Biomechanics of Joints and Orthopaedic Implants
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Lecture 21
Introduction to Musculoskeletal Modelling

Good morning everybody. Welcome to the 3rd lecture of the 4th module in the NPTEL Online Certification Course on Biomechanics of Joints and Orthopedic Implants.

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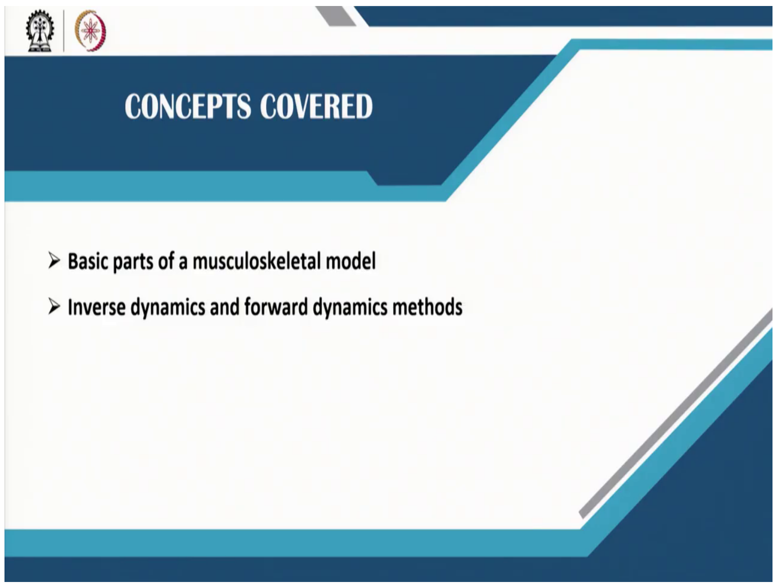

In this lecture, we will discuss the basic parts of a musculoskeletal model and the inverse dynamics and forward dynamics methods.

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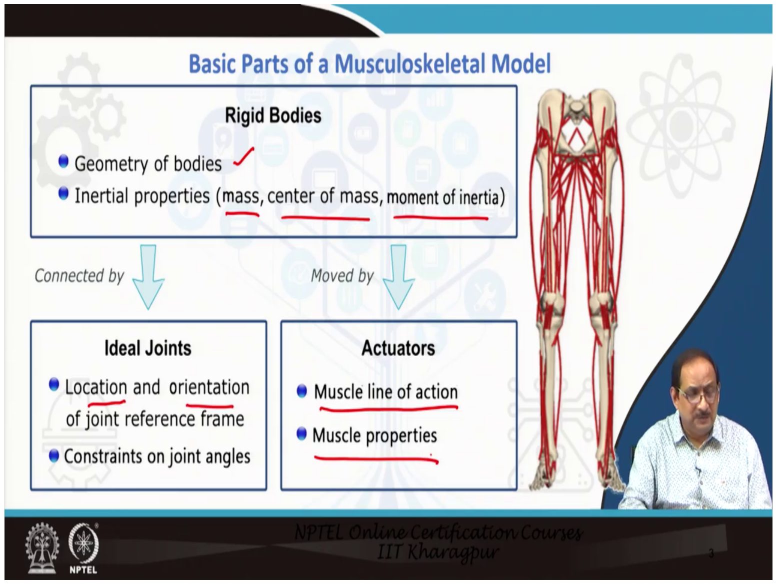

Now, let us first discuss the basic parts of a musculoskeletal model. Rigid bodies are characterized by mass, the center of mass, and the moment of inertia, regarded as inertial parameters. Apart from that, we need the geometry of rigid bodies.

Ideal joints are characterized by the location and orientation of the joint in the reference frame. It also requires constraints on the joint angles, which are regarded as kinematic constraints. The muscles are considered to be actuators. So, it is characterized by the muscle line of action and the muscle properties.

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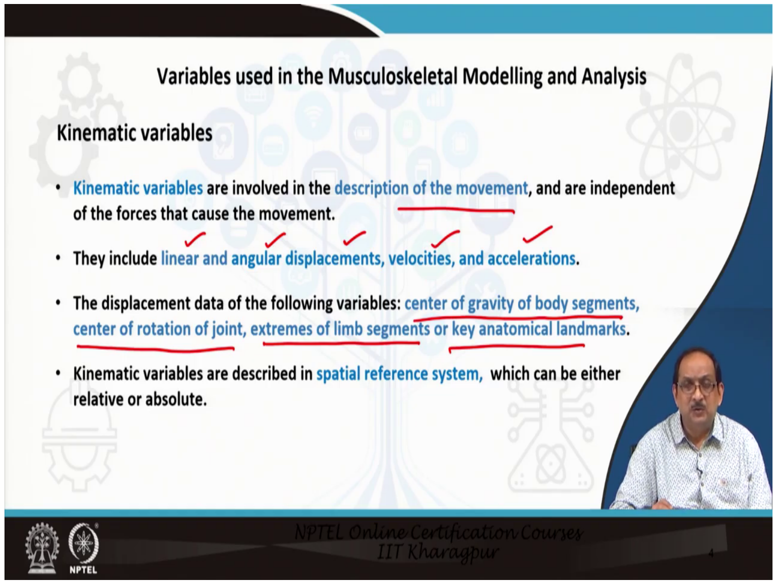

Now, let us discuss the role of the kinematic variables in musculoskeletal modelling and analysis. So, the role of the kinematic variables may be summarized as follows. The kinematic variables are involved in the description of movement and are independent of the forces that cause the movement. They include linear and angular displacements, velocities, and accelerations.

The displacement data of the following kinematic variables are the center of gravity of the body segment, center of rotation of the joint, and extremes of limb segments or key anatomical landmarks. All the displacement data of these variables are required for the musculoskeletal modeling and analysis. The kinematic variables are described in the spatial reference system, which can be either relative or absolute.

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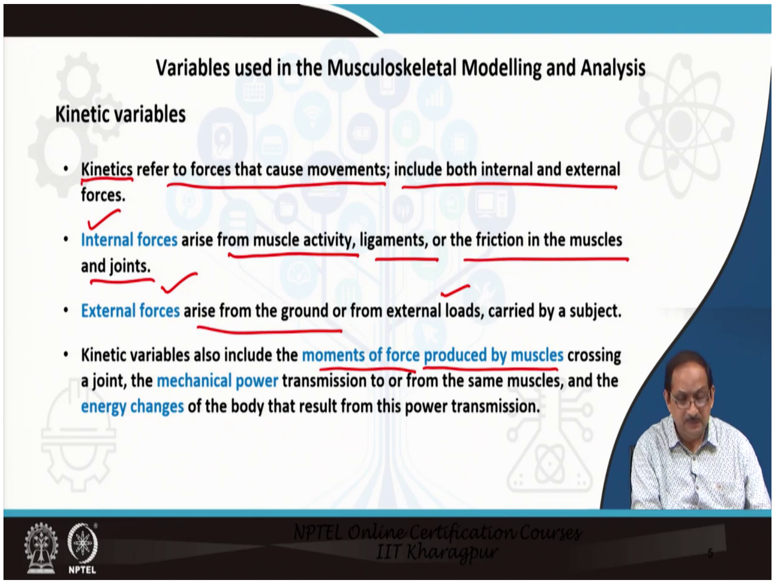

Let us now discuss the kinetic variables. Kinetics refer to forces that cause movements. So, these forces can include both internal and external forces. The internal forces arise from muscle activity, ligaments or friction in the muscles and joints. Whereas the external force arise from the ground is ground reaction force or from external loads carried by a subject.

The kinetic variables also include the moments of forces produced by the muscles crossing a joint, the mechanical power transmission to or from the same muscles, and the body's energy changes that result from this power transmission.

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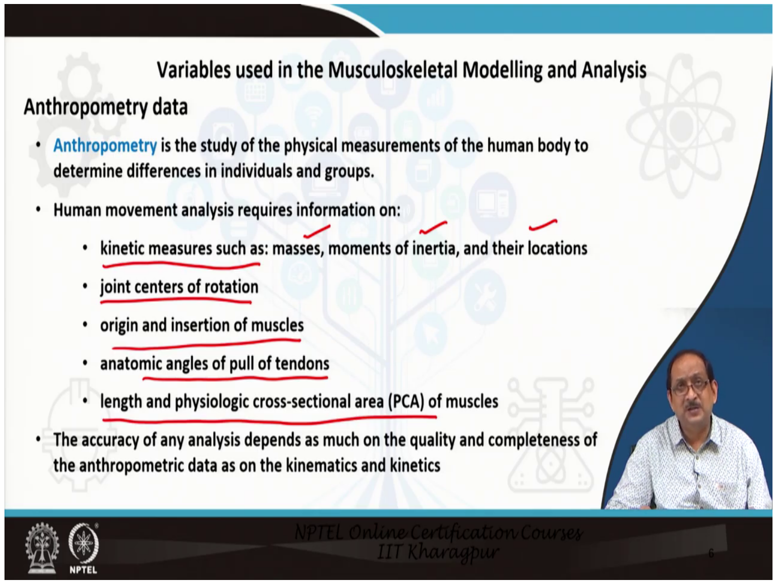

Now, let us focus on the anthropometry data. Anthropometry data consists of the length and mass properties of each body segment. So, anthropometry is the study of physical measurement of the body to determine differences in individuals or groups and or groups.

The human movement analysis requires information on kinetic measures such as masses, the moment of inertia and their locations, joint centre of rotations, origin and insertion of muscles, anatomic angles of the pull of tendons, and the length and physiological cross-sectional area of muscles. The accuracy of any analysis depends as much on the quality and completeness of the anthropometric data as on the kinematics and kinetics.

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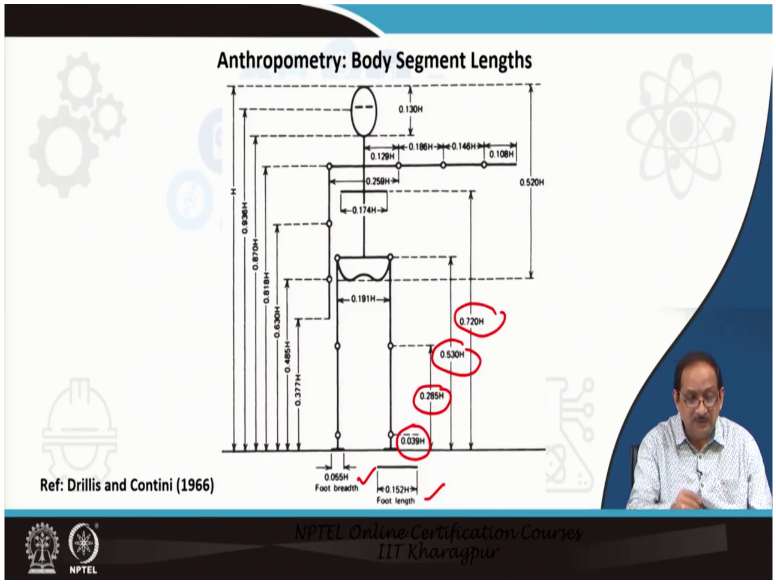

Now, let us see in the slide what is meant by the anthropometry data on body segment lengths. Now, most basic dimension of the body is the length of a segment between, for example, joints and these body segments can vary from one individual to the other based on ethnic origin, sex, and the basic built of the body.

Now, this average set of segment lengths are actually shown in terms of percentage of body height. So, the length, body length segments or body segments. Segment lengths are expressed in terms of body height, and this is shown in this figure.

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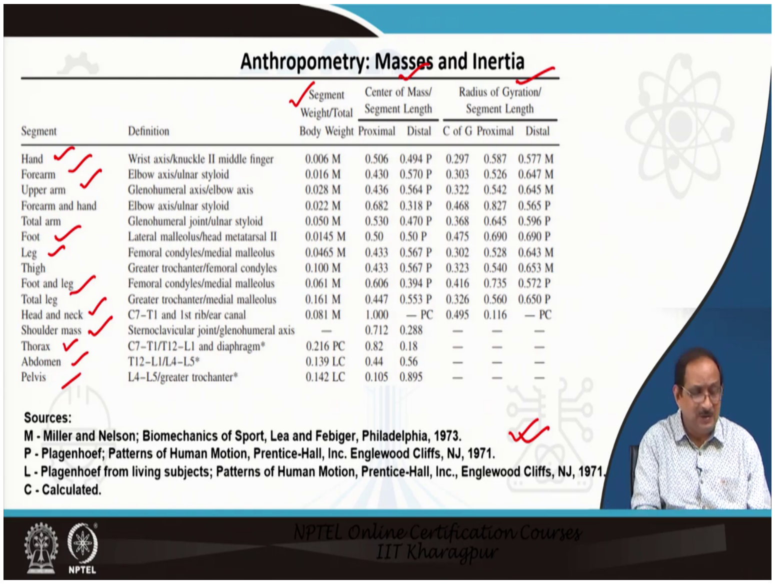

Now, let us come to the masses involved in the body and its inertial properties. Now, kinematic and kinetic analysis requires data regarding mass distribution, mass centres, and moments of inertia. Some of these measures have been determined directly from cadavers or image scanning.

So, this table presents the weight, center of mass and radius of gyration of the body segments, different body segments like hand, forearm, upper arm, foot, leg, total leg, head and neck, shoulder mass thorax, abdomen and pelvis. So, there is a host of references indicated in this slide from which we have gathered this data and have presented in this slide.

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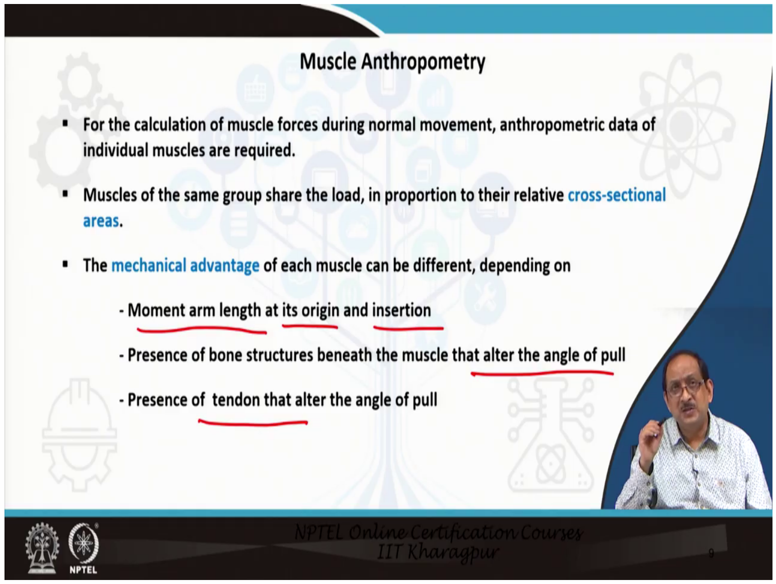

Now, anthropometric data of individual muscles is required to calculate muscle forces during normal movement. So, muscles of the same group share the load in proportion to their relative cross-sectional areas.

The mechanical advantage of each muscle can be different depending on the moment arm and its origin and insertion. So, muscles are attached to the bones via the tendons, and the essential locations of origin and insertion of the muscle would determine the moment arm length. Just repeat this part.

The mechanical advantage of each muscle can be different depending on the moment arm length at its origin and insertion on the bone. Presence of bone structure beneath the muscle can alter the angle of pull. The presence of the tendon can also change the angle of pull since the tendons are attaching muscles to bone.

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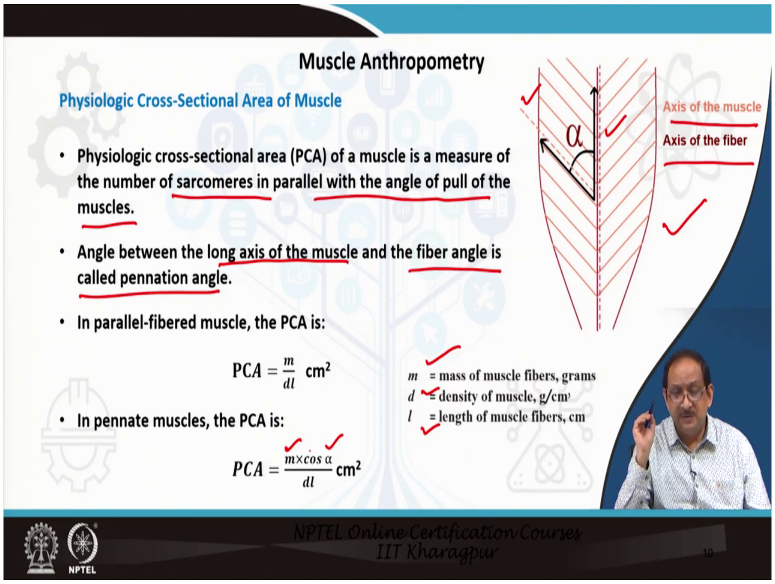

Now, let us discuss muscle anthropometry, the physiological cross-sectional area of muscle. So, the PCA of a muscle is a measure of the number of sarcomeres in parallel with the angle of pull of the muscles. Now, what is sarcomere? A sarcomere is the basic contractile unit of the muscle fiber.

The angle between the long axis of the muscle and the fibre angle is called pennation angle. This is presented in a schematic diagram of the muscle where you can see the axis of the muscle and the fibre's axis. The angle between these two axes is called the pennation angle.

In parallel fibered muscle, the physiological cross-sectional area can be expressed as the mass of the muscle fiber divided by the density and the length of the muscle fiber. So, PCA= m/dl; where m is the mass, d is the density of the muscle and l is the length of the muscle. In pennate muscles, the PCA physiological cross-sectional area is expressed as (m cosα /dl). So, that means, a component mcos(α) is actually taken into consideration for the calculation of PCA in case of pennate muscles.

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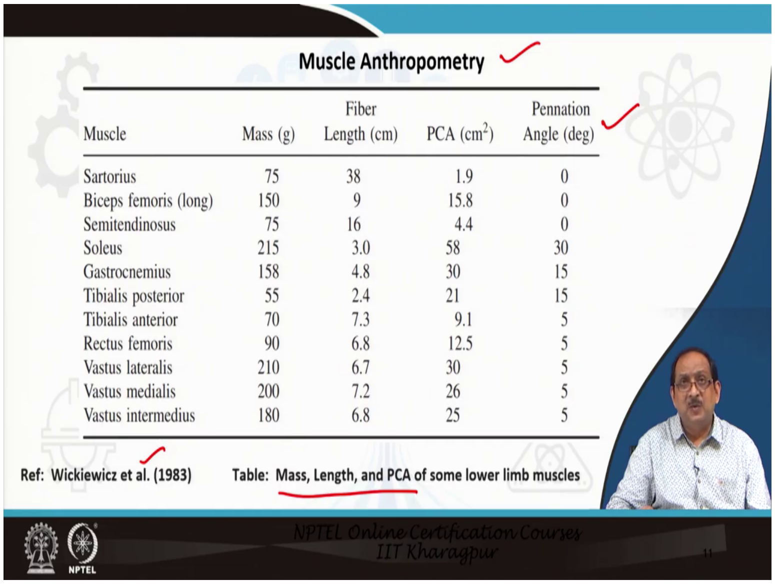

Now, let us come to the muscle, mass, length and PCA of some of the lower limb muscles that is data on muscle anthropometry. Now, there have been studies, but this study has been one of the eminent studies. Which have reported the muscle, mass, fibre, lengths, and pennation angle for 27 lower extremity muscles using data 3 three cadavers.

So, the data is presented here in the table is on the muscle length, muscle mass, and the physiological cross-sectional area. So, we are showing some of the lower limb muscles in this table as well as the pennation angle here for different muscles of the lower limb.

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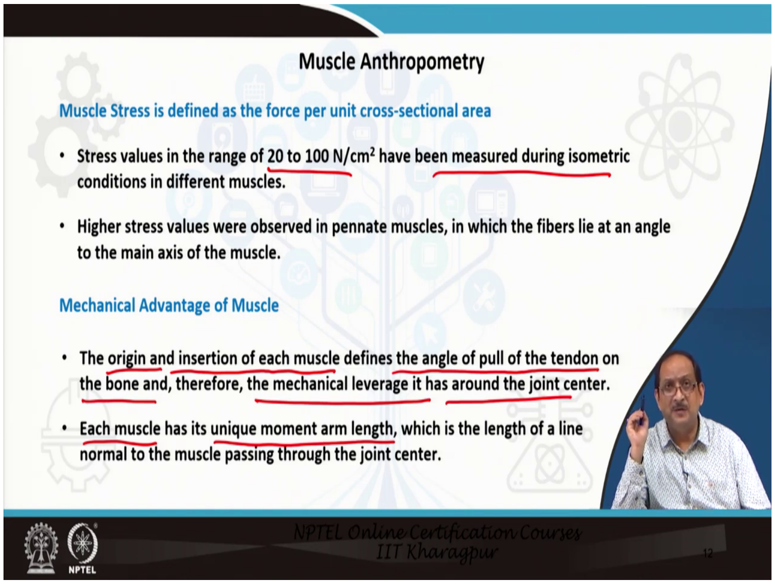

Now, let us discuss more muscle anthropometry. Muscle stress is defined as the force per unit cross-sectional area of a particular muscle. Muscle stress values in the range of 20 to 100N/cm^2 have been measured during isometric conditions in different muscles. Higher stress values were observed in pennate muscles in which the fibres lie at an angle to the main axis of the muscle as indicated in the earlier slide.

Now, let us discuss the mechanical advantage of muscle. The origin and insertion of each muscle define the angle of pull of the tendon. So, the origin and insertion of each muscle define the angle of pull of the tendon on the bone. And therefore, the mechanical leverage is it has around the joint center.

Each muscle has its unique moment arm length, the length of a line normal to the muscle passing through the joint center. So, each muscle has a unique moment arm length which is the length of a line normal to the muscle passing through the joint center.

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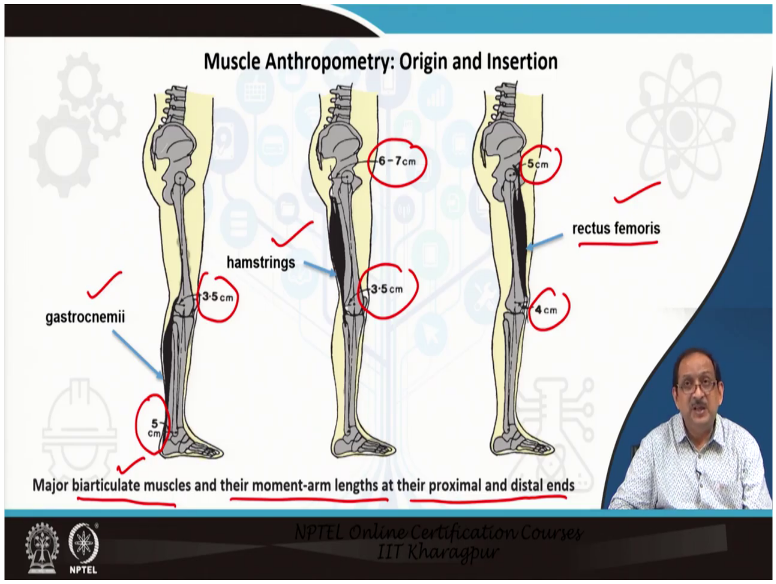

Now, we need to discuss the origin and insertion of some major muscles in the lower extremity. Now, the figure shows the major biarticulate muscles. And their moment arm lengths at the proximal and distal ends. So, we can see gastrocnemii's, hamstring and rectus femoris. The gastrocnemii have a moment arm of 5 centimeter at the ankle and 3.5 centimeter at moment arm at the knee.

The hamstring have moment arms of 6 to 7 centimeter at the hip and 3.5 centimeter at the knee. So, when these muscles are actually active during stance their contribution to hip extension is about twice their contribution to the knee flexion.

The moment arm of the rectus femoris at the hip is slightly larger than at the knee. So, it is 5 centimeter versus 4 centimeter at the knee. However, the uniarticulate quadriceps comprise 84 percent of the PCA of the whole quadricep group, which is responsible for the dominant action of knee extension.

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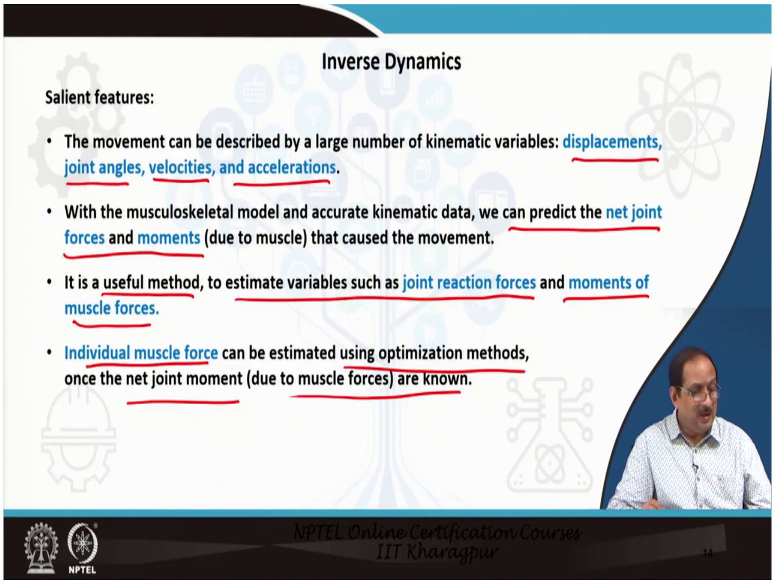

Let us now discuss the salient features of inverse dynamics. The movement can be described by kinematic variables like displacement, joint angles, velocities, and accelerations with the musculoskeletal model and accurate kinematic data. We can predict the net joint forces and moments. The net moments is a combined effect of the muscles, muscle moments.

Inverse dynamics is a helpful method for estimating variables like joint reaction forces and moments or moments of the muscle forces. Individual muscle forces can be estimated using an optimization method once the net joint moment due to the muscle forces is known.

So, this part will be discussed in the following lecture later in the module, in the same module of course. So, in summary, based on the kinematic variables and anthropometric data, joint forces and moments can be calculated using inverse dynamics method.

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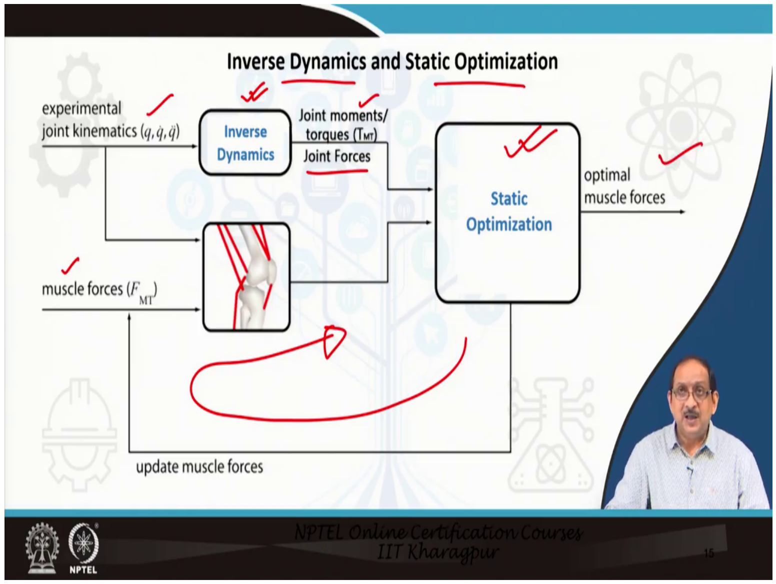

Now, this slide presents an overview of muscle force estimation using inverse dynamics and static optimization. The inverse dynamics method uses experimental joint kinematic information like joint angles, velocity, and acceleration to calculate joint forces and moments or torques. Now, joint moments and torques or torques are the net combined effect of individual muscle forces spanning the joint.

The contribution of each muscle can be calculated using a static optimization scheme, which will be discussed later. Now, in some procedures, an initial guess of the muscle force is made based on which joint equilibrium is verified and changes in the joint forces are made if necessary. The procedure is repeated until an optimal muscle force distribution is achieved.

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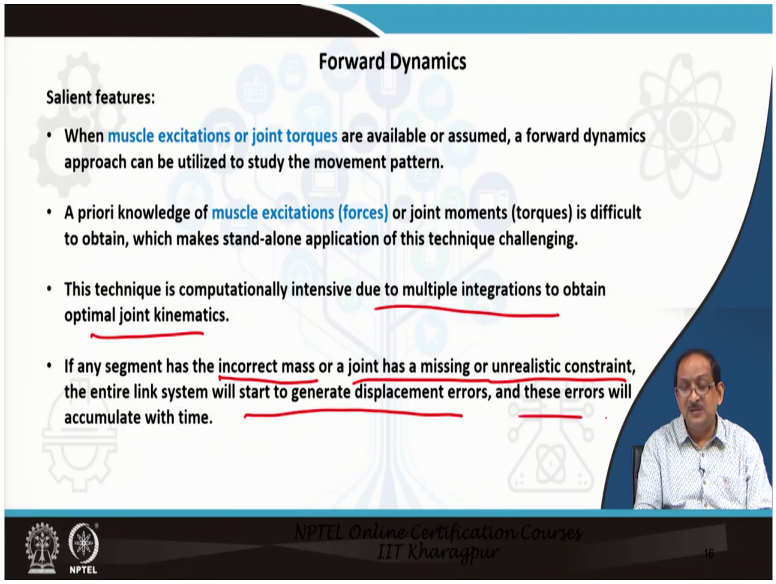

Let us now discuss the salient features of the forward dynamics. When muscle excitations or joint torques are available or assumed, a forward dynamics approach can be utilized to study the movement pattern. A priori knowledge of muscle excitation or forces or joint moments torques is difficult to obtain, which makes the standalone application of this forward dynamics technique quite challenging.

This technique is computationally intensive due to multiple integrations to obtain optimal joint kinematics. If any segment has incorrect mass or a joint has a missing or unrealistic constraint, the entire link system will generate or start to generate displacement errors, and these errors will accumulate with time.

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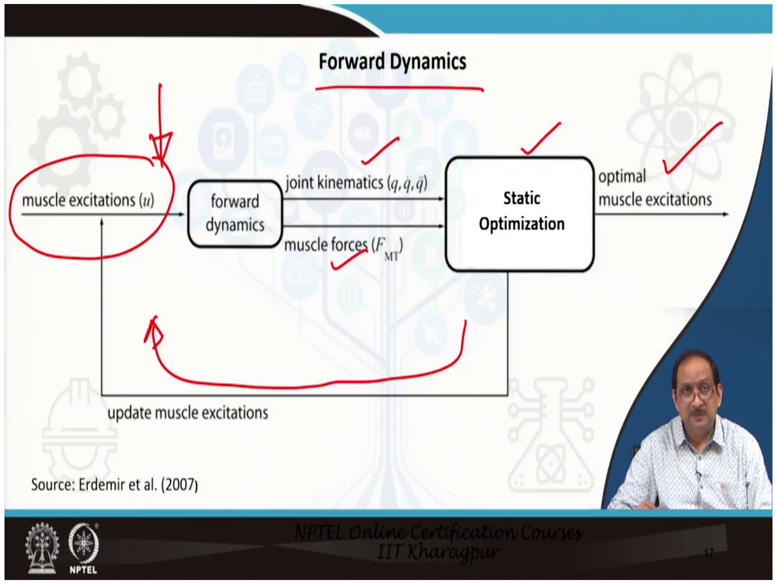

The figure presented here in this slide gives us an overview of the muscle force estimation using the forward dynamics method. The muscle excitation is analogous to neural signal to the muscle. Muscle force generated in the individual muscle depends on physiological parameters like PCA and the pennation angle as discussed earlier.

Initial information on muscle excitation is the input to the forward dynamics method.

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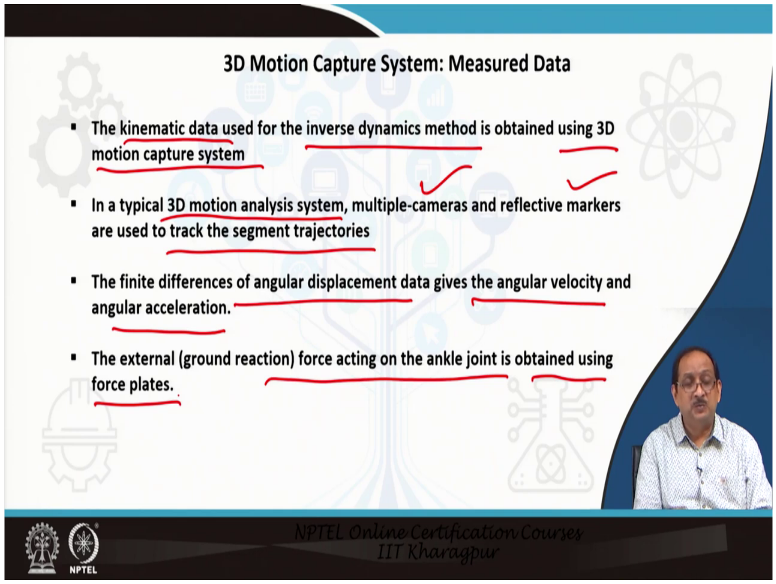

Let us summarize the role of the significant data from the 3D motion capture system that we have discussed in detail in the earlier module. The kinematic data used for the inverse dynamics method is obtained using a 3D motion capture system. In a typical 3D motion analysis system, multiple cameras and reflective markers are used to track the segment trajectories.

The finite differences of angular displacement data give the angular velocity and the angular acceleration. Whereas the external ground reaction force acting on the ankle joint is obtained using force plates.

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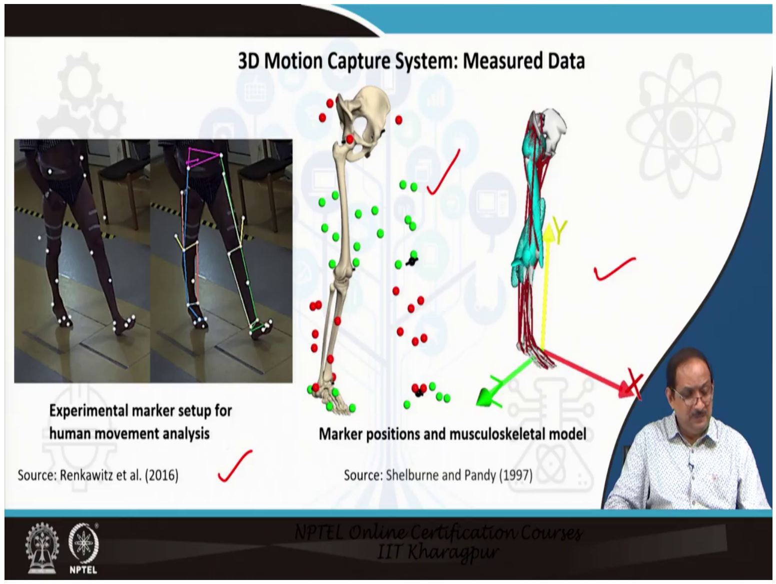

So, this figure summarizes the 3D motion capture system with the marker, with the experimental markers, fixed on different locations of the human body. So, the marker position can now be located in space and the musculoskeletal model can be useful in analyzing the various forces in the joints and the muscle for different applications.

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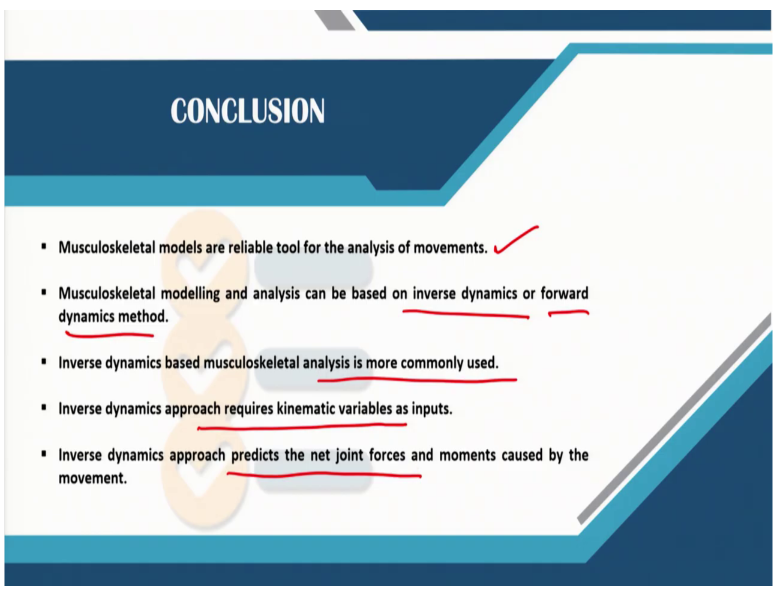

Let us come to the conclusions of the study. The musculoskeletal models are reliable tool for the analysis of movement. The musculoskeletal modelling analysis can be based on inverse dynamics method or forward dynamics method. The inverse dynamics based musculoskeletal analysis, however is more commonly used. Inverse dynamics approach require kinematic variable as inputs. The inverse dynamics approach can predict the net joint forces and moments caused by different movements.

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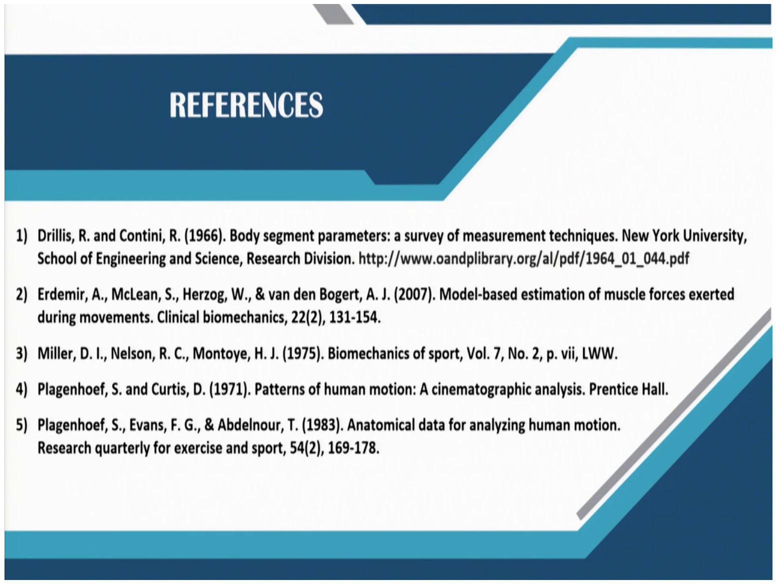

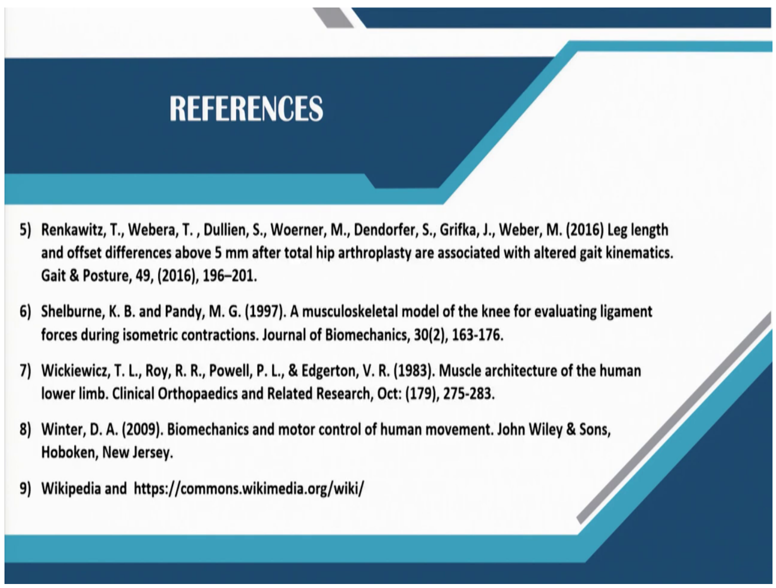

The references are listed here in this slide. In two slides based on which the lecture has been prepared. Thank you for listening.