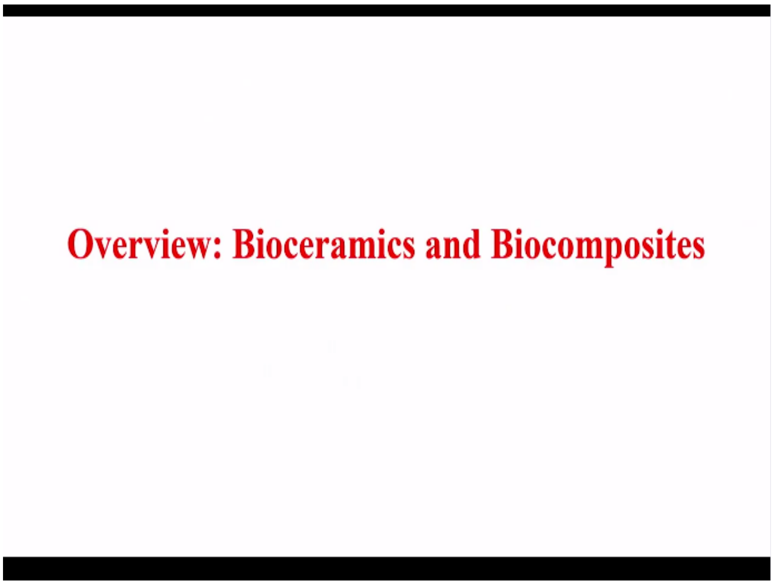

And in particular to the materials which can be used at articulating joints for biomedical applications okay. So essentially I will define some of the key terms in this particular field of biomaterials and explain them their physical meaning and other implications which are of relevance to the tribological applications of these materials.

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This brief introduction to this broad field of societal relevance that is biomaterial science and tissue engineering, one NPTEL one small lecture of half an hour is not sufficient. So therefore readers can go through some of my very recent books and this is one of the undergraduate textbook what I have written and it is published by Cambridge University Press that is Biomaterials Science and Tissue Engineering Principles and Methods. So this particular book a reader can use as a reference.

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And there is other two books which are published by Springer and this is the books for Biomaterials for Musculoskeletal Regeneration, one is concepts and one is applications. In both these two volume books, I have discussed at length what are the requirements, property requirements for biomaterials for musculoskeletal regeneration with repetitive case studies.

Also I have mentioned what is the relevance for the biomechanical property, evaluation including friction and wear properties okay.

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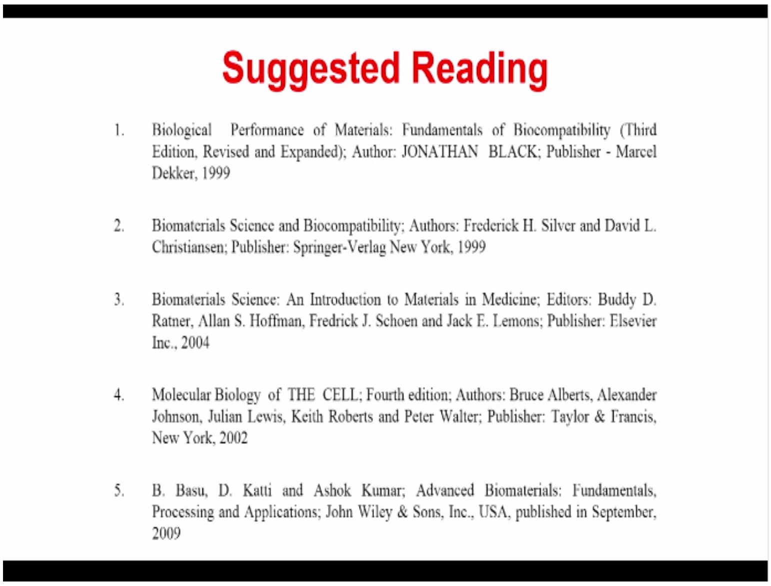

So these are the other books standard textbooks in the field and this 4 or 5 I have mentioned, 5 I have mentioned and first one is by Jonathan Black that is quite old that is 1999 almost like 20 years ago. The second one is Silver and Christiansen. Third one is a Buddy Ratner, Allan Hoffman. These are colleagues from University of Washington at Seattle and they have written this book on biomaterial science, introduction to materials in medicine.

And some of the cell biology aspects, this is considered as a Bible in cell biology that is published by Bruce Alberts.

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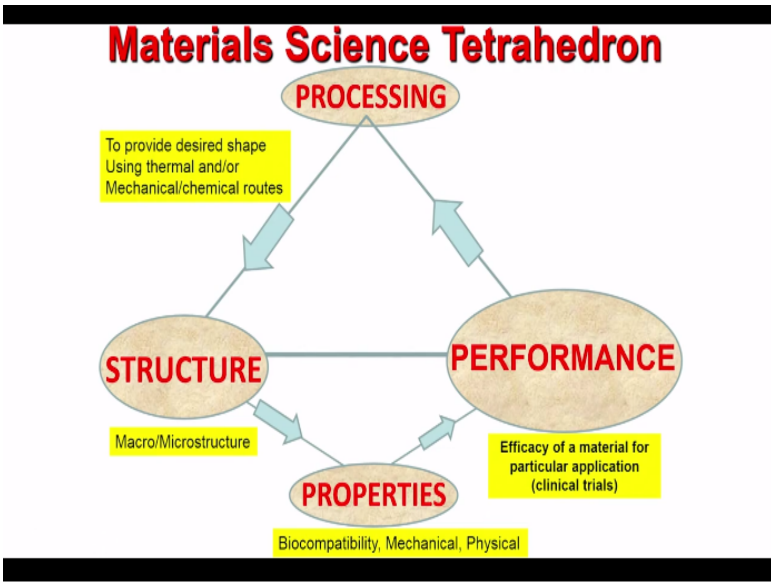

Now this is the typical material science tetrahedron which is very popular in the field of material science but in the biomaterial science what is more important for you to remember is that processing structure property and these properties biocompatibility and mechanical property and physical property and performance is like efficacy of a material for a particular application like clinical trials and so on.

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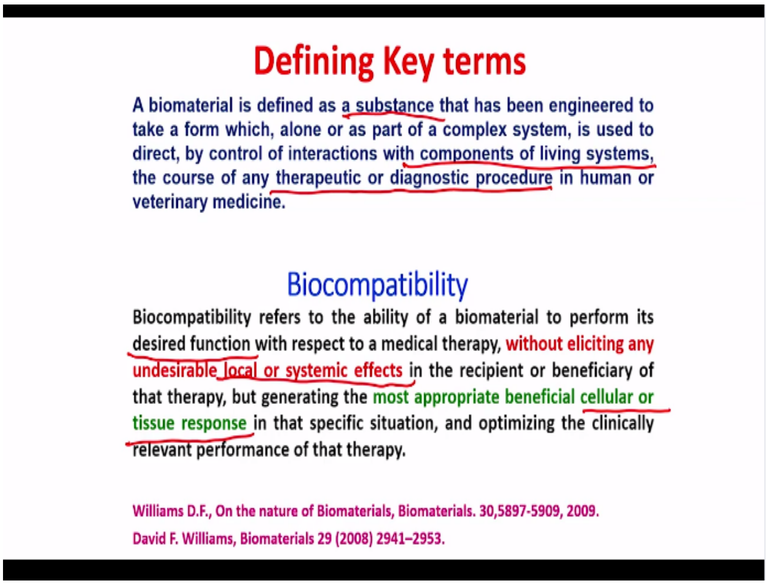

Now as I said that I will try to define, I will define some of the key terms in the biomaterials, so the first one certainly what is a biomaterial? So this biomaterial is defined as a substance that has been engineered to take a form which, alone or as part of the complex system, is used to direct by control of interactions with components of living systems. Components of living systems means cell, bacteria, protein, blood, etc.

The course of any therapeutic and diagnostic procedure in human or veterinary science medicines. At this point, I must mention that David Williams recently organized a very important meeting, that meeting is called definitions in biomaterial science and that was held in last June that is that means June this year in Chengdu in China where 50 offers from different parts of the world have made.

And reviewed all the existing definitions like biomaterials, biocompatibility, host response and so on so forth and then we have voted for any modifications of this part of all these definitions and then we have come up with our very new definitions or revised versions of these definitions as well as certainly we have also coined certain new terms like biomaterialomics for example as well as various other terms we have revised like inflammation and so on.

So this was a very key meeting and this meeting we have revised and then these definitions will now be accepted in the community. So if I go back to these definitions of biomaterials what you see is that it has been it is a kind of a substance. Now drug is certainly not considered as a biomaterial but titanium which is used as an implant which goes into human body that is certainly you consider as a bioimplant.

Interactions with components of living systems as I mentioned that which are the components of living systems, therapeutic or diagnostic procedure in human medicines like for the human beings this particular substance, biomaterials that is used. Now biocompatibility this is an important property which distinguishes biomaterials from all other classes of materials.

Biocompatibility refers to the ability of a material to perform its desired function with respect to a medical therapy, without eliciting any undesirable local or systemic effects. So local or systemic effects in the recipient or beneficiary of that therapy. In the recipient means that is the human beings but generating the most appropriate beneficial cellular or tissue response. Cellular or tissue response means at the cell level or tissue level response in that specific situation and optimizing the clinically relevant performance of that therapy.

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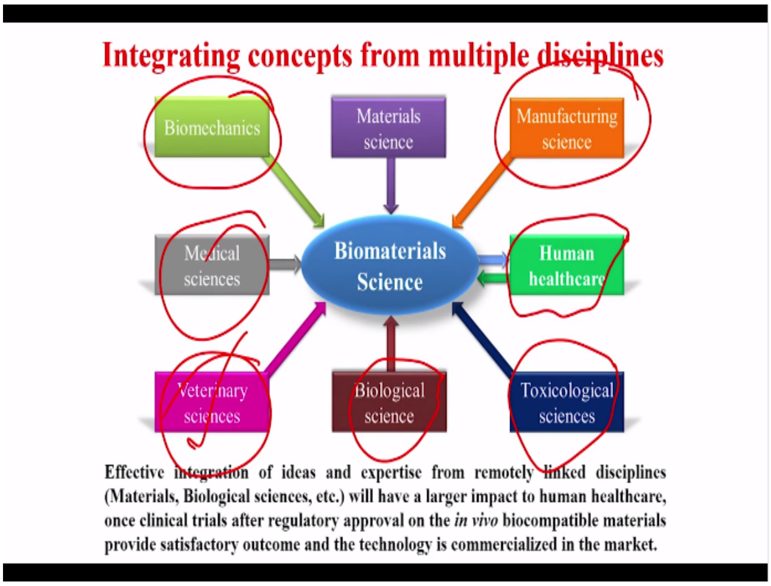

Now this biomaterial science as you know that it is a very interdisciplinary like tribology it is much more interdisciplinary discipline and here we need concepts and ideas from multiple disciplines. For example, biomechanics, biomechanics means that principle of mechanics apply to biological systems like you know in the same stress strain response and establishing the criteria of failure.

And all those things when it is applied to biological systems, it is of relevance. Material science, material science means that same processing structure, property, performance, correlations in synthetic materials like aluminum unlike titanium alloy, stainless steel, cobalt chrome and so on. Manufacturing science means I have discussed in one of the earlier lectures that is called conventional manufacturing technique.

And there is something called advanced manufacturing techniques like 3-D printing and so on and so forth so and then medical sciences certainly is important because the clinical relevance of the biomaterials is far more important. Then, veterinary sciences like when you do this preclinical studies in the rabbit animal model or mouse animal model you need a veterinarian to involve in the study.

So therefore it is important, biological science certainly it requires no explanation because biomaterials means materials which are to be integrated in the biological system means it has to interact with cells, proteins and so on. So therefore you need to have good understanding. Biological sciences as well as toxicological sciences means when a material new material is used, it should not cause any undesired toxicity in the cell or tissue.

And for that we need to evaluate the potential of the materials to cause toxicity. Now while development of this particular idea or understanding is very complex and very complicated, this biomaterial science in fact is far more important because it has direct relevance for human health care. Now if you see these arrows are both ways here. Why? Why these arrows are both ways?

Because human healthcare needs actually will drive the innovations in the field of biomaterial science and ultimately when some new material is developed with lot of with good biocompatibility and it is being tested at preclinical study and clinical trials, again it will help in advancing that the way human healthcare is currently being pursued or it will really help in advancing human healthcare okay.

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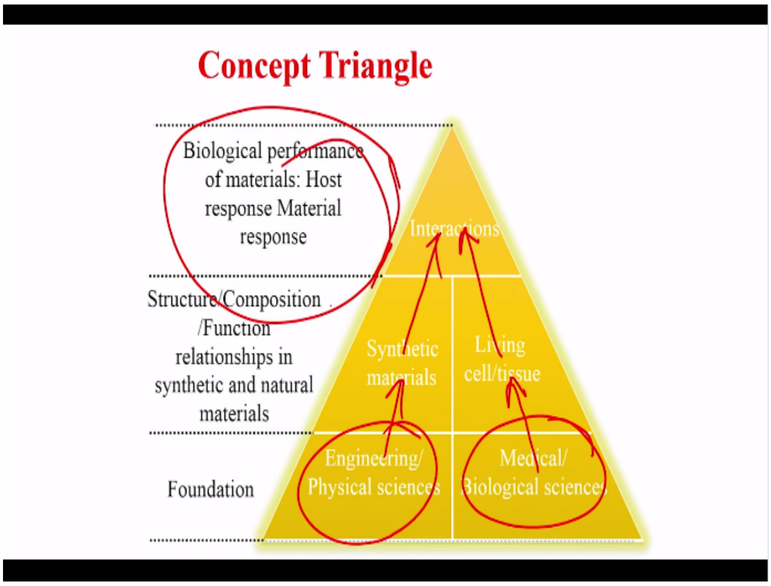

So having said that this kind of concept triangle I have also shown in terms of while defining the tribology but here what you see that this kind of concept triangle is also important for biomaterial science. So what you see that base discipline or fundamental discipline is the engineering or physical sciences in one hand and medical or biological sciences on other hand.

Engineering and physical sciences that will be used to develop synthetic materials, medical or biological sciences that will give you the understanding of the living cells and tissues. Synthetic materials and living cells and tissues, how they interact that will actually define the biological performance of materials of host response and materials response.

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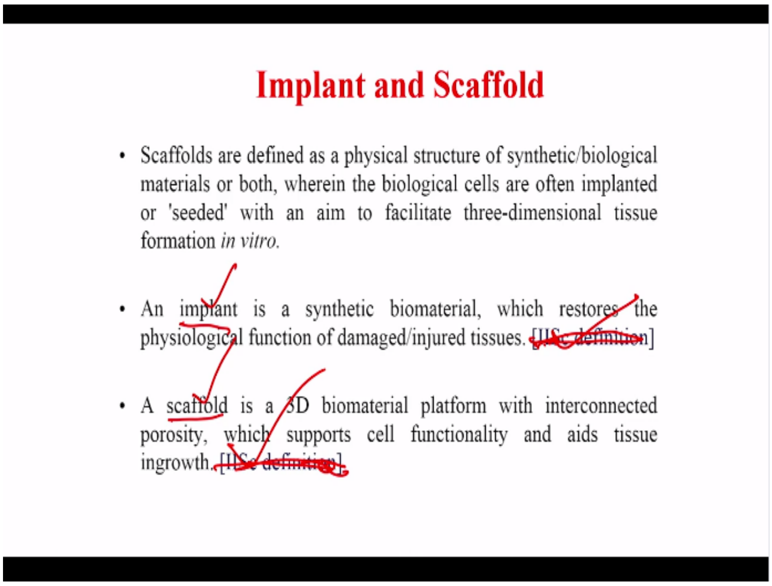

The other things are called the implant and scaffold. Implant and scaffold, an implant is a synthetic materials which restores the physiological function of damaged or injured tissue whereas the scaffold is essentially 3-D biomaterial platform with interconnected porosity. Those who are not from biomaterials background, often they think implant and scaffold are synonymous.

But you must understand that implant and scaffold are not synonymous, they are developed for two different purposes and their functionality also quite different. For tribological applications, mostly it is the implants which are much more largely used at the articulating surfaces, load-bearing articulating surfaces okay.

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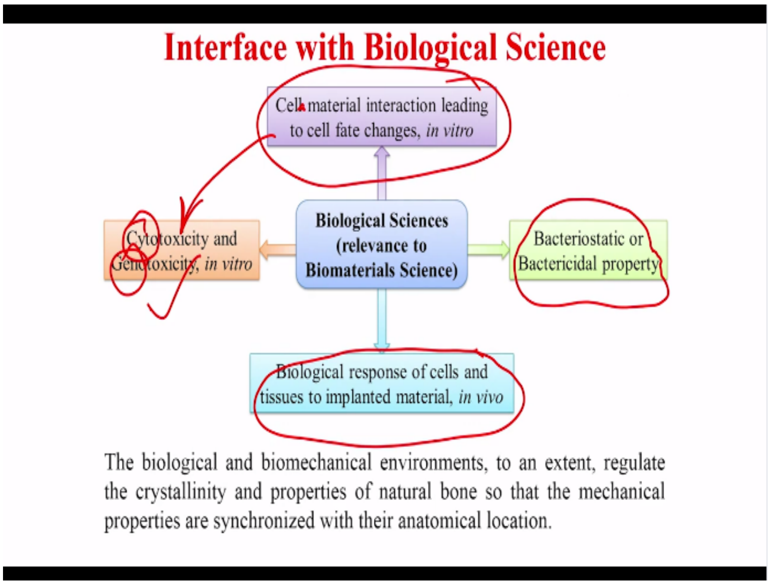

And this is little bit more explanation that how biomaterial science interfaces with the biological sciences. So often the students they think that if they may not be able to work in the field of biomaterials because they may not have sufficient background in biology. My answer to all such questions is that biology according to me is like ocean of knowledge.

And it is not possible for any single biomaterials researcher to have the equivalent and comparable knowledge like that of a biologist who has got very extensive training right from the basic undergraduate study to the postgraduate to the graduate studies only in biological sciences. However, it is important to perceive here that one has to intelligently draw and blame the concept of biological sciences which are of direct relevance to biomaterial sciences.

One other thing I have mentioned here is a cell material interaction leading to the cell phase changes. Now cell material interaction is one of the important things because that will give you that how a biological cell interacts with the materials. Then, cell toxicity or cytotoxicity, cyto means cell and genome means DNA damage, so genotoxicity means DNA damage and cytotoxicity means what is the cell level toxicity.

Third one biological response of cells and tissues to implanted material in vivo. So what is the in vivo, what is a response biocompatibility response for in vivo and fourth one is that a bacteriostatic or bactericidal property. This is also another important thing that how this bacteriostatic property is evaluated for the biomaterials.

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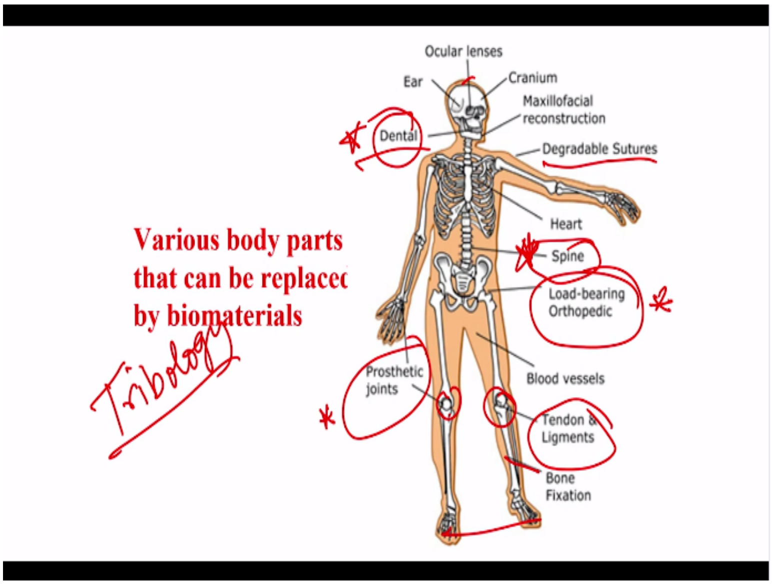

Now this is the human skeleton, just to show you that how biomaterials can be used right from head to toe, so you can see here that even for that ear orbital implants, middle ear orbital implants that is made of hydroxyapatite, you have cranium where you can do for example decompressive craniectomy you need cranioplast. So essentially patient's brain will be opened up and the people can put the cranioplast in the patient's brain.

Ocular lenses, maxillofacial reconstruction, degradable sutures and dental that is dental implants, prosthetic joints that is also another implants that is for hip, knee replacement. Now bone fixes and tendons and ligaments, load-bearing orthopedic implants like hip, in case of the spine there are some spine surgery neurosurgery applications also biomaterials are important but out of that which of the places friction and wear is most important?

So what I am saying where tribological properties play an important role? Now I will put a star here, so these are the star joints like load-bearing orthopedic, prosthetic joints and also the knee joints, these are friction and wear is important, dental applications friction and wear is important, to some extent spine neurosurgical implants. So these are the major areas where tribology plays an important role or friction wear properties plays an important role okay.

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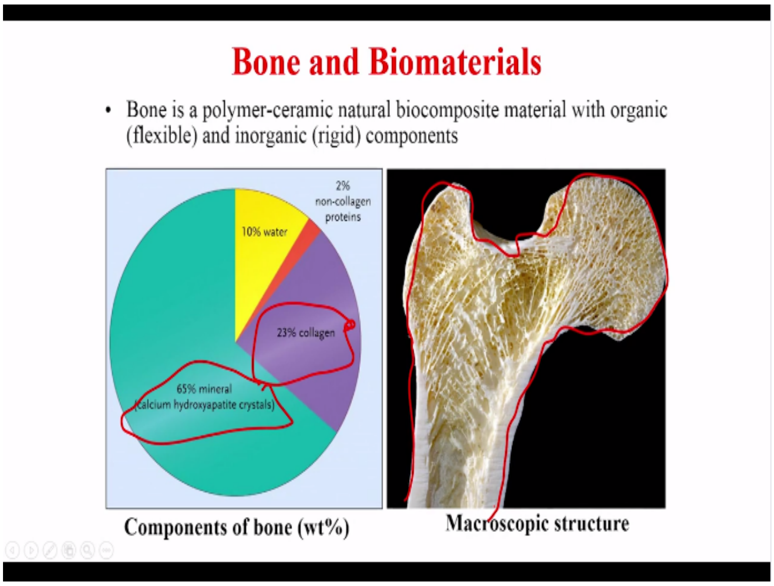

Now if you see that what is bone, bone is a polymer ceramic biocomposite materials and in case of bone if you see that that as I told you multiple times in one of the few earlier lectures, bone is made up of the collagen and hydroxyapatite composites and with organic flexible inorganic rigid components. Now if you see that out of these bones 65% mineral is that calcium hydroxyapatite crystals and then you have 23% is the collagen okay.

Rest of the things are other materials. Other important thing is that many times you will see that it is important for you to realize that bone has a very complex structure.

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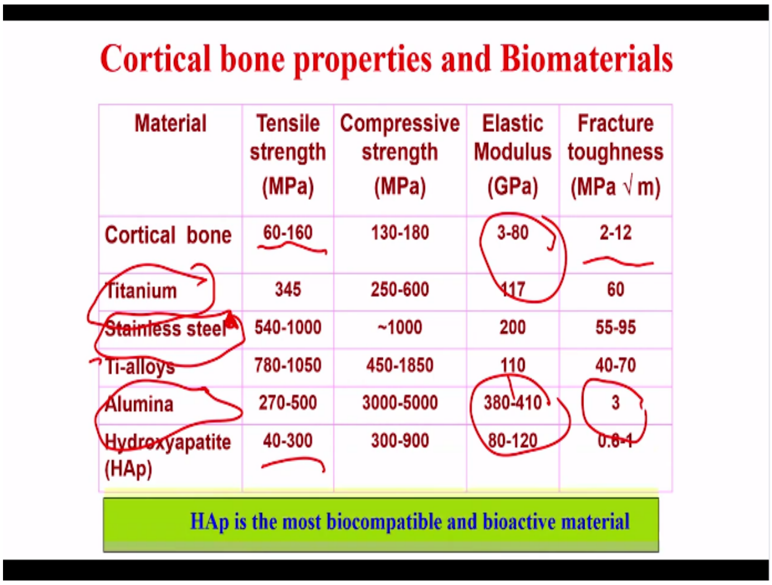

Cortical bone properties and Biomaterials

Material	Tensile strength (MPa)	Compressive strength (MPa)	Elastic Modulus (GPa)	Fracture toughness (MPa √m)
Cortical bone	60-160	130-180	3-80	2-12
Titanium	345	250-600	117	60
Stainless steel	540-1000	~1000	200	55-95
Ti-alloys	780-1050	450-1850	110	40-70
Alumina	270-500	3000-5000	380-410	3
Hydroxyapatite (HAp)	40-300	300-900	80-120	0.6-1

HAp is the most biocompatible and bioactive material

These are the different materials, some of them which are used for the tribological applications in the load-bearing by articulating joints like stainless steel for example, alumina people have tried with the femoral head and if you see that hydroxyapatite is a bone replacement materials, so if you look at the compare that bone properties, these are like static properties, fracture toughness 2 to 12 MPa squared meter whereas fractured toughness of alumina is 3.

Elastic modulus is 3 to 80 whereas alumina elastic modulus is very high. So there is a difference in the elastic modulus and fracture toughness. So if the elastic modulus difference is quite high then it causes the aseptic loosening at the biomechanical load-bearing joints okay.

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Many of the orthopedic surgeries, after that many of the orthopedic surgery for knee or hip joint, patients often has to undergo revision surgery and that is important, longer healing time or slow host response, lack of antibacterial property of implants like prosthetic infection, chronic wound healing that is also another problem, translational approaches to take biomaterials to patients.

This is very important in Indian context. Manufacturability to complex shapes with desired porous architecture, engineering approaches to biomedical treatment and bone-mimicking physical properties along with biocompatibility.

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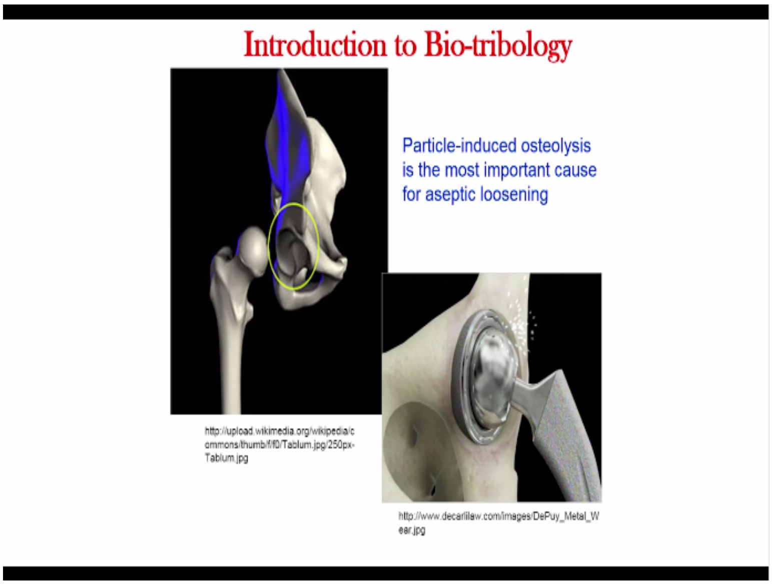

So bio-tribology, this bio-tribology is very important where biomechanical forces lead to friction and wear at the biomaterials in relative motion with another articulating surfaces. So let me emphasize my statement a little bit more clearly.

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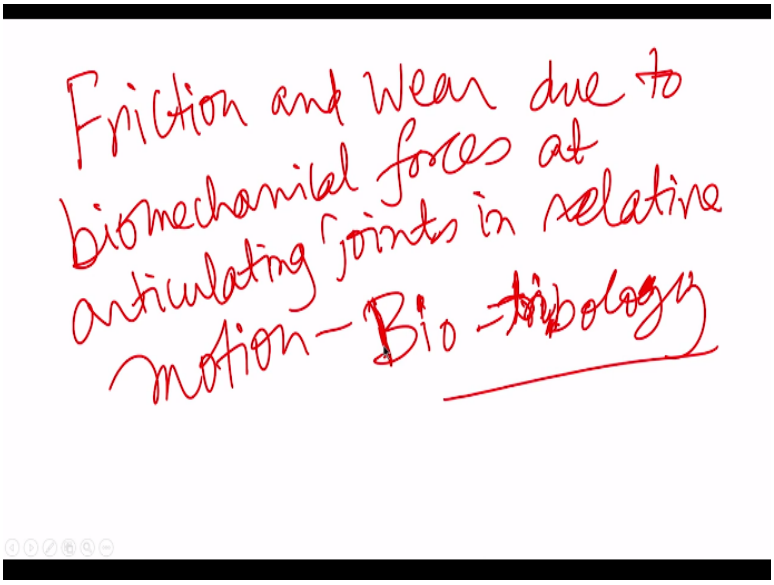

So what I am saying is that so friction and wear due to biomechanical forces at articulating joints in relative motion. This I think is a good definition of bio-tribology okay. So in this kind of friction and wear due to biomechanical forces articulating joints in relative motion, this is a very important concept and then how tribology is being applied to biological systems.

So this is fairly important and this has been kind of illustrated in this particular cases of this total hip joint replacement where this femoral head and acetabular sockets they are in contact and this white flakes like things small particles, you can see that is like a signature of the debris formation.

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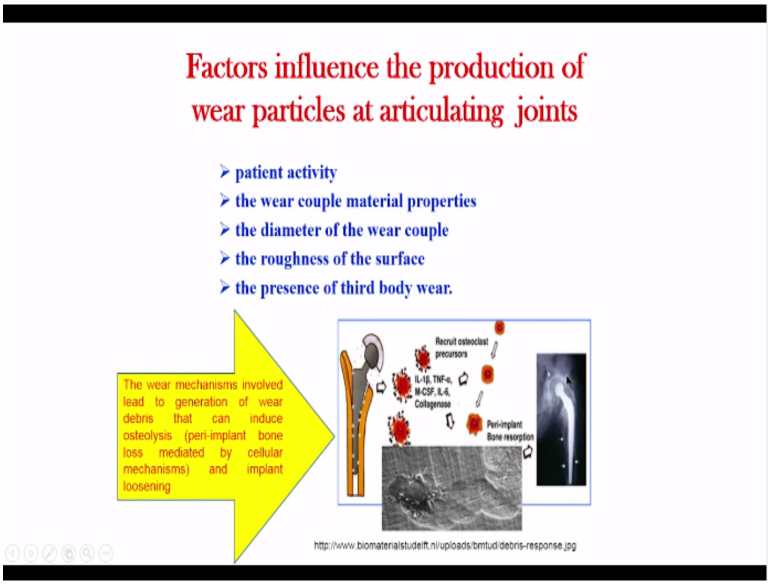

Factors which influence the production of the wear particles at articulating joints, patient activity like after the surgery wear couple material properties like what is femoral what is acetabular socket, diameter of the wear couple, roughness of the surfaces and presence of third body wear. So these are like biological consequences that how wear debris particles can lead to inflammatory reactions in the patients.

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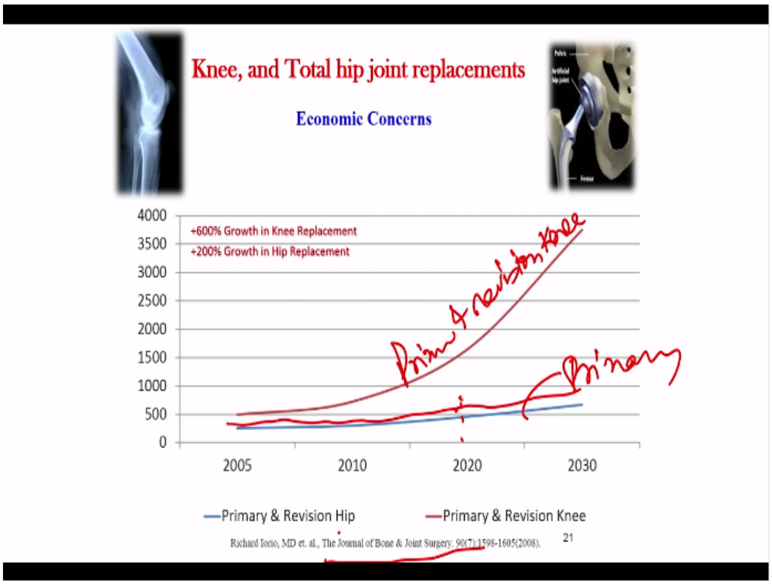

Now if you look at in terms of numbers that how that hip and knee replacement that has gone over the years. Now if we look at that 2005 early 2005 onwards to today is close to 2020, so at least 500 cases which are used in this hip replacement. So this is the primary and revision hip surgery, you can see this is the first one, so this is your primary hip surgery, so this is the data from Journal of Bone and Joint Surgery and primary and revision hip.

And this is the primary and revision knee, so what it shows that knee surgery by far is more predominant or more number of patients they undergo knee surgery or knee replacement than hip replacement.

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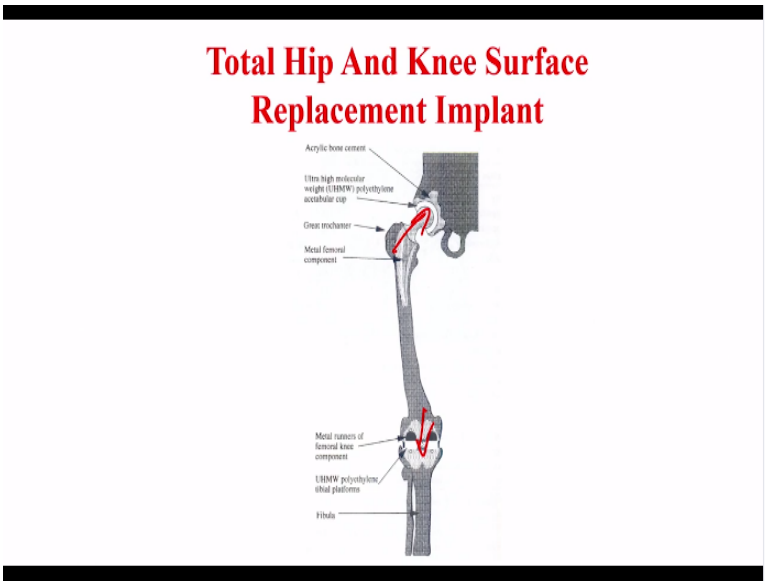

And this is the kind of more biomechanical joints that were hip, the biomechanical forces for example here and biomechanical forces here like when a patient walk after the surgery total hip replacement, there is a continuous experiences of biomechanical forces that the femoral head, acetabular socket interface.

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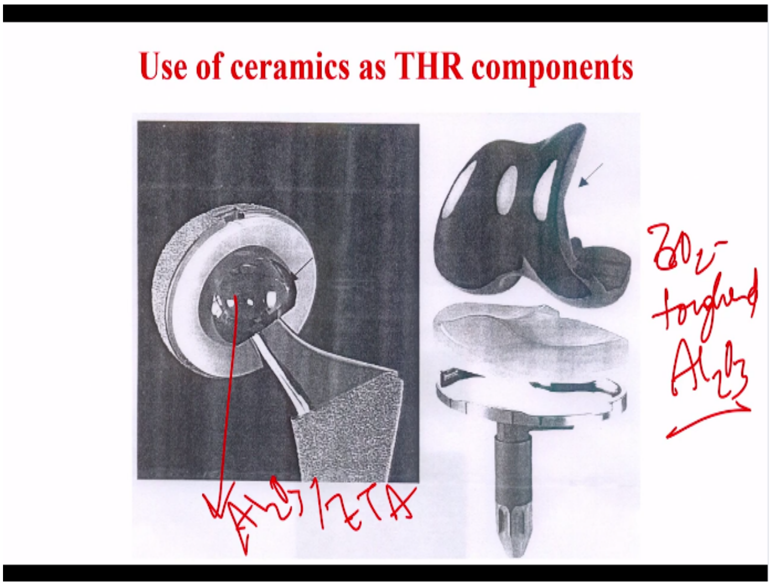

So what are the different ceramics they are used as a total hip joint replacement, this is the femoral head which is made up of the alumina or ZTA. ZTA stands for zirconia toughened alumina, so this is one of the materials which are composite materials which this femoral head can be made of and that also is very important.

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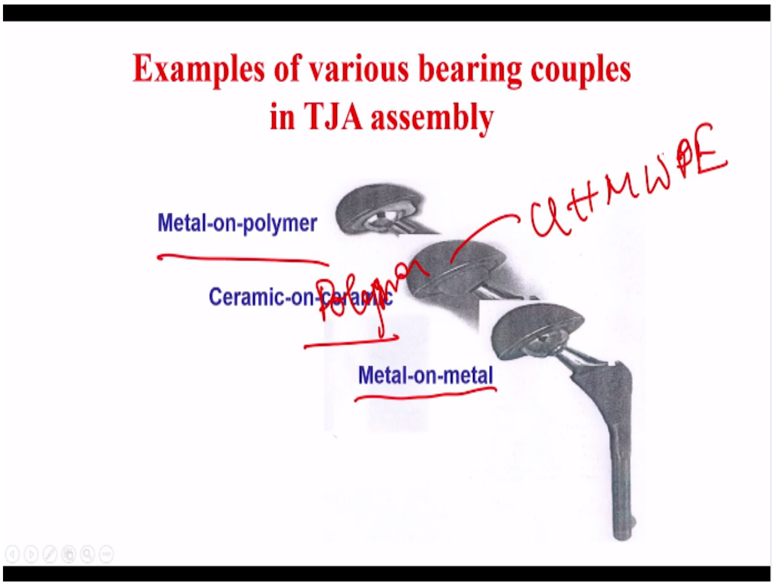

So there are different kinds of combinations of the femoral and acetabular socket that is possible, very earlier one is metal-on-metal. Sometimes people have used ceramic-on-ceramic but mostly people use now clinicians used is ceramic-on-polymer and there is also examples on metal-on-polymer. So in the polymer acetabular socket, people have used this ultra-high-molecular-weight-polyethylene which I have mentioned earlier. That is UHMWP ultra high molecular weight polyethylene.

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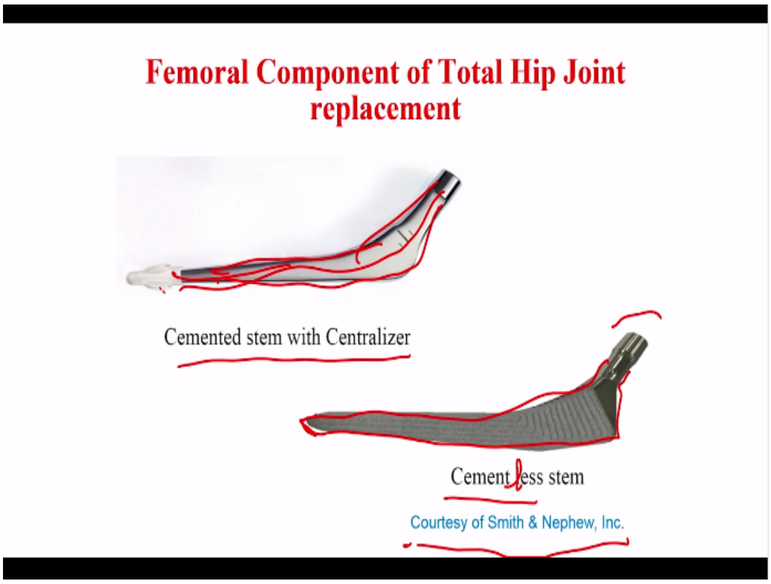

So what is the different commercially used implants which are available in the market as far as the stem is concerned of the total hip joint replacement, it is the cemented stream with centralizer. So this is one of the design concept. So all these implant figures are essentially obtained from Smith and Nephew Incorporate and therefore in every slides which wherever I will show the implants, I have recognized and I have acknowledged the Smith and Nephew towards giving this kind of implants picture.

Now if you see that another one is a cement less stem, so essentially here in the cemented stem then people use that polymethyl methacrylate bone cement but cement less stem they do not use those kind of materials.

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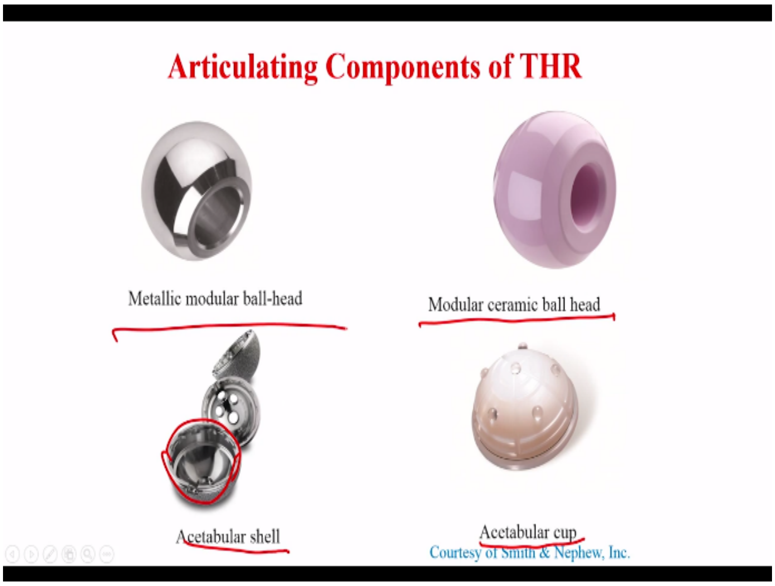

Now femoral head as I told you that femoral head can be made up of metals or ceramic. So this is modular ceramic ball head and this is the acetabular cup and this acetabular shell that is with a metal shell that with the titanium and this metallic modular ball-head.

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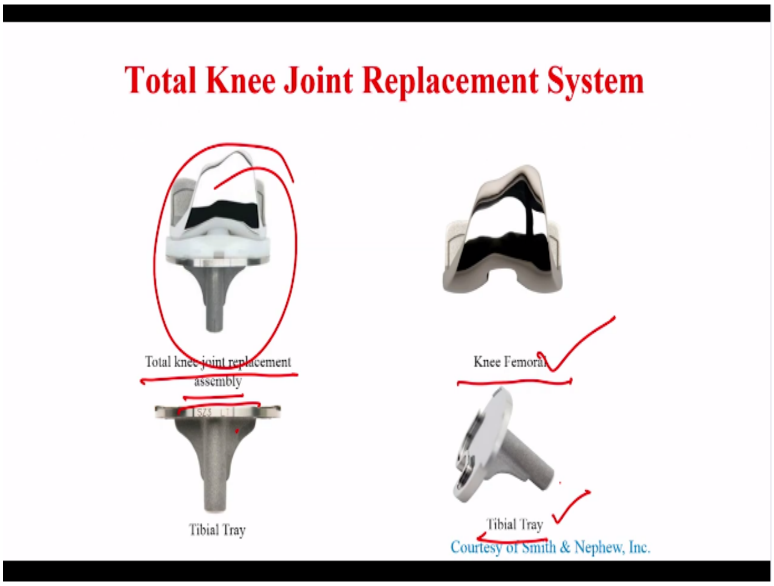

In total knee replacement, you have a knee femoral here and you have a tibial tray and this is your tibial tray and this is your total knee joint replacement, this is the complete assembly like if you go through this one this is a complete assembly, similarly for the knee joint this is the complete assembly and if you look at this knee joint assembly, you have the knee femoral, tibial tray and you have the entire assembly in place.

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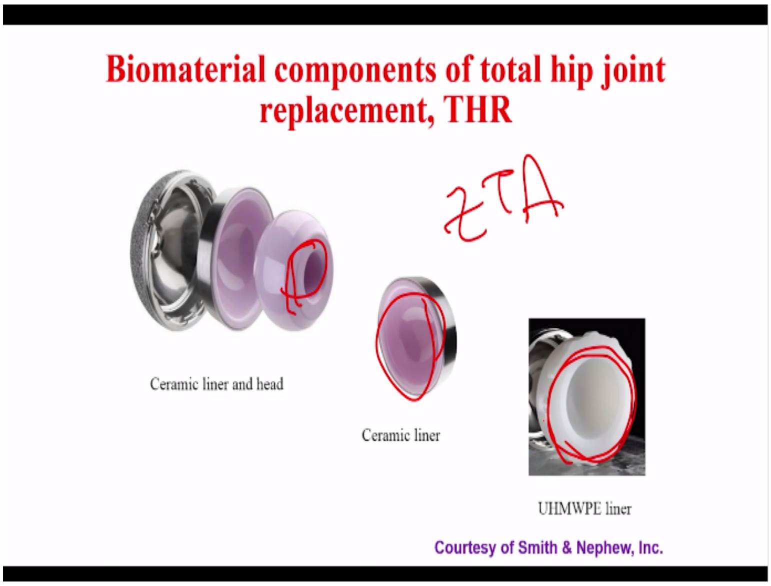

Now there is always some recent innovations and development in the field of total hip replacement surgery and as I told you that ceramic liner and ceramic head both are possible and this is typically ceramic type product or sometimes people use it also other companies they also produce this kind of materials and this is made up of again ZTA zirconia toughened alumina and this is an example of the ceramic liner and this is the ultra-high-molecular-weight-polyethylene liner which also we have used.

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These are articulating surfaces in total hip joint replacement, so this particular femoral stem it goes inside that femoral head and this head goes in contact with this acetabular socket but the wear properties are more important here at this particular interface that is femoral head acetabular socket.

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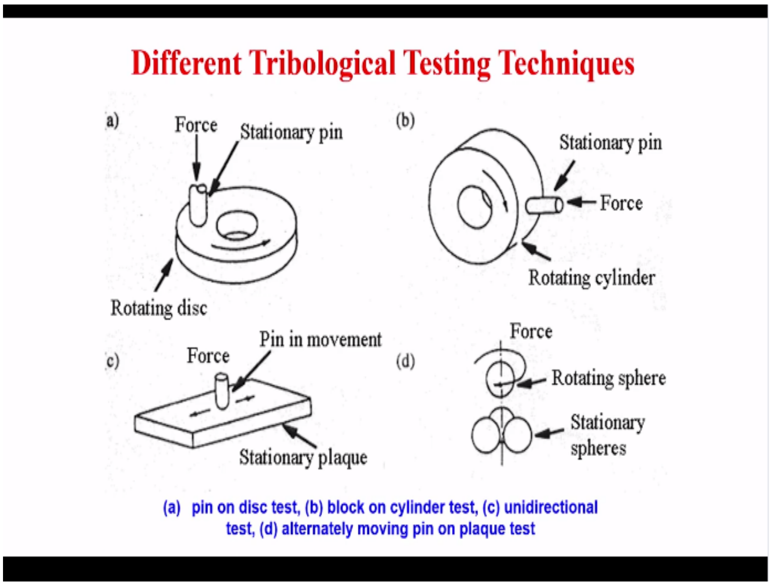

Now these are the standard, very conventional wear testing machines which I have mentioned earlier as well but these in order to simulate these biomechanical conditions, biomechanical forces whether it is femoral head versus acetabular socket or knee joint, there are two different type of equipments which I have not described here but it is fairly important is I will just mention it.

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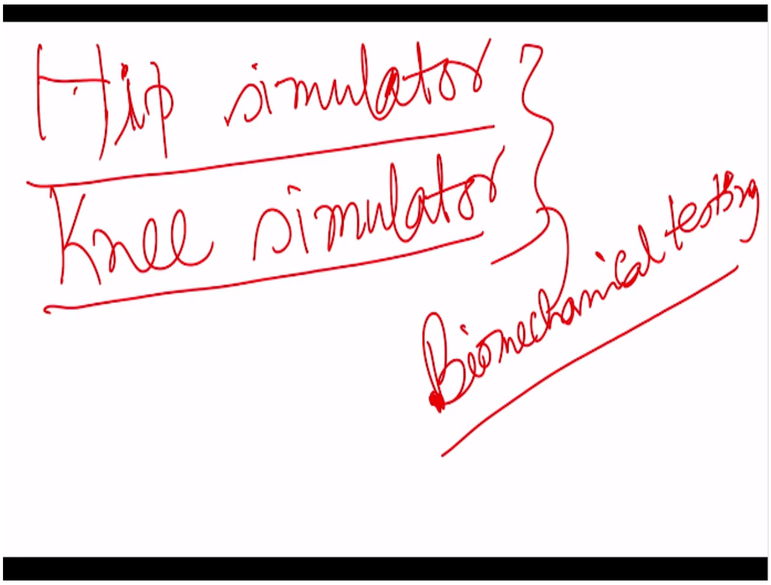

So they are called biotribometers but more importantly one is called hip simulator, so hip simulator essentially they will not only simulate the biomechanical stresses but they will also simulate the gait cycle and knee simulator. So this hip simulator and knee simulator these are the most important tribolo-biomechanical testing, so this we call biomechanical testing where long-term fatigue wear properties can be evaluated for implant materials.

And this is used as a preclinical studies, so what people do and what is recommended that you put your femoral head. Suppose new femoral head you have manufactured, so that one you can test against clinically used acetabular socket. So after the test is over let us say 1 million cycles and so on under the walking cycle for example walking phase of the gait cycle, then you can collect the debris particles.

And you can use all the toxicity study for this debris. Same thing one can do for the knee simulator study, so after the knee simulator experiments is over, one can also do the similar toxicity study for the implant materials. So I think I will stop now. Thank you.