Mechanics of Human Movement

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Lecture – 34

Inverse Dynamics Analysis

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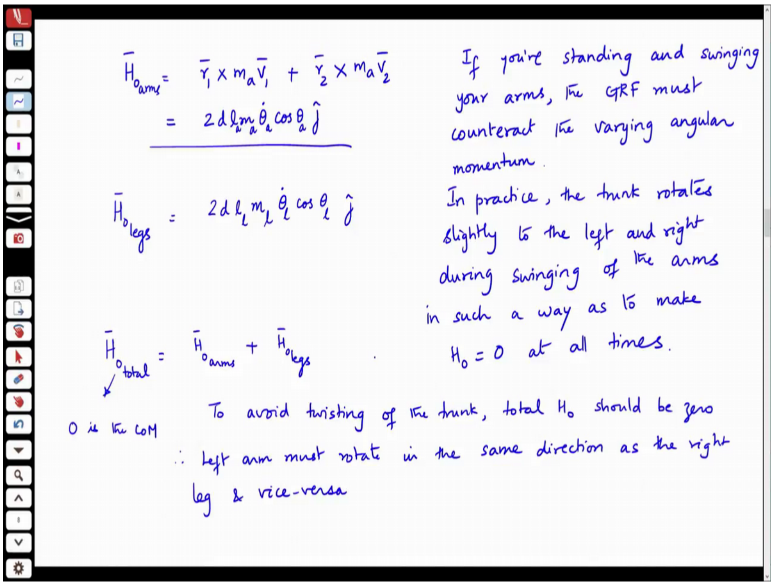

So, we were looking at the swinging of the arms and how if you look at the swinging of the arms and the legs and you look at the total angular momentum of that, about the center of mass here o is the center of mass in this case, total equals this plus that of the legs. So, for it to cancel out ok, they have to be in opposite directions. So, that to the swinging has to happen in to avoid, twisting of the trunk. Total H 0 should be 0, which implies that the contributions of the arms and the legs have to cancel.

Therefore, left arm must rotate in the same direction as the right leg, right leg and vice versa, to cancel the contributions to be able to cancel the contributions and then, also because the legs, made a mistake here. This should be mass of the leg also because; the legs have a higher mass and are longer. So, if ll is greater than la and ml is greater than ma therefore, theta dot a should be greater than theta dot l it has to rotate faster.

The arms in order to be able to cancel and because they have to have the same time period ok, because they have to be coordinated right, when you reach the maximum amplitude for the leg that should correspond to the maximum amplitude of the arms therefore, theta a is now larger than theta l. So, that is why your arms swing more than your legs and they also need to the theta dot is also larger ok.

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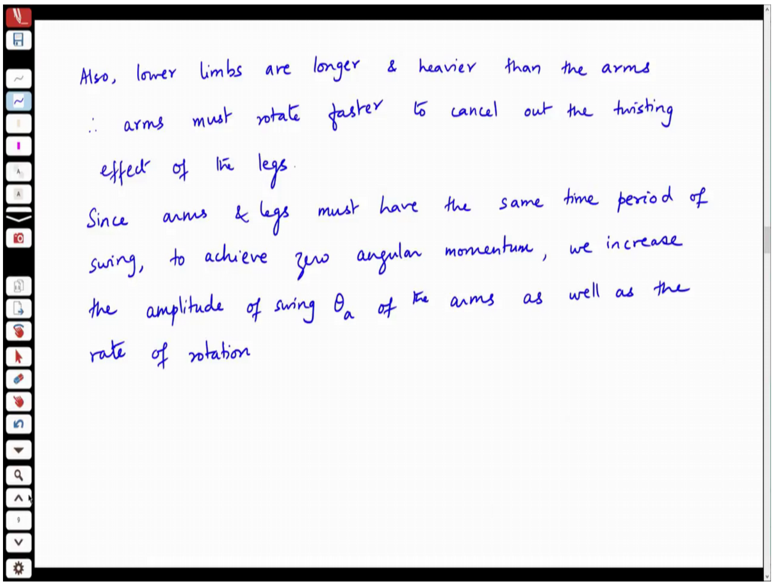

In order to cancel out this total angular momentum, also lower limbs therefore, arms must rotate faster. Since the arms and legs must have the same time period of swing to achieve the 0 angular momentum. We increase the amplitude of swing of the arm. So, theta a as well as the rate of rotation.

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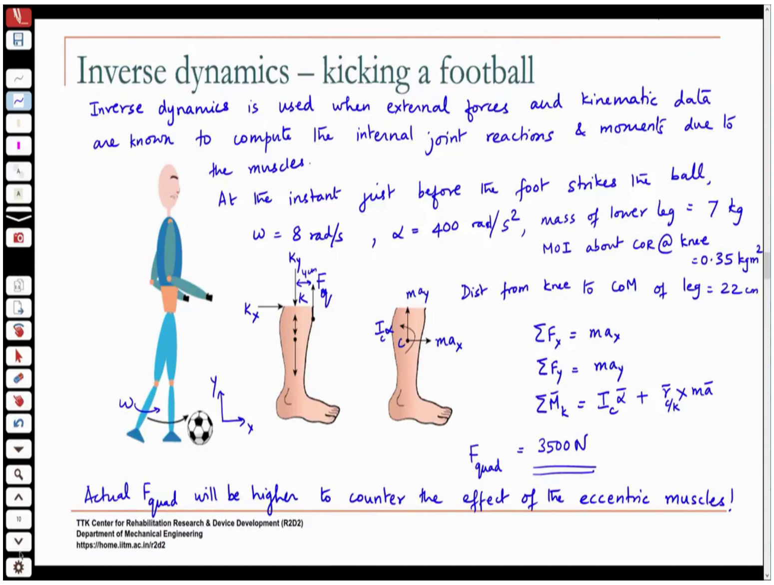

Now let us look at. So, we have looked at some of the dynamic analysis of whole body motions, now we look at what is known in bio in biomechanics especially as the inverse dynamics procedure.

It is there even in robotics, you would see inverse dynamics appear often in any multi body dynamics ah, but in inverse dynamics in the case of biomechanics is basically, to determine the forces and moments that you cannot measure directly right.

So, you want to find out in this multi segmented system knowing some of the external forces and the body segment parameters to be able to determine the internal forces in the system, which is what we have now, we are doing it for a dynamic situation, we did that for the static situation. And in the general inverse dynamics, we do not really use as I mentioned earlier we look at joint moments rather than forces in individual muscles ok. We look at the knee joint, what is going to be the net moment that would have to be applied for a certain situation.

So, inverse dynamics is used, when you know kinematic data are known to compute the internal joint reactions and moments; moments which are primarily due to the muscles. So, take this case of kicking a football. So let us say at the instant, just before striking the ball. You have omega equal to say 8 radians per second, this direction and alpha 400 radians per second square you have the mass of the lower and moment of inertia about the knee the center of rotation at the knee is given as 0.35 kg meter square.

The perpendicular distance from say, this is the center of rotation, this is not a um. So, assume the knee is here we are looking at the knee joint reactions Kx and Ky, this is the force from what? The muscle, which is the in this case, it would be the quadriceps in the patellar tendon, the force that is exerted by the quadriceps muscle and you have the distance from the knee to the center of mass of the leg is 22 centimeters and this moment arm here is 4 centimeters ok.

So you want to find out, what is the force in the quadriceps muscle and the knee reactions, just before the foot kicks the ball ok. This in this case omega and alpha we have done cases, where earlier in the static situations we have looked at this here, it always helps to draw the kinetic diagram. So, I have if this is my xy coordinate system, I have max and may acting at the center of mass and I have, I alpha I would be about this center of mass the this is about c.

What you are actually given is I about K ok. So, you have to be careful here, you have given the moment of inertia about the knee joint ok. So, anyway you can do the you know it is straightforward, I will let you do the calculations sigma Fx equal to max sigma Fy equal to m a y and sigma M Mc. If you take it will be this thing or if you take Mk, it will be you can do Ic alpha plus r cross m ax r ma x into that distance.

So, let us just put this in the, to make sure you get the right, r would be distance of c from max, but why is we are assuming? It passes through the knee joint. So, it does not contribute to the moment, but yeah you can use to be more precise. you can just use the full vector. So, when you solve these equations. You get the F and the quadriceps muscle to be about 3500 Newton’s ok. In actuality, do you think the force in the quadriceps would be more or less than this value? In all these cases, we have used a single muscle right to find the contribution to the moment.

Do you think this value is under predicted or over predicted? Think about how muscles act? Muscles act in typically in pairs like about a joint. So, when you have the quadriceps exerting a force, you also have the hamstrings exerting a force ok, the hamstrings may be lengthening as they are exerting a force, but their force that is exerted by the hamstrings. So this, the actual; so, that is causing a say a clockwise moment, this is causing a counterclockwise moment.

So, for the net moment to be counter clockwise this actually has to be higher than what is predicted by this analysis. So, if you have a net joint moment counterclockwise. So, we always talk about the net joint moment, which means there is a clockwise moment and a counterclockwise moment, the net moment is counterclockwise, which implies that the muscle causing that net counterclockwise moment actually, has to exert a higher force than, what is predicted by this analysis ok.

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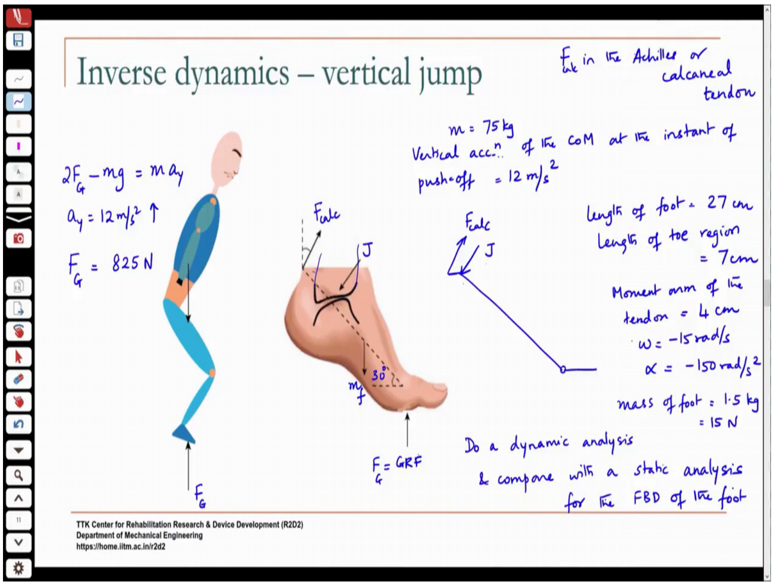

So, actual F quad is going to be higher, because of the action of the antagonist muscles. So, that is something you should remember another example. In the case of a vertical jump, you want to look at whatis going to be the force exerted by the, what tendon is this or what muscles would be acting here. This would be your calf muscles right and this would be your Achilles tendon or Calcaneal tendon.

So, F in the Calcaneal or Achilles tendon, the Calcaneus is your heel bone, which is where that tendon inserts. So at the instant of vertical jumping, what would be the tension in that tendon? So, you have the joint reaction here ok, J acting you have the mass of the foot, if you look at the free body diagram of the foot then, you have the ground reaction force and let us say the mass of the person is 75 kg's and the vertical acceleration at the instant of push off is 12 meter per second square.

This angle here is 30 degrees the sole of the foot makes that angle. So, you can have a free body diagram like this, this is the and the length of the foot is say 27 centimeters length of the toe region, 7 momentum of the Achilles tendon, 4 centimeters and we know that omega equal to minus 15 radians per second, alpha equal to minus 150 radians per second square.

So the first thing you do is from the, you are given the acceleration of the center of mass ok. In this case, you are given some of the kinematics, but you do not know the ground reaction force ok. So, to determine the ground reaction force ok, you have to use this information. You are given the vertical acceleration of the whole body center of mass. So, you say if this is FG the ground reaction force, then 2 FG. So, if I am looking at each foot right 2 FG minus mg in the vertical direction gives me ma in the vertical direction, a y is given as 12 meter per second square.

If you look at this structure of the foot here ok; this is the joint the Calcaneal tendon is acting at the on the heel bone right. So the joint reaction, I am assuming at somewhere in the, this is the joint. So, these are the 2 the ankle joint is here ok. The Calcaneal tendon is acting slightly away from that, it is not passing through that joint ok, this is not a very accurate anatomical representation, but you get basically to give you the idea that that joint reaction force arises from the contact.

Student: (Refer Time: 19:44) go along the same horizontal (Refer Time: 19:46).

So, here yeah the, I would know from the anatomy from the anthropometric data. Those relative dimensions here it is a simplification; I am saying this is what it is I am just giving you the momentum of the tendon about the joint anyway. So, if you have this, then you get FG equal to 825 Newton's on each foot, which is what I would then use here in the free body diagram of the foot. So I look at the whole body, find the ground reaction force then, use that in the free body diagram of the foot to compute my unknowns, which would be F calc and the 2 components of J ok.

So here, the mass of the foot is 1.5 kg, which is 15 Newton's and in this particular case, you could perhaps you can actually compare there were dynamic analysis and a static analysis ok. So, dynamic analysis meaning, you think you take the acceleration of the center of mass of the foot to be 0, you say that there is no harm.

Student: For static.

For static, for static sorry for a yeah for a dynamic analysis, you take the omega and alpha. So, you draw the kinetic diagram, but you can do and compare with the static analysis, you may find that in this case, because the ground reaction forces are much higher, it may not be there may not be a significant change between the 2 types of analysis, but I will you leave you to do that as homework.

Student: In the static case, we will have to imply that (Refer Time: 22:09) the vertical (Refer Time: 22:10).

No, no, no, no. So you do not neglect. So, you do for this part of the analysis alone. See if this was a static analysis then this FG would only it is like a standing on tiptoe ok, the FG would just be half the body weight here, it is 7.

Student: 50.

50 right. 750 divided by 2, which is only 375 that is not the case. So, you cannot neglect it for this part. So, you find the actual ground reaction force and then for this part alone because, the mass of the foot itself is so small, in comparison to the ground reaction force, you could do a static analysis for the foot. This is for the second portion alone for the using for the free of FBD of the foot; this part you have to do it is a significant contribution. So, you are just simplifying a one part of the analysis ok.

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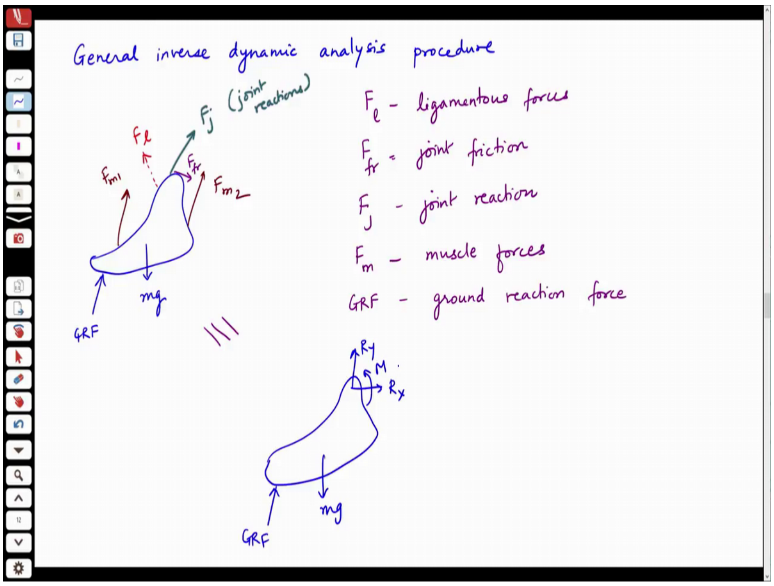

So, the general procedure for an inverse dynamic analysis is this you start from say, the most distal segment the foot, you may actually have multiple. So, you may have the ground reaction force acting on the foot, you have say, the weight of the foot you may have multiple muscles, you may have ligaments acting at various. So, you may have forces due to ligaments, you may have you have the joint reactions. Let us call that Fj and then you may also have frictional forces at the joint interfaces.

So, there are a whole bunch of forces that could be acting on this body, is the joint friction, Fj is the joint reaction force and Fm are the muscle forces. GRF is the ground reaction forces. Now this, you say is equivalent to you have the weight external force, you have the ground reaction force and then the net effect of all the other forces, you say R Rx, Ry and some moment the combination of all these forces.

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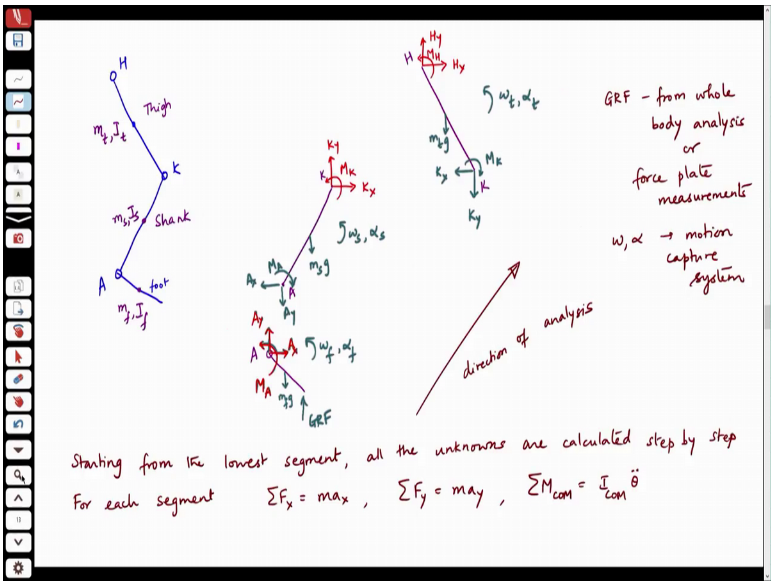

So, in your inverse dynamics, you reduce all those unknowns basically to these 3 unknowns in a planar case, you have 2 components of the joint reaction and a net moment at that joint and then because the, if you look at the body. It is a multi-segmented body. So, this is for an individual's body then you sort of propagate this method upwards and you say ok. So, I have if I have say, hip, knee, ankle to take the example of a lower limb ok, this is my foot each one of these. So, this is my thigh, I have the center of mass of the thigh here and I have some mass, some moment of inertia body segment parameters that I have from anthropometric data.

Similarly for the shank so, this is the thigh, this is the shank and this is the foot here, I have some mass of the shank, some moment of inertia about it is center of mass. Similarly for the foot mf comma If. So, what I would do? Is I start from here and I say if this is my point A I say this is A acted on by some GRF this may have some omega A alpha A actually, I should call that omega f alpha f, because the angular velocity and acceleration are for the rigid body in this case the foot.

Then at the ankle I have Ax Ay as the reactions and an MA, the net joint moment. So, I take this rigid body the foot, I apply the equations and I have Ax Ay and A can solve for.

Student: (Refer Time: 29:35) for mg.

Mg m f g. I apply the equations to that then, I look at my next, I move up the chain and I have my shank. So, this is my A this is my K ankle and so for this one. So, let me represent the unknowns here in red ok. So, these are the unknowns, I solve for Ax Ay and MA, once I do it for this now Ax Ay and MA are known ok. So, I go to this one, now I have Ax opposite to what I had on the ankle Newton’s third law.

So, then i have Ay and MA is now in this direction, these are now known then I have ms g I may have some omega s alpha s for the shank, the kinematics known kinematics then at the knee my unknowns become Kx, Ky and MK. So, I use this free body diagram with the known kinematics to solve for Kx, Ky and MK do the move higher up and then I have the thigh. So, if I look at the thigh, this is my knee, this is my hip from the previous analysis I now know.

Student: Kx.

Kx, Ky and sorry MK should be MK mass mtg and the thigh has some omega thigh, alpha thigh and this gives rise to reactions unknown reactions at the hip, which are Hx Hy and MH ok. So, this is the procedure you follow. So, you go from you go in this direction solving for the unknown joint reactions and joint moments along the segments of the body. So, you can do this um. So, this is the general inverse dynamics procedure, you so far we have sort of focused on just one that we looked at.

But, the inverse dynamics procedure and biomechanics kind of goes through this multi segmented. So, you have a model for the body, you decide how many segments you are going to have, you know the level of complexity. So, for the foot you know you could have a toe region and a foot. So, then you would start off at the toe region, find the joint reactions and moments at that joint at the Metatarso Phalangeal joint and then go to the ankle and then go to the knee, to the hip and so on ok.

So, this is the direction of the analysis. So, starting from the lowest segment, all the unknowns are calculated step by step and for each segment you apply a sigma Fx equal to max sigma Fy equal to may and sigma M about the center of mass equal to ICOM theta double dot of that particular segment, typically you would calculate the GRF, like we did in the previous case from the whole body. So, we knew the acceleration of the center of mass in that particular, you knew how much the person was jumping. So, you estimated the acceleration of the center of mass and computed the GRF.

In the lab there are usually ways to measure the GRF using 4 splits. So, you do not you would just measure the GRF directly and then you would measure the kinematics of all these segments, you would know the inertial parameters the body segment parameters from the data. So, the kinematics would give you omega F alpha F omega S alpha S, all that and then you would have the GRF from the. So, GRF from a whole body analysis or force plate, force plate measurements then omegas alphas from some motion capture system.

And then you would look at the, you would measure the internal joint reactions and ah. So, this is the form of a inverse dynamics analysis, where you know you calculate not individual contributions, but the net moment because, this is a statically determinate system you do not you have as many unknowns as you have equations. So, you can do this. If you go to most, more complex models like if you include multiple like you know we saw that, this is the result of many contributions ok.

So, there are models, there is a very active field called musculoskeletal modeling, where they actually have models for each type of these forces. So, the muscle forces you remember we had the hills muscle model that we looked at. So, they would have a contractor, they would have properties that have been determined from say, cadaver studies and based on that they would have created a mechanical model for a muscle and they would say that is the model. So, you also take into account the viscoelastic nature of the muscle and all that to estimate those forces and you would have multiple muscles and it may not be a simple algorithm like, you know saying constant stress in the muscle, meaning the force is proportional to cross sectional area. It may be something more, it may be based on say some weightage based on EMG data that, they have gathered in the lab, it could be based on like an overall optimization.

So, energy consumption is a very typical quantity objective function, because as humans we tend to, we try to do most of our activities using minimal energy. So, they would look at various the contributions, they would try to estimate the contributions from the various muscles based on these other parameters using some kind of minimization of some object of a function. So obviously, those are computationally very intensive, you have lots of variables lots of and there is no direct way of validating those models. I know unless you actually go in an instrument, you know you cut somebody up put in sensors that will measure the forces in each of their muscles and ligaments and all that.

So, these are, but you try to look at validation on a, you look at experimental data. So EMG for instance, is one way if you know that ok, these are the muscles that are acting then you look at your model. So, you have different methods of validation of this, but there is no direct validation, to say that this is exactly what this muscle force is going to be. In many cases, this kind of a general this kind of an inverse dynamic analysis procedure is still pretty useful to give you a good idea of what is happening inside the body.

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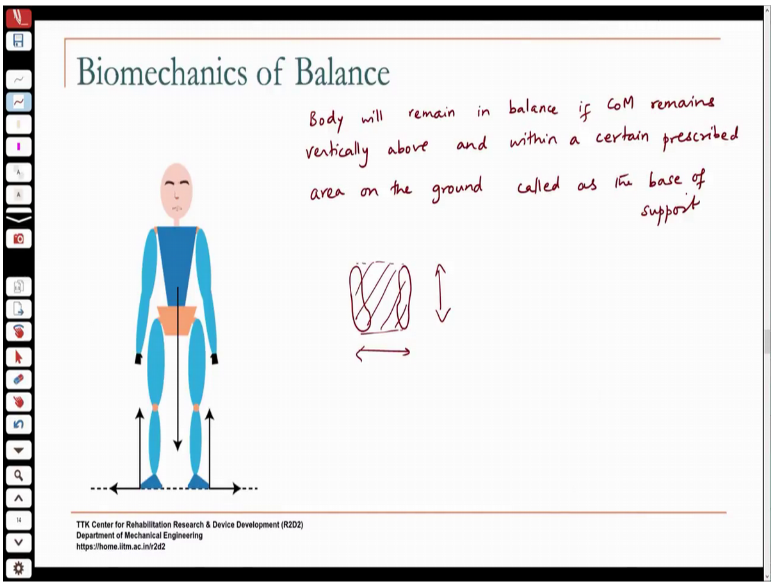

So, the next few classes, we will again be looking at the biomechanics involved in certain whole body movements similar to. So, balance is something again very key to how we operate as to operate effectively because, as bipeds you know we are looking at if you look at our feet. So, this is the area of our base of support ok. So, when you are standing as long as the line from the center of mass of your body, the center of gravity falls within this area ok, you are stable, you are not going to fall over.

When it crosses this then, you become unstable and so your muscle so even, when you are standing because you are a multi jointed, multi segmented structure, your muscles are always working that is why even standing tires, you see technically if standing did not take any effort, then you should be able to stand forever, but standing also tires you because, the there are the slight changes that are being made you know to maintain your balance. So, your muscles are always acting about all these different joints, in order to help maintain your balance and that is why so you have, when you are standing this depending on.

So, if you see as you get older, you may tend to have like a wider stance because, you are trying to increase the base of support or you have to hold on to you know you add a walker or something. So that now, that base becomes much larger because when you start having balance problems, that is when you start going in for assistive devices like that even your walking pattern, you may change you will see that people walk with a wider stance, when they are unsure of that.

Whereas, if you look at walking on a tightrope for instance, you know highly skilled gymnast or when they are on that ah, what is that called the pommel horse that bar you know they have. So, they put one foot in front of the other, they are balancing on a very narrow base of support in the medial lateral direction. So, they will have um. So, this is your support area and your objective is to maintain, make sure your cg falls in that support area to maintain balance.

So, the body will remain in balance, if the center of mass remains vertically above and within a certain prescribed area on the ground called as the base of support. Now standing on your legs is challenging enough ok, you have seen some acrobats, do a gymnast do a handstand right, see one thing your leg muscles like your um the gastroc muscles and the soleus muscles are big, they can generate enough force to stabilize the ankle joint.

If you look at a handstand then essentially, your base of support, your hands, your palms are generally smaller than your feet. So, your base of support drastically goes down and you are going to have to apply a huge force through your, what muscles are these? The wrist flexors ok. So, it is a; so, people who do that generally, have very strong wrist flexors, most of us cannot just do a handstand in one shot, it is not something it is something that takes a lot of practice and a lot of muscle development in this in the wrist area ok.