Biomechanics of Joints and Orthopaedic Implants
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Lecture 22
Inverse Dynamics in Musculoskeletal Modelling

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Good afternoon everybody, welcome to lecture 4 of module 4 on Inverse Dynamics in Musculoskeletal Modelling.

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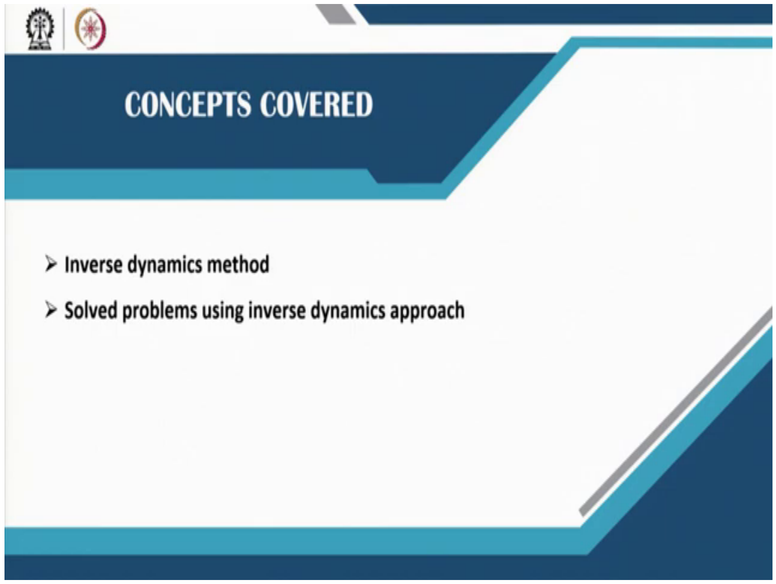

In this lecture, we would discuss inverse dynamics method in more detail and discuss solving problems using the inverse dynamics approach. This lecture is in continuation to the earlier lecture on introduction to musculoskeletal modeling. This lecture focuses on the inverse dynamics method as applicable to musculoskeletal modeling along with the solutions of some solved problems.

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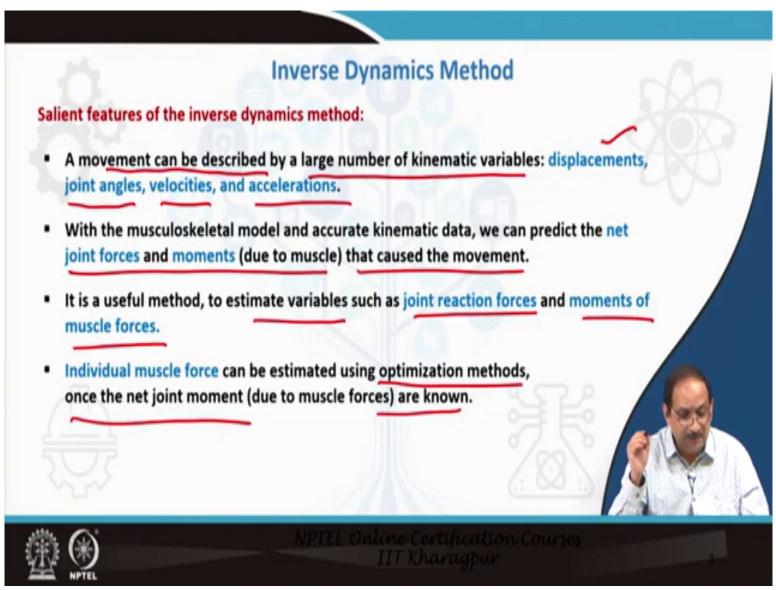

Let us first discuss the salient features of the inverse dynamics method as applicable to the musculoskeletal modeling and analysis, as relevant to musculoskeletal modeling and analysis. A movement can be described by a large number of kinematic variables, displacements, joint angles, velocities and accelerations.

With the musculoskeletal model and accurate kinematic data, we can predict the net joint forces and moments. The inverse dynamics method is a valuable method to estimate variables such as joint reaction forces and moments of muscle forces.

Individual muscle force can be estimated using an optimization method.

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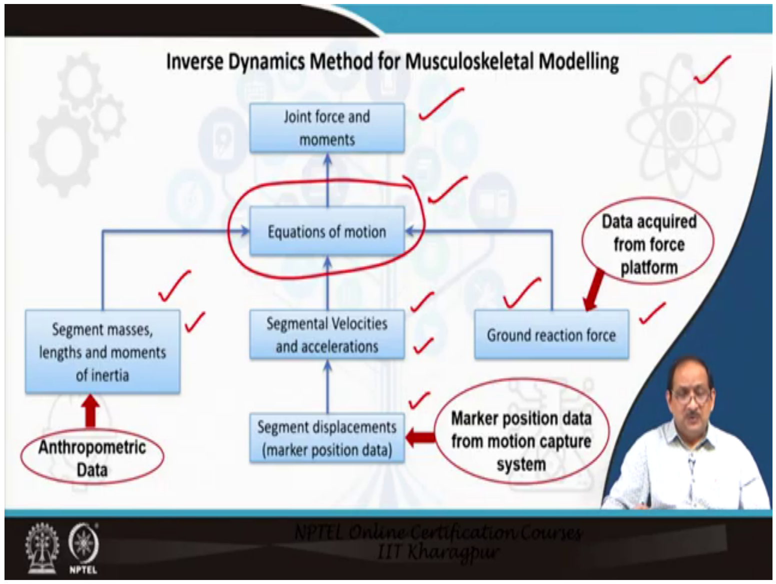

An overview of the inverse dynamics method as applicable to rigid body dynamics of the musculoskeletal system is presented in this slide. Segmental displacements are calculated from marker position data and the marker position data is obtained from the 3D motion capture system.

After that, segmental velocities and accelerations are obtained using numerical differentiation. Knowing the segmental properties such as mass, length and moment of inertia from anthropometric data, ground reaction forces from force platform, and segmental kinematic data as calculated earlier, we can obtain joint forces and moments using the equation of motion.

So, the segmental mass properties, ground reaction forces, segmental velocities, and acceleration that is segmental kinematics, all three in combination with the equation of motion, can be used to find out the joint forces and moments.

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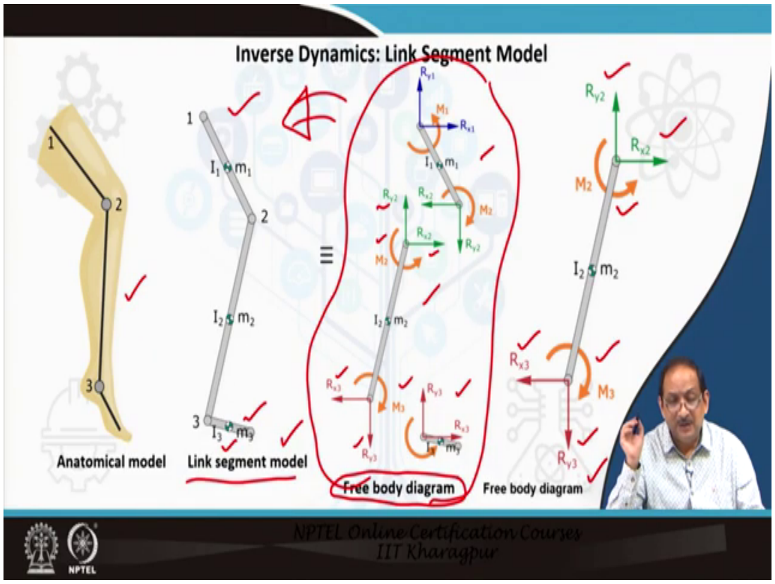

Let us now consider the link segment model. We have discussed this in the introductory lecture 4.1. As discussed in the earlier lecture, the anatomical segment of the body, say for instance, a leg can be represented with rigid segments. This mathematical model of the rigid segments is known as the link segment model, as indicated in the figure.

Each segment is characterized by the mass and moment of inertia acting at the center of gravity of each link. So, together we can call this a link segment model. The intersegmental forces and moments, as you can see here, the intersegmental forces and moments can be calculated using the free body diagram of each segment after isolating each member from the link segment model, similar to the frame structure in engineering mechanics.

Furthermore, the intersegmental forces and moments can be calculated using the equations of motion and the inverse dynamics approach. Now, you can see here that we have one, two, three segments when we isolate the body from the link segment.

Typically, we are taking out one segment and drawing the free body diagram of the segment and the reaction forces at the joints and the moments indicated for one segment. Now, if you consider this part of the free body and assemble these three segments, you will end up getting back the link segment model as indicated in the figure.

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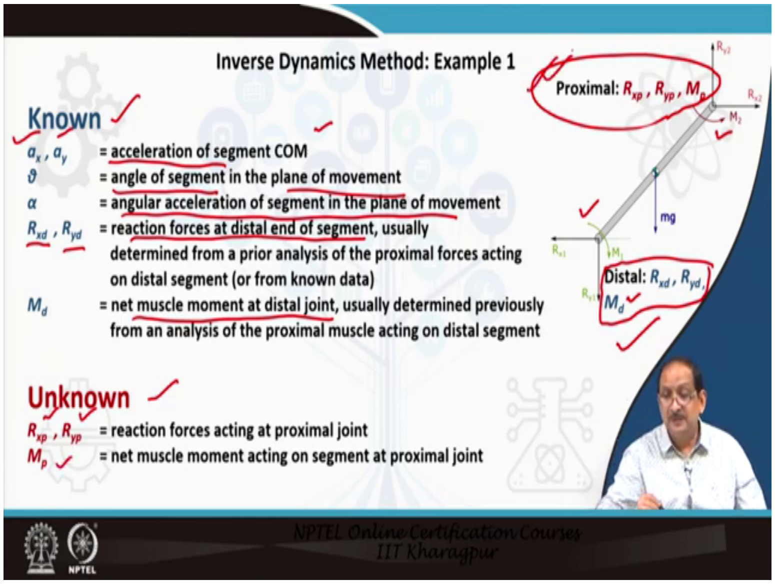

Now, let us consider the first example of one problem that we are going to solve now. So, in a free body diagram of a link segment model, few known variables and some unknown variables are presented in this slide. So, the known variables are the acceleration of the segment COM, a_x and a_y, the angle of the segment in the plane of movement, the accelerations a_x and a_y is indicated here. The α is the angular acceleration of the segment in the plane of the movement.

The R_{xd} and R_{yd} are the reaction forces at the distal end of the segment, as you can see here in the figure. So, we consider this as the distal end and the top end as the proximal end. M_d is the net muscle moment at the distal joint, usually determined from an analysis of the proximal muscles acting on the distal segment.

Now, the unknown variables are on the proximal side, which is indicated here in this part of the figure. So, R_{xp} and R_{yp} are the reaction forces acting at the proximal joint and M_p is the net muscle moment acting on the segment at the proximal end.

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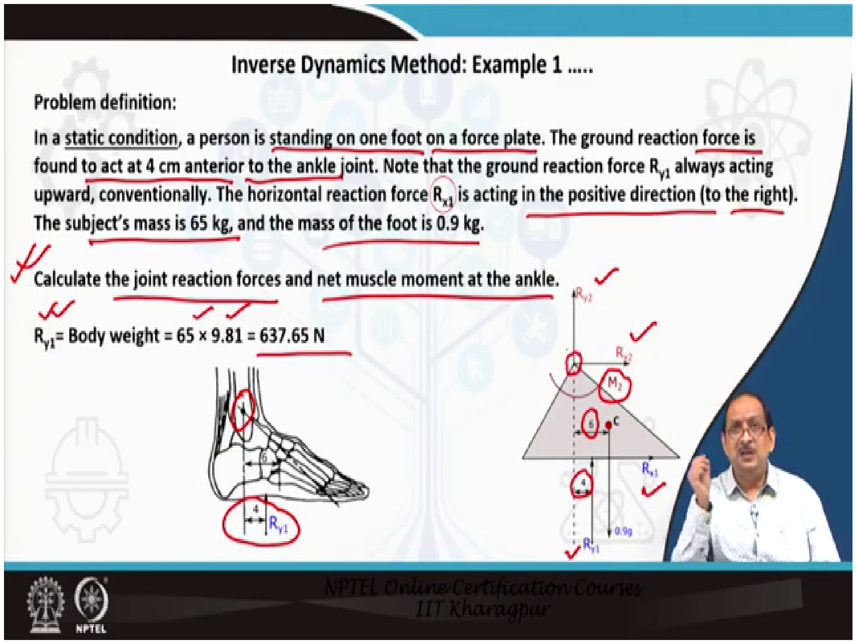

Now, let us come to the problem definition of example number 1, so we first assume that this is a static problem and a person is standing on one foot on a force platform or a force plate. The ground reaction force is found to act at four centimeters anterior as you can see here to the ankle joint, four centimeter anterior to the ankle joint, the ankle joint center is indicated and I had rounded it off.

Note that the ground reaction force R_{y1} is always acting upwards conventionally. The horizontal reaction force R_{x1} is acting in the positive direction towards the right and the mass of the subject is given as 65 kg, and the mass of the foot alone is 0.9 kg. So, we are supposed to calculate the joint reaction force and the net muscle moment around the ankle.

So, considering a static situation R_{y1} is obviously equal to the body weight but opposite, acting opposite in direction to the body weight, so it is 65 m and g, so we get 637.65N as R_{y1}. Now, let us consider the free body diagram of this problem. As you can see, the R_{x1} is acting in the positive direction towards the right, R_{y1} is vertically upwards.

The C is the center of mass of the foot through which the bodyweight is acting and it is acting 6 centimetre from the line of action of the vertical reaction force at the ankle joint center.

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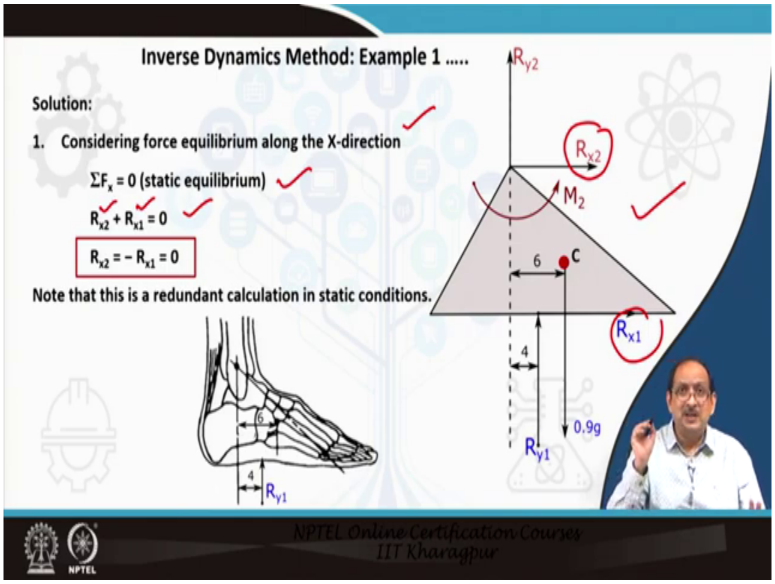

So, let us come to the solution. In step number 1, we again consider the foot's free body diagram and considering force equilibrium along the x-direction, summation of all the forces along x direction is equal to 0. So, the only two forces R_{x2} and R_{x1} are acting along the x-direction.

$$\Sigma F_x = 0;$$

$$R_{x2} + R_{x1} = 0;$$

$R_{x1} = 0$, Assuming **zero horizontal force** is registered at the force plate;

$$\therefore\ R_{x2} = 0$$

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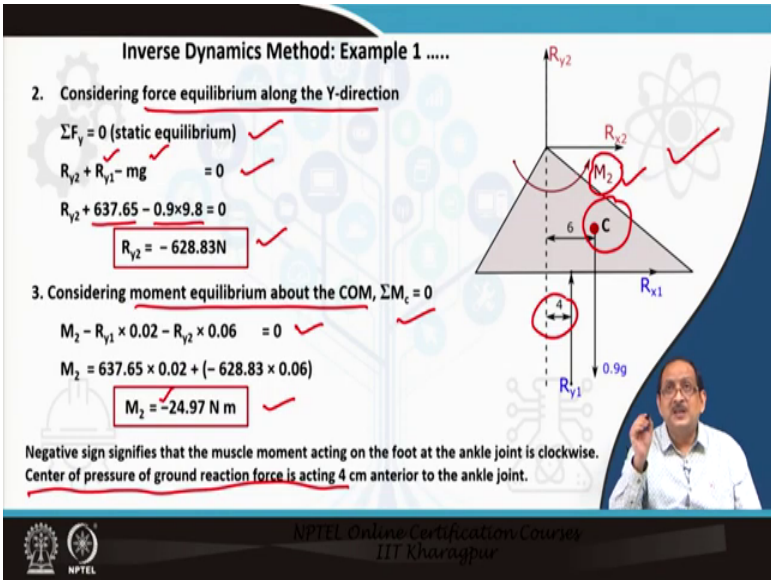

Let us move to step number 2, we calculate the reaction force R_{y2} along the vertical direction. So, considering the free body diagram and the force equilibrium along the y direction again, summation F_y is equal to 0, considering static equilibrium, and we write down the equations.

$$\Sigma F_y = 0;$$

$$R_{y2} + R_{y1} - mg = 0;$$

$$R_{y2} = -628.83 \text{ N}.$$

So, the third step is by considering moment equilibrium about the COM that is C. So, we consider the sum of the moments about the center of mass of the foot, and we calculate M_2.

$$\Sigma M_c = 0;$$

$$M_2 - R_{y1} \times 0.02 - R_{y2} \times 0.06 = 0;$$

$$M_2 = -24.97 \text{ Nm}.$$

Please note the negative sign here. The negative sign signifies that the muscle moment acting on the foot at the ankle joint is clockwise. The center of pressure of ground reaction force is acting 4 centimeter anterior to the ankle joint, and please note that.

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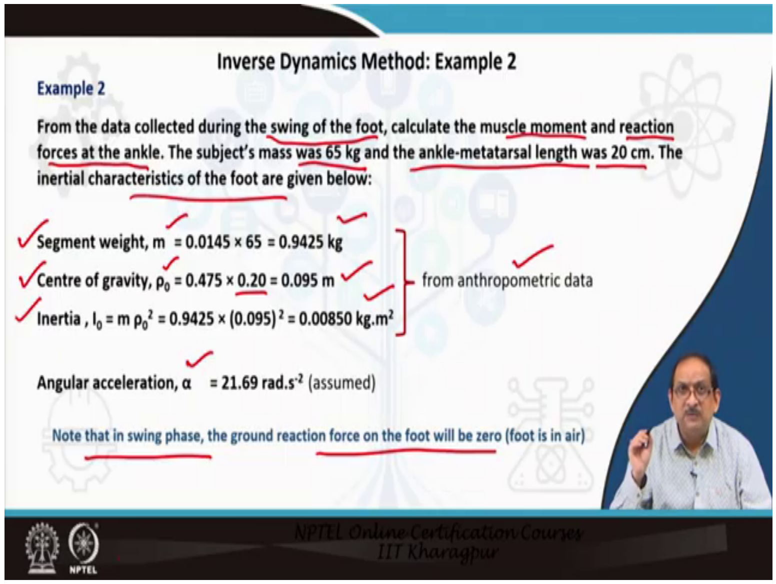

Let us discuss the second example on Inverse Dynamics Method. So, let me define the problem here. From the data collected during the swing phase of the foot, we are asked to calculate the muscle moment and the reaction forces at the ankle joint. The given data are the subject's mass 65 kg, and the link, segment length between ankle to the metatarsal length that is the link segment length is mentioned as 20 centimeter.

So, the inertial characteristics of the foot can be actually calculated based on the anthropometry data which are given here, the segment weight, the mass is calculated in terms of the body weight, 0.9425 kg is the segment weight. The center of gravity position is indicated here ρ_0 and it is related to the length of the limb segment, that is 0.20, so the center of gravity is located at a position 0.095 meters.

The inertia, moment of inertia can be calculated as a product of the mass and the radius of gyration squared, so it is calculated as 0.00850 kg per meter square. The angular acceleration α is assumed as 21.69 for this problem. Please note that this problem is on dynamics of the foot, so we will be considering dynamic equilibrium conditions and it should be also noted that the foot is in the swing phase. Therefore, the ground reaction force on foot will be 0, since the foot is in the air during the swing phase.

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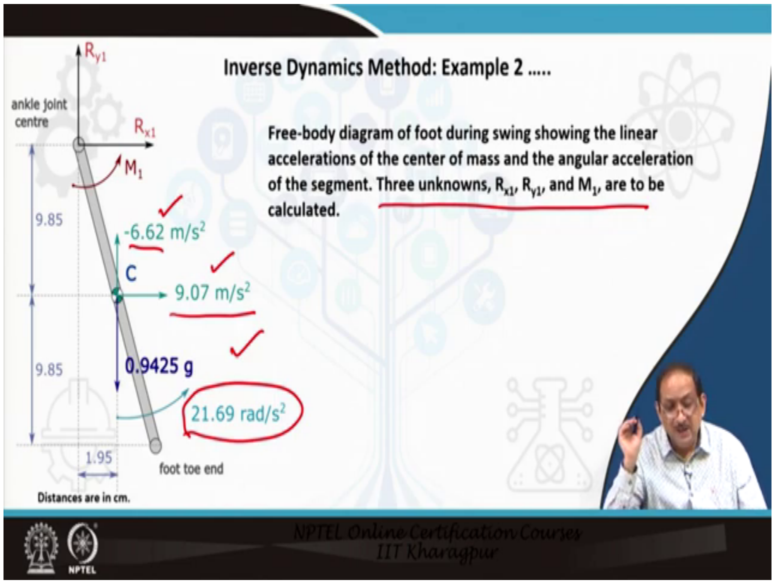

Now, let us come to the problem. The free-body diagram of the foot as you can see, is presented here on the left during the swing phase showing the linear acceleration of the center of mass and the angular acceleration of the segment. We need to calculate now the three unknowns R_{x1}, R_{y1} and M_1 from the given data and the condition.

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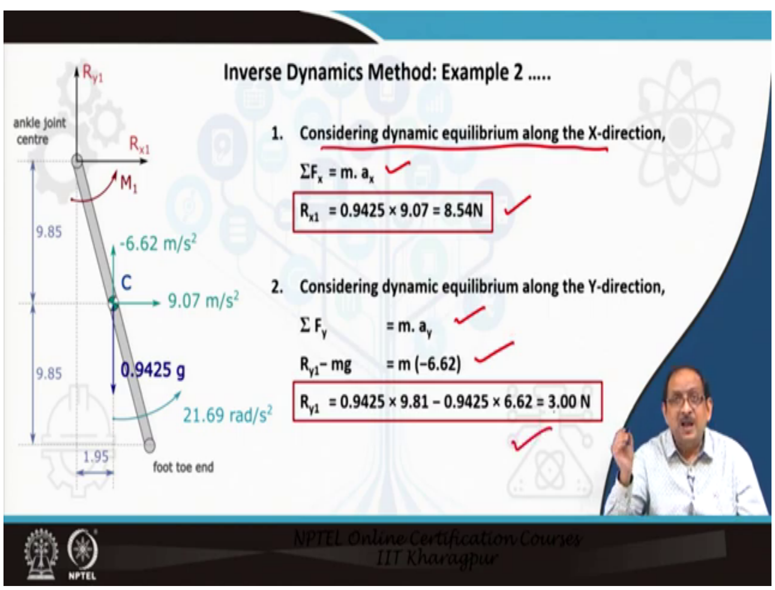

Let us consider the solution of example 2, and please note that this is a dynamic problem. So, we will be considering dynamic equilibrium along the x-direction, y-direction and the moment due to rotation about a joint center.

$$\Sigma F_x = m.a_x;$$

$$R_{x1} = 0.9425 \times 9.07 = 8.54 \text{ N};$$

Considering dynamic equilibrium along the y-direction, we can write summation F_y is equal to the mass and the acceleration, linear acceleration along the y-direction.

$$\Sigma F_y = m.a_y;$$

$$R_{y1} - mg = m.(-6.62);$$

$$R_{y1} = 3.00 \text{ N}$$

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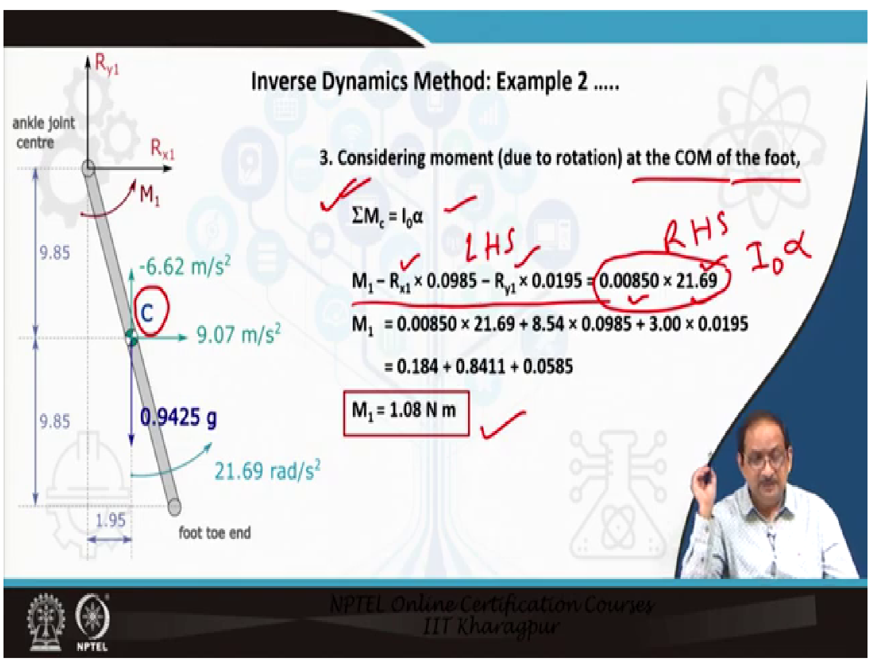

Now, considering moment so this is rotation about a joint center at the center of mass. So, we are taking the moment about the center of mass of the foot, so summation of M_c is equal to $I_0\alpha$.

$\Sigma M_c = I_0\alpha$;

$M_1 - R_{x1} \text{ x } 0.0985 - R_{y1} \text{ x } 0.0195 = 0.00850 \text{ x } 21.69$

M_1=1.08Nm.

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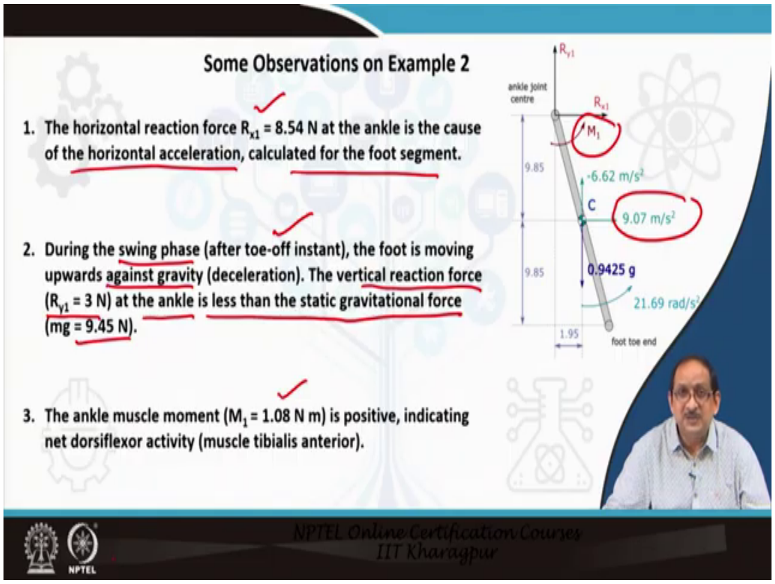

Let us discuss about some observations on the results obtained from example 2. The horizontal reaction force at the ankle joint is the cause of the horizontal acceleration calculated for the foot segment. So, the horizontal acceleration is indicated in the free body diagram just for clarity.

During the swing phase, that is, after the toe-off instant the foot is actually moving upwards against gravity. That means the foot is decelerating. The vertical reaction force at the ankle joint is actually less than the static gravitational force. And the third important observation from the problem is the ankle muscle moment, as indicated in the diagram, is positive. It is acting anti-clockwise or counter clockwisem, indicating net dorsiflexor activity due to the muscle tibialis anterior.

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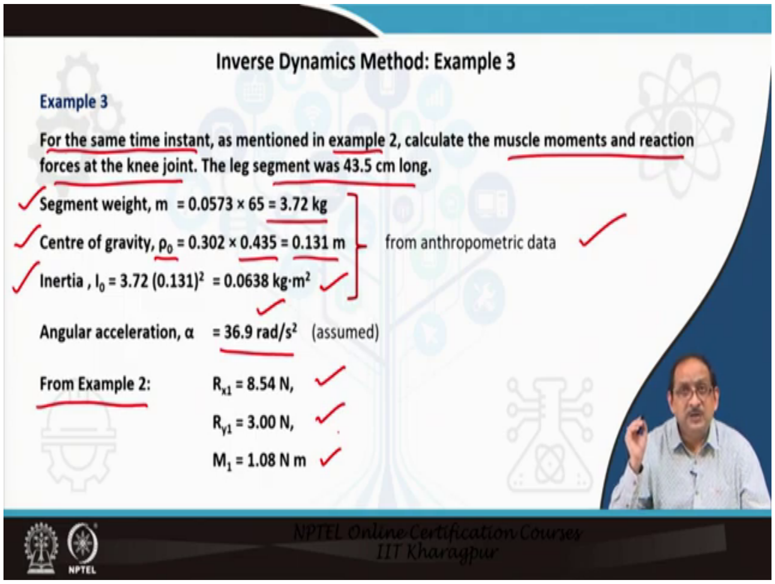

Let us now discuss another problem; this is example 3 of this lecture. In this example, we consider the same time instant as example 2. We need to calculate the muscle moments and reaction forces at the knee joint. In example 2, it was on the ankle joint, but here in example 3, we will be finding the muscle moments and reaction forces or joint reaction forces and moments at the knee joint.

The leg segment is given as 43.5 cm long. So, again based on the anthropometric data, the segment weight, the limb segment weight can be calculated in relation to the bodyweight of 65 kg, so it comes out to be 3.72 kg. The center of gravity position can also be calculated based on the length of the lengths leg segment, so the centre of position comes to 0.131 m and the moment of inertia can be calculated based on the mass and the radius of gyration it comes to 0.0638 kg m^3.

So, all these variables can be actually calculated from the anthropometric data. The angular acceleration α is assumed to be 36.9 rad/m^2. And from example 2, we will use the magnitude of the ankle joint reaction forces and moments, ankle joint reaction forces and moments.

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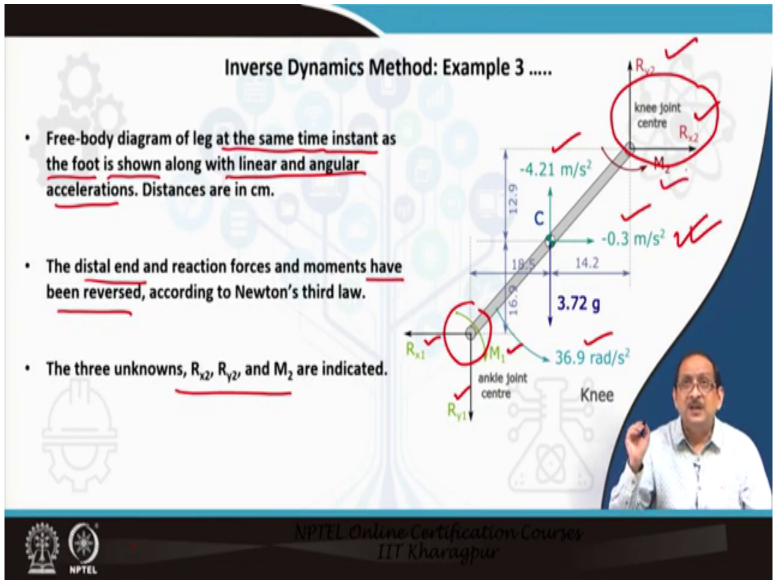

Let us now discuss the third example. This example is based on a free body diagram of a leg at the same instant as the foot, as discussed earlier in example 2. So, same time instant, but this is for the leg, earlier we had solved for the foot and the ankle joint reaction forces and moments.

So, the same time instant as the foot is shown here, the free body diagram of the lower leg. So, the linear and angular accelerations are indicated, and the distances, the linear accelerations are given here in the free body, the angular acceleration is shown here in the free body as well, and the distances are in cm.

As mentioned earlier, if we know the distal joint moments and forces, the net moment and forces can be calculated at the proximal end of the segment or proximal joint or the joint at the proximal end of the segment. Since we had calculated the ankle joint moments and forces earlier, we could now estimate the net joint forces and moments at the knee joint.

So, this example demonstrates the estimation of the net forces and moments at the knee joint based on the prior knowledge of the ankle joint moments and forces. Now, the distal end reaction forces and moments have been reversed because this is a separate lower leg segment where this is the joint, ankle joint at the distal end, so according to newton's third law, the reaction forces should cancel each other when the two link segments are assembled.

Therefore, the R_{x1} and R_{y1} as well as the moment should be in the opposite direction when we consider the attached link, the lower leg segment, as indicated in this free body diagram. The three unknowns that are required to be calculated are R_{x2}, R_{y2} and M_2 at the knee joint centre.

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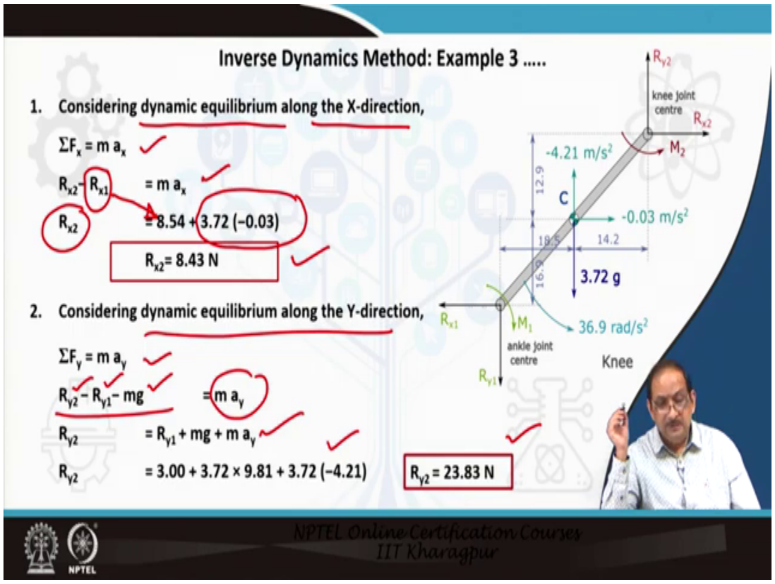

Let us now consider the solution of example 3. Similar to example 2, we consider the dynamic equilibrium along the X-axis and write down the equation of motion,

$$\Sigma F_x = m.a_x ;$$

$$R_{x2} - R_{x1} = 3.72.(-0.03);$$

$$R_{x2} = 8.43 \text{ N};$$

Considering dynamic equilibrium along the y-direction,

$$\Sigma F_y = m.a_y ;$$

$$R_{y2} - R_{y1} - mg = m. (-4.21);$$

$$R_{y2} = 23.38 \text{ N}$$

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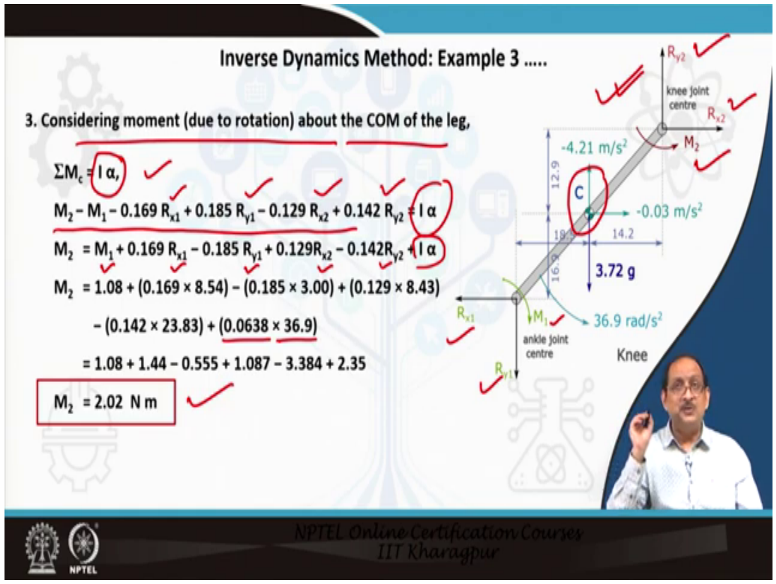

The third step is finding out the moment due to the rotation. So, considering moment about the center of mass of the leg that is the C, we can form or write down the equation of the moments and you can see on the right-hand side we have the I α, the moment of inertia multiplied by the angular acceleration.

$$\Sigma M_c = I \alpha ;$$

$$M_2 - M_1 - R_{x1} \times 0.169 + R_{y1} \times 0.185 - R_{x2} \times 0.129 + R_{y2} \times 0.142 = 0.0638 \times 36.9$$

$$M_1 = 2.02 Nm.$$

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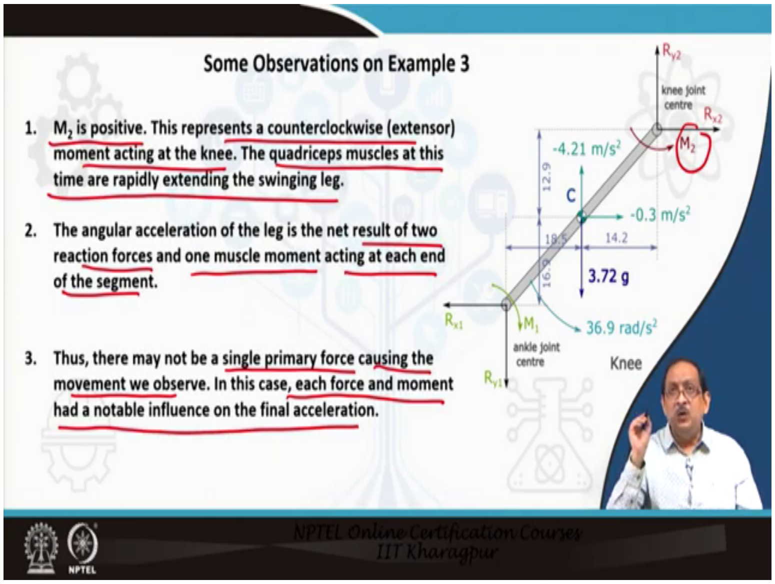

So, let us now discuss some observations on this example 3. M_2 is found out to be positive; this represents a counterclockwise extensor moment acting at the knee. So, this M_2 is positive and anti-clockwise, so it is trying to extend the knee. The quadriceps muscles at this time are rapidly extending the swinging leg. This is the physical interpretation of this time instant or the configuration of this problem.

The angular acceleration of the leg is the net result of two reaction forces and one muscle moment. Therefore, there may not be a single primary force causing the movement we observe here. In this case, each force and moment had a notable influence on the acceleration of the lower leg segment.

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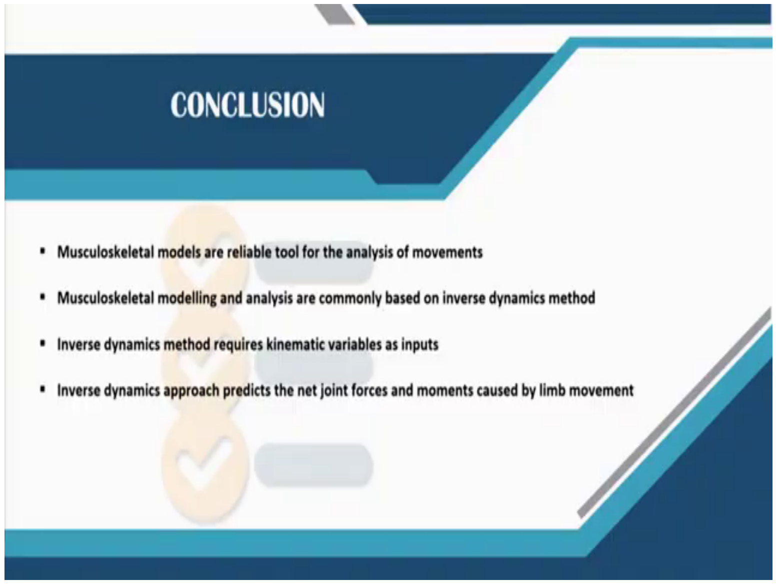

Let us come to the conclusion of this lecture. The musculoskeletal models are reliable tool for the analysis of movements. This we had also observed the same conclusion in the earlier lecture. So, since this lecture is a continuation of the earlier lecture, so we are now drawing the conclusions somewhat together.

Musculoskeletal modeling and analysis are commonly based on the inverse dynamics method and we have discussed in detail about this method in this lecture. The inverse dynamics method requires kinematic variables as inputs. And the inverse dynamics approach predicts the net joint forces and moments caused by limb movement.

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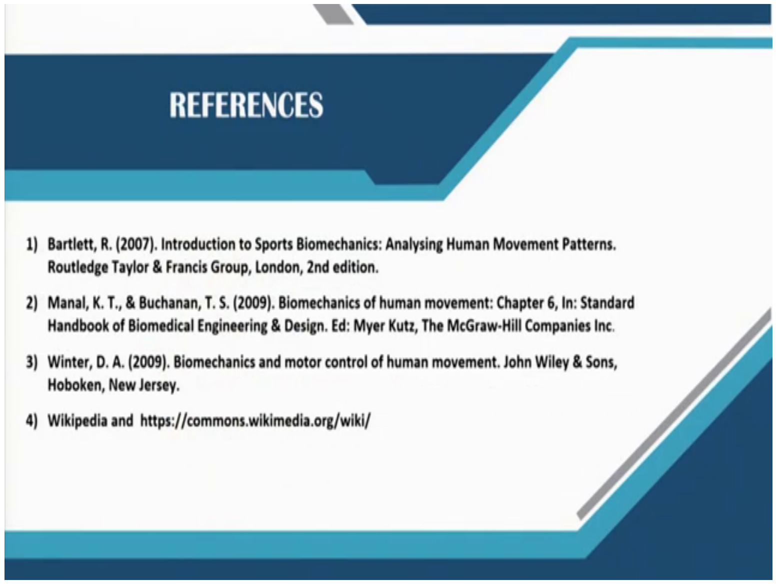

The references are listed here based on which the lecture has been prepared. Thank you for listening.