Biomechanics
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Lecture - 66
Tendon Forces and Factors Affecting Tendon Property

Welcome to this video on biomechanics. We have been looking at the mechanics of soft tissues. In the previous videos we looked at soft tissues like cartilage ligaments, in the last video we looked at tendons specifically we looked at the relationship between stress and strain in tendons. We discussed about some models of non-linear elasticity in a tendon.

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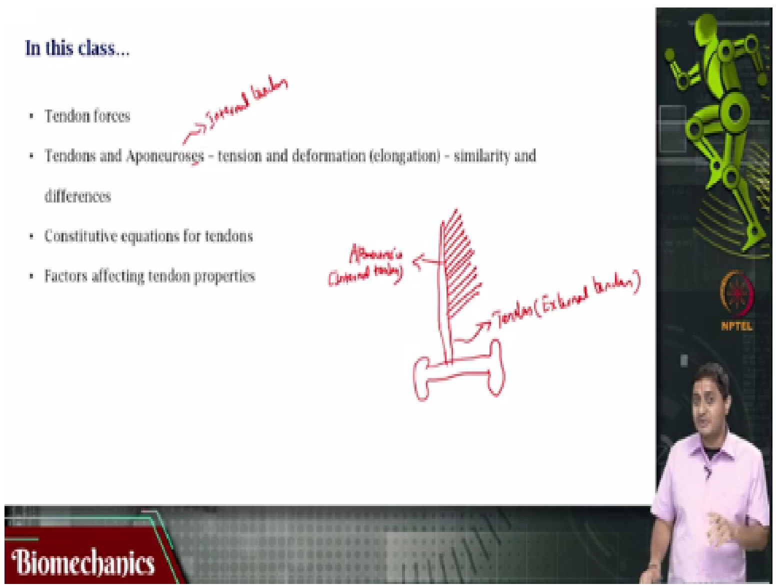

In this video we will look at forces that are exerted by a tendon, forces found in a tendon, differences and similarity between tendons and aponeurosis, what should be some constitutive equations that we can use for tendons and what are the factors that affect properties of tendons. Remember what is aponeurosis? Aponeurosis is the internal tendon. Let us suppose that you have a pinnate muscle where the muscle fibres attach to the tendon at some angle.

Then this part of the tendon that is connecting to the fibres muscle fibres is called as internal tendon are aponeurosis then it continues on to attach to the bone. This part of the tendon where the tendon attaches to the bone is called as tendon; simply called as tendon or external tendon.

That part of the tendon that attaches to the muscle fibres and then on the other end attaches to the external tendon is called aponeurosis.

Aponeurosis in singular aponeurosis with e in plural or otherwise called as internal tendon. Crucially as the internal tendon or the aponeurosis proceeds closer to the external tendon its breadth increases or its ability to resist forces increases and that makes sense. Because it is able to carry or transmit more and more force as you go down from the top to the bottom in this picture that makes sense.

So, that such an efficient arrangement. You want to have only as much tissue to support the force but not more, a very efficient arrangement. So, we will discuss about the similarity or dissimilarity between an aponeurosis and tendons in the tension and deformation or elongation.

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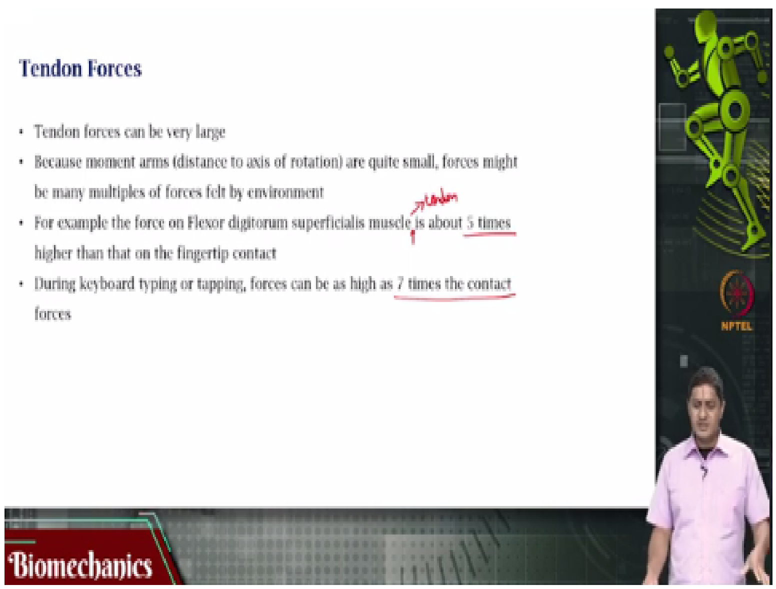

So, what about forces that are filled by the; tendons or forces that are present are found in the tendons. It turns out the tendon forces can be huge; tendon forces can be really very large and because they are usually almost always, they are present close to the axis of rotation. You see because the motors are the muscles they are away, tendons are those that attach to the bones no and bones are where the rotation happens is it and usually, they are very close to the axis of rotation.

So, because the moment arms are actually very small because of this reason force that is felt by the environment is the force that is applied by the bone on the environment. So, force that is felt by the environment will be much smaller than the force that is felt by the tendon. Or in other words the forces in the tendon can be many multiples many times the force that is felt by the environment itself.

For example, the force on flexor digitorum superficialis, a muscle in the finger it is about five times or flexor digitorum superficialis muscle tendon specifically measured at the tendon the force that is felt by the flux digitorum superficialis muscles tendon is about five times higher than the contact that the finger is making. So, fingertip force if I am measuring if it is 10 Newton's the tendon force is about 50 Newton's huge.

And during keyboard typing or tapping you may think that I am just performing feather touch keyboard. But the forces in the tendons can be as high as seven times the contact force. So, tendon forces can be really huge and not intuitive, you cannot intuitively guess this is going to be just you know just as much as the force. You might be touching soft but the force at the tendon might still be very large.

Something that is not easily understandable it is not intuitive also because this is complicated. Because of the momentum situation because what is felt in the environment is what is applied by the bone. But what is felt in the tendon is what is felt in the tendon. So, in other words because of this momentum situation depending on the attachment of momentums also vary. There are many complications, depending on the configuration the momentums vary there are many complications that we are not discussing here.

We are over simplifying the situation. But in general, the momentums are small. So, forces are usually many times the environmental forces.

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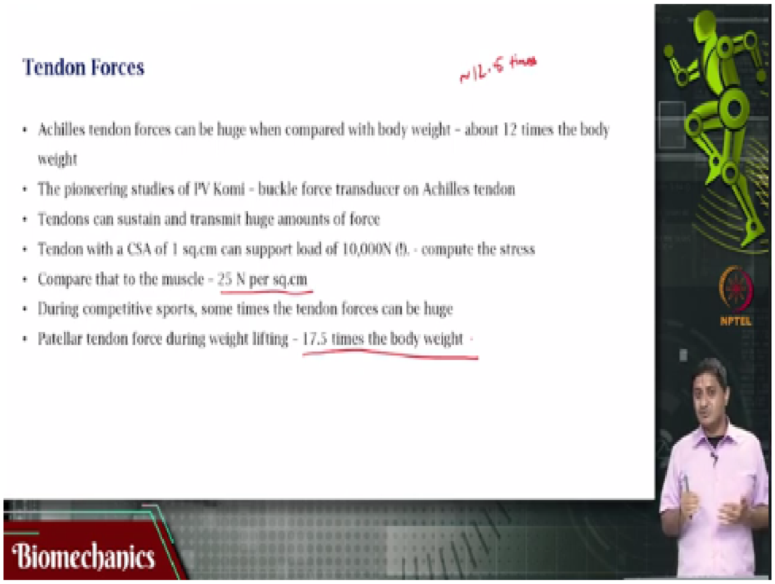

For example, Achilles tendon forces can be huge when compared with the body weight about 12 times the body weight of sometimes depending on the specific activity that is performed. This kind of study is where pioneered by a researcher named PV Komi who used a buckle force transducer that he surgically implanted in Achilles. And important to note these kinds of experiments are not easy to perform because the ethical approval for these kinds of experiments are extraordinarily difficult to get.

You will almost always never get this kind of approvals, ethical, approval for these kinds of experiments. Why? Because it is extremely difficult for anyone to convince the benefits that you will get from this kind of study is going to outweigh the risk from the invasive nature of these studies. Because you have to actually perform under local anaesthesia you have to insert a force transducer into the tendon and then implant this force transducer on inside the tendon.

And then perform some action by the way when the transducer is still inside you have to perform some action and then make the measurement it is not exactly a trivial experiment. So, in good tradition of science PV Komi actually implanted Achilles tendon with this buckle force transducer and perform some activities and he found that the forces in the Achilles tendon is about 12.5 times the body weight depending on the about 12 and a half times the body weight.

So, from this what we learned is the tendons can sustain and transmit a huge amount of force. Tendons have this ability to resist sustain and transmitter very large amount of force. For example, a tendon with a cross sectional area of about one square centimetre can support a load of 10 kilo Newton that is a lot compute the stress. What is the stress? Force by unit area, compute that and find out the stress.

You will realize that the stress is huge, one square centimetre can support a load of 10 kilo Newton a very large load. Suppose discussing this case of PV Komi 12 and half times the body weight. Let us assume his body weight was about 800 Newton's little more than 80 kg so 12.5 times that is about you know 1000 Newton's. So, you are and he is jumping or performing some explosive force action the force might even increase more but that is not what we are discussing.

The load on the Achilles tendon which might have a slightly smaller area than one square centimetre. The stress on that will be huge. Compared with the muscle, a muscle stress usually is about 25 Newton per square centimetre of physiological cross sectional area. So, the stresses that are felt under overcome by tendencies huge very high when compared even with the muscles. Muscles are big, this is of course because muscles are big but not just that muscles are active force producers or force generators.

They are huge but even in muscles we are only computing per square centimetre resistance to force that is only 25 Newton in the case of a muscle. In tendon it is much higher that 1 centimetre can support 10000 Newton's that is a lot. Sometimes in competitive sports the amount of tendon forces can be huge extremely large. For example, during Olympic weightlifting the load that will be felt in the petal or tendon will be huge.

You are discussing about lifting hundreds of kilograms of weight, is it not? So, in one particular case there is a study in which they observed a rupture. As it was happening the experiment was being performed or as they were performing an experimental rupture happened. And they found during weight lifting when the patellar tendon ruptured it was supporting about 17.5 times the body weight of course at this point rupture already happened.

So, perhaps somewhere below this level is where the microscopic failure started and somewhere below this level is where it was able to support the load without getting ruptured. So, you are talking about again you know that number is not really unrealistic because there are cases where this has been able to support without getting ruptured. So, tendon forces can be huge and the stress in tendons can be huge very high.

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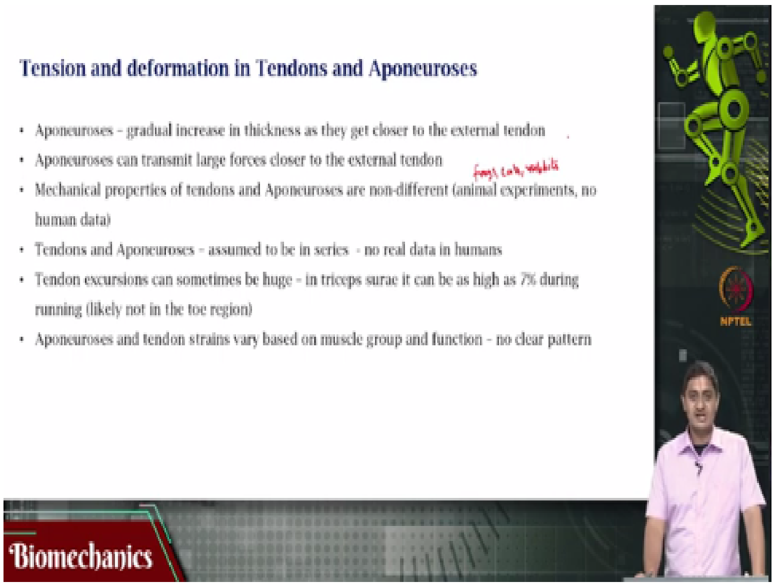

So, when we discussed aponeurosis, we saw that there is a gradual increase in thickness as the aponeurosis proceeded from the tip to the external tendon. As it got closer to the external tendon the thickness of the aponeurosis increased because it will have to support a larger force and I said that is a very efficient arrangement. Remember biological systems are almost always efficient. Of course, engineers might challenge this idea but they are efficient in their own way.

One has to really study the whole the big picture the global biological phenomenon to understand how biological systems are efficient. In this case of course it is very efficient because of this reason as they proceed from the tip to the external tendon, they become larger the breadth increases, the thickness increases. Because of this reason aponeurosis are capable of transmitting huge forces to the external tendon.

People have attempted to study if there are any differences between tendons and aponeurosis and turns out those mechanical properties of tendons and aponeurosis are not different from each other. Of course, these studies were performed on frogs, cats, rabbit's small animal experiments. Of course, these kinds of experiments are nearly impossible or impossible to perform in humans. So, no human data is available but you can generalize this from animal experiments.

Perhaps this is also true in humans likely true in humans also that the mechanical properties of tendons and aponeurosis are not different. In some experiments it has been shown that well you would assume that because the aponeurosis continues on to become the external tendon that these two are in series but it is not clear whether these two are indeed in series. But people have performed some experiments where they tested if the tendons and aponeurosis behave as if they are in series.

And based on that you know there is some evidence to suggest the idea that they are indeed in series they behave as if they are in series. Of course, this is not human experiments, these are animal experiments. But you can try to see if you can generalize this. Usually these are generalizable. Something to keep in mind is that tendon excursions or tendon elongations can sometimes be huge.

For example, in triceps surau muscle it can be as high as 7 percent during running. Of course, it varies between the functions that are being performed it whereas depending on whether you are walking or whether you are running. So, tendon excursions are elongations is a function of the activity that you are performing. Tendon excursions can also be huge and very large. Also, one more thing is that the properties of tendons, aponeurosis and tendons.

And their strains vary based on which muscle group and the function performed by that muscle group is it a finger muscle, is it a leg muscle, is it a back muscle, is it a breathing muscle, different muscles, tendons of different muscles perform different functions. Based on that the properties the strains that they can take also varies. We already saw this example. For example, in the source tendon there is a possibility for it to take as much as 10 percent deformation 10 percent strain.

So, these properties vary based on the particular function that it is performing. So, which muscle group and what is the function performed by that muscle group dictates the properties of aponeurosis and tendons.

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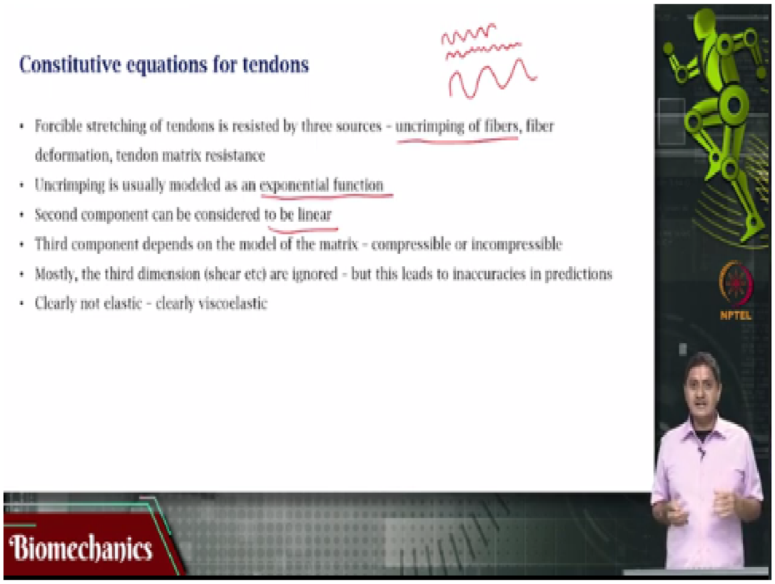

One question is how is the tendon even resisting the forces. This resistance is developed is coming because of three different sources one is uncramping of collagen fibres. Remember we mentioned collagen is having this characteristic wave is crimp patterns. Of course, we already mentioned that there are different levels at which crimp can be present. For example, these different levels at which it can be there but the point is that as there is a resistance.

This resistance is because of uncrimping of fibres and then fibres themselves deform and tendons are not composed only of collagen. But they are located in a matrix of tendinous material. So, there are other things other than collagen that form the tender matrix. This tendon matrix also has mechanical properties. So, there is resistance offered by the tendon matrix or matrix of tendinous materials. In this the first source is the uncrimping of fibres.

This is usually modelled as an exponential function. So, uncrimping is an exponential function can be accurately relatively accurately captured using an exponential function. The second component which is fibre deformation may be assumed to be linear can be considered. We can for most cases can be considered to be linear. The third component actually depends on the model of the matrix and the components of the matrix itself is that it composed or compressible or incompressible material or is it.

So, how do you model that will define whether the third source or the tendon matrix resistance is linear or not linear depending on that. Also, when you are interested in measuring all this the third dimension are transmission in the lateral direction, shear etcetera ignored but then again that would lead to inaccuracies in predictions of your model. One thing is clear that tendons are not elastic and they are clearly viscoelastic.

Why? You are having this exponential function and a somewhat linear function. So, you are going to have a viscoelastic behaviour. So, tendons are viscoelastic materials as with many other biological materials. Tendons are also viscoelastic materials but here we try and delineate the sources of this viscoelasticity or delineate the sources of this non-linear elasticity.

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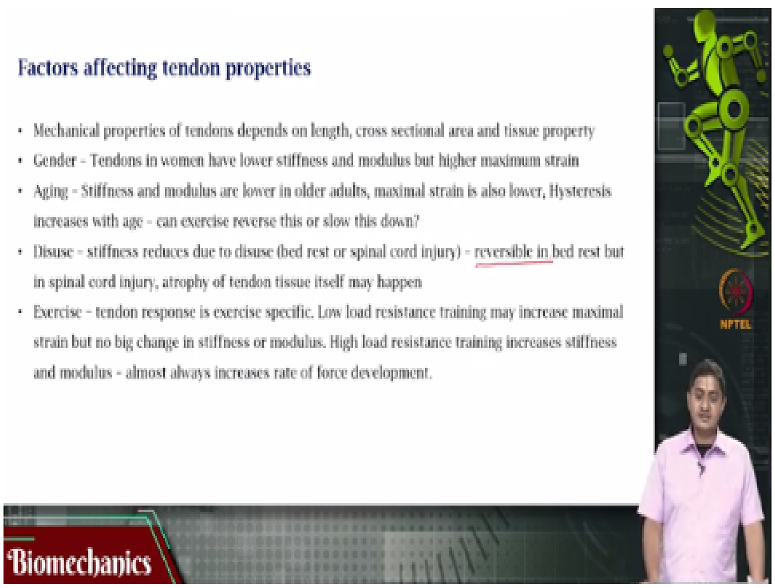

A question is what are the factors that affect mechanical properties of tendons. Mechanical properties depend on many things. For example, it depends on the length of the tendon slack length or elongated length or how much strain it can take different lengths. Then the cross-sectional area of the tendon also affects the properties. And the property of the underlying biological tissue itself the health and the property of the underlying biological tissue also affects the mechanical property of the tendon.

Some factors that are usually discussed in these kinds of discussions are gender, aging, disuse, exercise. Let us see what happens with gender. Women generally have lower stiffness or tendons in women are they tend to have lower stiffness and lower modulus. But the strain the maximal strain is higher in women when compared with men then what about aging, how does aging affect tendon behaviour.

As you would expect as people get older the stiffness and modulus reduces. As people get older stiffness reduces, modulus reduces but the maximal strain also reduces. In women stiffness and modulus reduces but maximal strain increases in women when compared with men. But when compared with young people older people have lower modulus and lower stiffness but, in this case, this lower modulation lower stiffness is accompanied by a lower maximal strain that is found.

Also, older adults have or show a higher hysteresis with age and that makes sense. So, you are going to be a little less efficient as your age because hysteresis if there is more hysteresis that means that you are not very efficient and you are losing more work. The work that can be recovered is lower as yesterday's increases so that makes sense. A question is can exercise reverse this or slow this down.

The answer is yes, it turns out that people who exercise regularly show a lower amount of reduction with age. They also even in those cases stiffness and modulus reduces even in exercise older adults who do exercise. Even in those people the stiffness and modulus are lower when compared with younger adults but they are not as low as that found in the group that does not exercise. What is the message?

The message is that this deterioration in stiffness, modulus and maximal strain can be partly offset by exercise, not fully offset but exercise asset benefits. So, exercise may not be able to reverse this completely but we can definitely slow this down and reverse this partially that is possible. Then the other one is disuse. What happens when a person is bedridden, when a person is asked to be in bed rest for a long time.

In this case stiffness and modulus reduces but as the person recovers from bed rest and starts using the tendons more starts using the body move starts making movements there is a improvement in the properties of tendons that is seen. So, that means this is reversible in people recovering from bed rest but in some people are those who have spinal cord injury movements are completely depending on where the injury is movements may be completely rested.

In these people this is a chronic condition continues forever in almost all these cases. So, in these cases there is reduction in size of the tendon tissue itself or atrophy of tendon tissue happens. Actually, there is muscle atrophy that happens but tendon atrophy also happens. This happens in spinal cord injury patients but not in patients who have taken bed rest. So, for this tendon atrophy to happen, the amount of distributes must be much larger than the regular bed rest or bedridden cases that we see.

So, the disuse related atrophy is more prevalent in people with spinal cord injuries. Then exercise, in general exercise is good for tendon health that is known we just discussed that how exercise can help reduce the amount of you know deterioration of tendon function tendon health in with aging we just discussed that. So, in general exercise is good for tendon health but then it turns out that it is exercise specific.

So, which exercise you are performing and what intensity you are performing appears to matter. That is if you are stretching simply stretching it is having some effect. If you are performing resistance exercises or strength training, weight training type of resistance exercises at lower loads this increases maximum strain. But it does not change stiffness or modulus. At high loads as the load increases are when you perform high load resistance training.

For example, 70 percent maximum something like that or 80, 90 percent maximum you do something like that or high load resistance training stiffness and modulus increases. It turns out that in those cases where you increase stiffness through exercise or through high resistance exercise almost always the rate of force development also increases. What this means is that you are able to produce an explosive amount of force or a large amount of force in a relatively small amount of time that makes sense.

Those who are doing this high resistance exercises are those who are building muscles those who are aiming to produce this explosive forces under in almost all these cases there is an increase in the rate of force development. So, if the interest is to produce high rate of force development or an explosive force for high force in a very small amount of time then high load resistance exercises are the way to go.

Low resistance is good it increases maximal strength but it does not have any big change on the modulus itself, stretching has relatively minor or minimal effects. So, what we learned from this is exercise helps but not all exercises are the same. So, the response is specific to the exercise performed. So, from this slide what we learned is that you know gender has an effect, aging has an effect, the effect on aging can be reversed with the exercise.

Or can be at least partly offset by exercise, diffuse has an effect, bed rest when you are recovering from bed rest when someone is recurring from bitters it is advisable that they slowly increase the amount of or gradually increase the amount of activity. It is not like you know when someone recovers from bed rest, they can directly go to the gym next day must avoid that of course. It is reversible in bed rest or the changes in tendon properties are reversible from in people who are recovering from bed rest.

But in people with spinal cord injury there is an atrophy or reduction in size of tendon itself that happens. And the response of the tendon to exercise is specific to the exercise being performed and the intensity of the exercise are the amount of load that the exercise involves.

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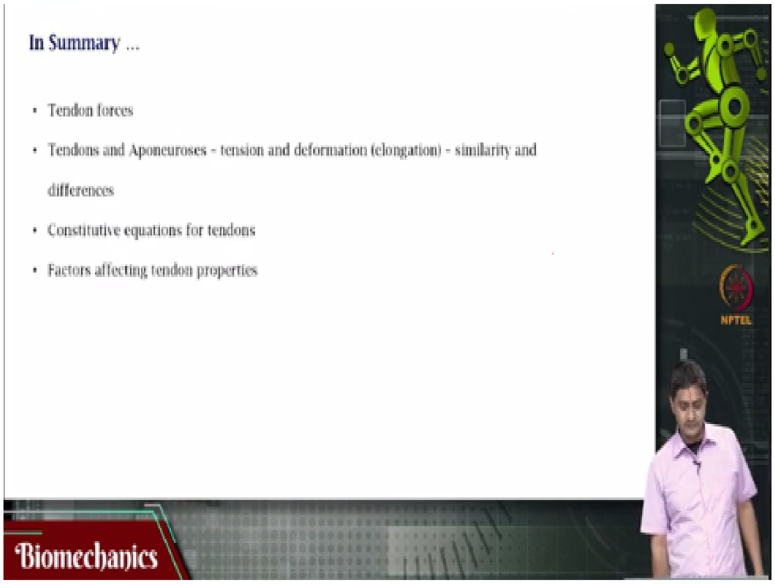

So, in this video it is a relatively long video what we saw was forces in tendons and we found that the tendon forces can be huge, sometimes as high as 12 and half times the body weight huge force and the stresses can be you know very high that one is square centimetre of tendon can support 10000 Newtons and the differences and similarity, mostly similarity between tendons and aponeurosis in terms of the tension and deformation.

And what should be some constitutive equations that we use for tendons and what are the factors that affect properties mechanical properties of tendons. We looked at aging, we looked at issues, we looked at gender and we looked at exercise. So, with this we come to the end of this video, thank you very much for your attention.