Biomechanics of Joints and Orthopaedic Implants
Professor Sanjay Gupta
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur
Lecture 14
Gait Cycle

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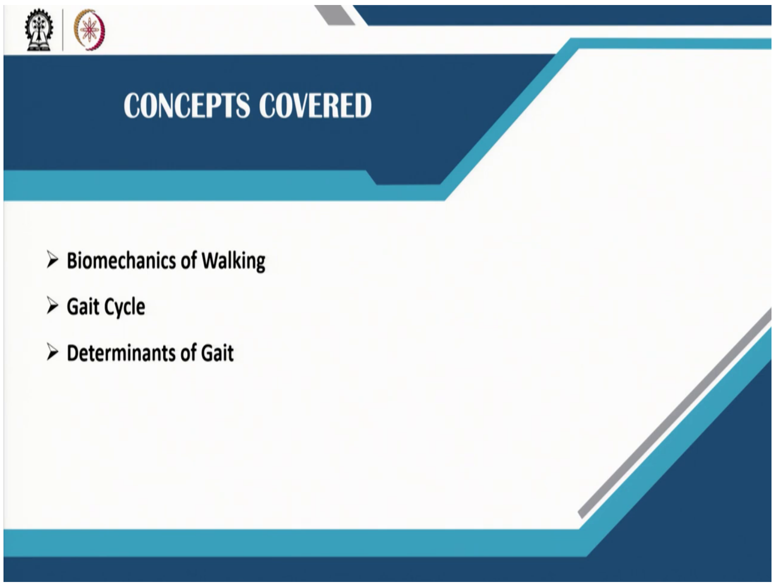

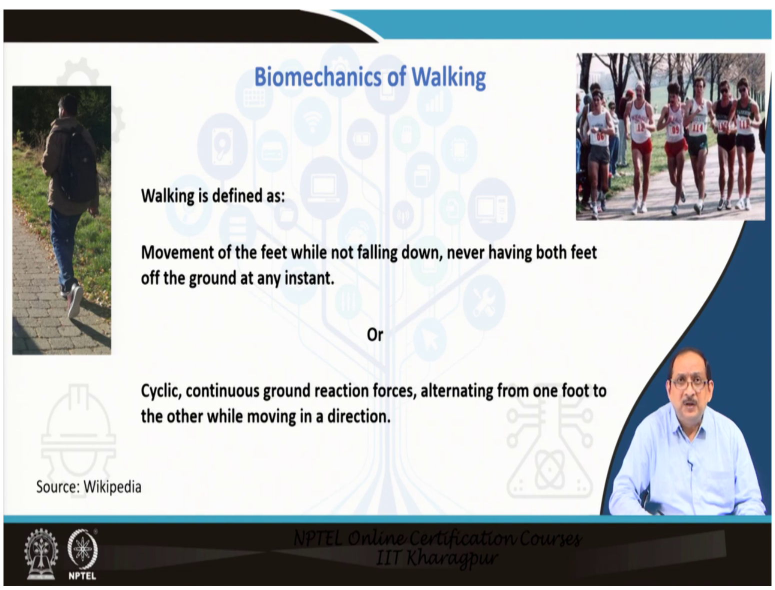

Good afternoon everybody. Welcome to the lecture on Gait Cycle. The contents covered in this lecture are biomechanics of walking, gait cycle, and the determinants of gait. We will be discussing about the biomechanics of walking. Before we move into more details, let us first define walking. Walking is defined as the movement of the feet while not falling down, never having both feet off the ground at any instant or cyclic, continuous ground reaction forces, alternating from one foot to the other while moving in a direction. A complex definition of simple walking indeed, you generate ground reaction forces from one foot to the other, and then you move in a particular direction.

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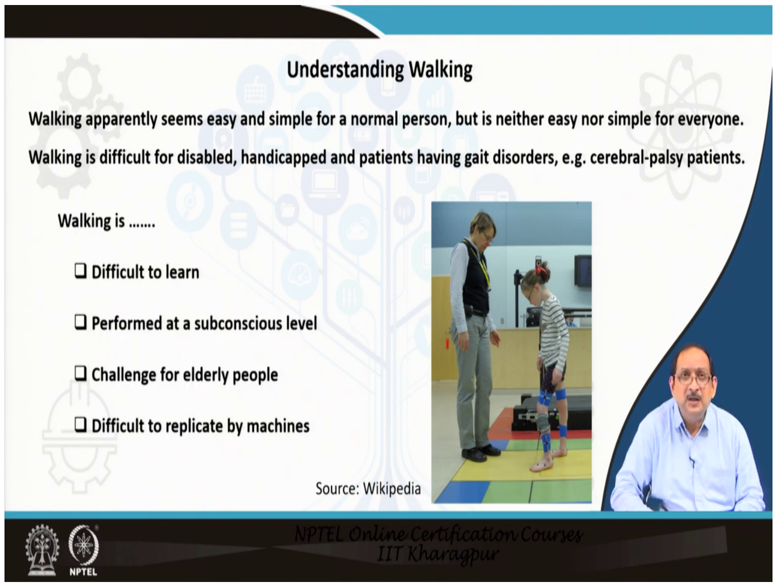

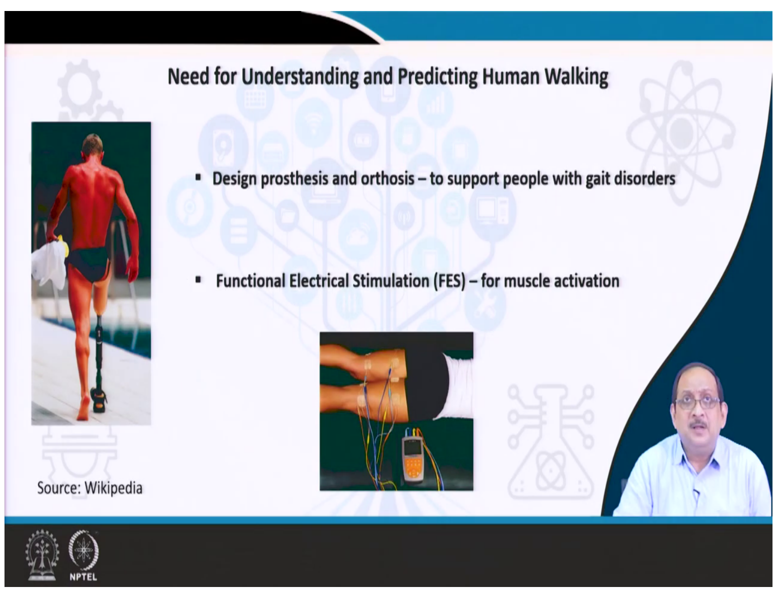

Walking apparently seems easy and simple for a normal person, but it is neither easy nor simple for everyone. Walking is difficult for disabled, handicapped, and patients having gait disorders, such as cerebral-palsy patients. Walking is difficult to learn. It takes a number of years before one can learn how to walk properly. Walking is performed at a subconscious level and it is a real challenge for elderly people.

It is difficult to replicate by machines, especially the balance. You can design a machine that moves on two legs, but then keeping it in balance during movement is always a real challenge. There is a need for understanding and predicting human walking. The human gait cycle is useful for the design of prosthesis and orthosis which is required to support people with gait disorders. It is also useful for patients who require functional electrical stimulation for muscle activation.

So, for a paralyzed patient, for example, activation of muscle at the right moment and order can actually make a paralyzed patient walk again. If a person encounters spinal cord injury due to an accident, muscle activation in a controlled manner can enable the person to walk again.

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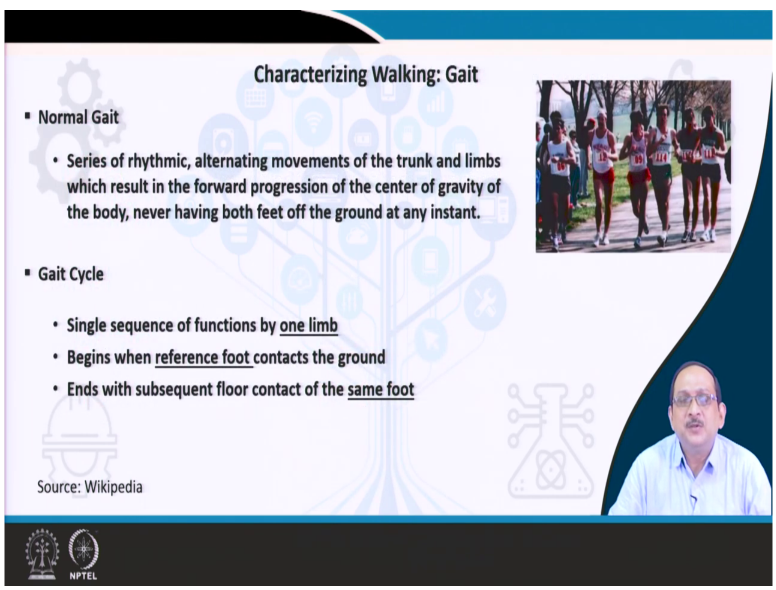

Let us characterize walking and define what normal gait is. Normal gait is a series of rhythmic, alternating movements of the trunk and limbs, which result in forward progression of the center of gravity of the body, never having both feet off the ground at any instant. A gait cycle, on the other hand, is a single sequence of functions of one limb. It begins when the reference foot contacts the ground and ends with subsequent floor contact of the same foot.

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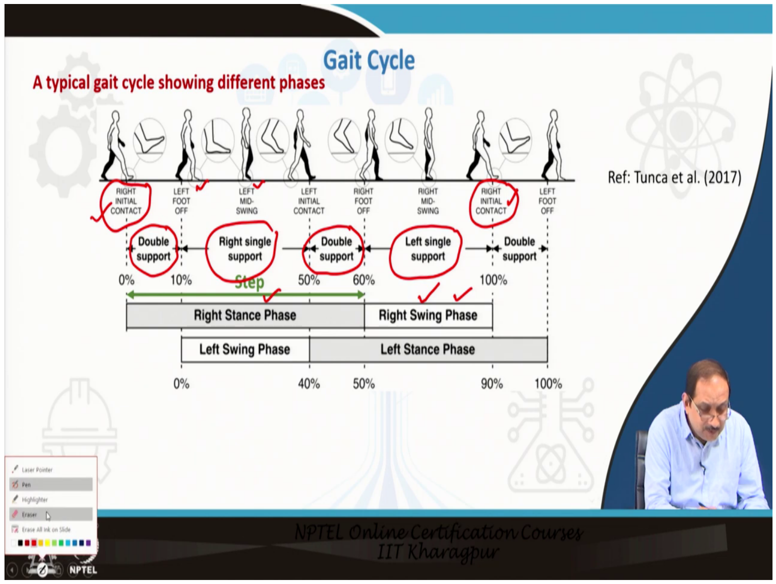

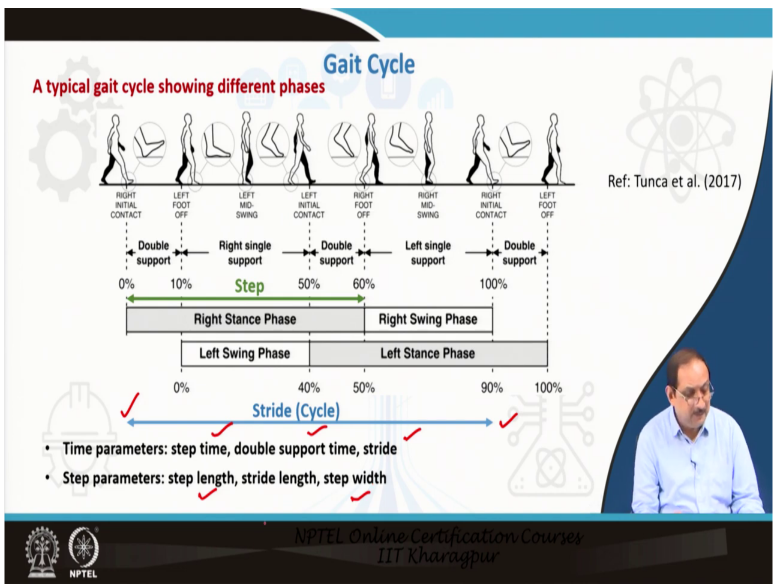

The gait cycle is shown in this slide. I would request all of you to pay attention here because there is a lot of information on this slide and we have to really concentrate on getting an idea of the details of the gait cycle. Broadly, gait cycle can be classified as stance phase and swing phase. So, please pay attention to the right leg because the gait cycle will be explained with respect to the right leg to start with. So, the right leg contacts the ground. So, that is heel strike, where the gait cycle starts.

During this initial phase, the double support phase, both the legs left and right is in contact with the ground. The next phase is the right single support phase, where the right leg is on the ground, but the left leg may be moving. So, the right single support phase is between 10 percent to 50 percent of the gait cycle. It is followed by a double support phase where again both the legs are in contact. Up to 60 percent, this cycle is in the stance phase.

It is followed by the swing phase of the right leg where the right leg is swinging in the air and is not in contact with the ground. During that phase, actually, the left leg is in contact with the ground and the body is supported by the left leg. Finally, we arrive at the position where the right leg again comes in contact with the ground, and this position is the same as the position where we started.

So, the initial and final position of the right leg coming in contact with the ground is the heel strike position and this entire period of movement of the right leg can be defined as the full complete gait cycle. So, we define two important things here.

We define a step which is the start of heel strike to the toe off, which is defined as one full step. So, we hit the ground with the heel and then we take the toe off from the ground that is end of the stance phase, which is defined as one step. The stride is actually defined as the full cycle of the gait. So, one complete cycle is known as starting from this position to the 100 percent, one complete cycle is known as the stride.

Let us discuss the time parameters and the step parameters that have an influence on the gait cycle. The time parameters are step time, double support time, and stride, where step parameters are the step length, stride length and step width.

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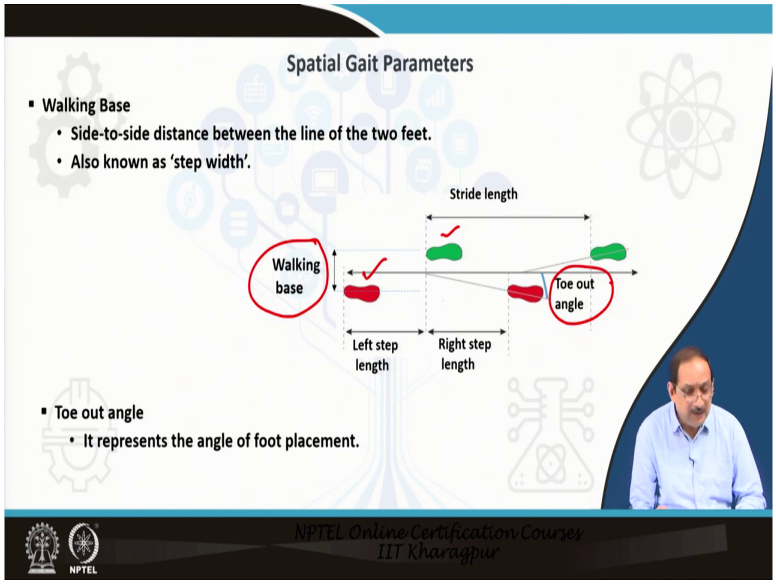

Now, let us define the spatial gait parameters. The distance between corresponding successive points of heel contact of the opposite feet is the step length. So, you have the left step length and the right step length indicated here. In normal gait, the right step length is equal to the left step length. The stride length is the distance of successive points of heel contact of the same foot, which is shown here.

It is actually double the step length in normal gait. The step width is actually the width of the step. So, the side to side distance between the line of two feet is called the step width or the walking base. The toe out angle is the angle of foot placement with the forward direction.

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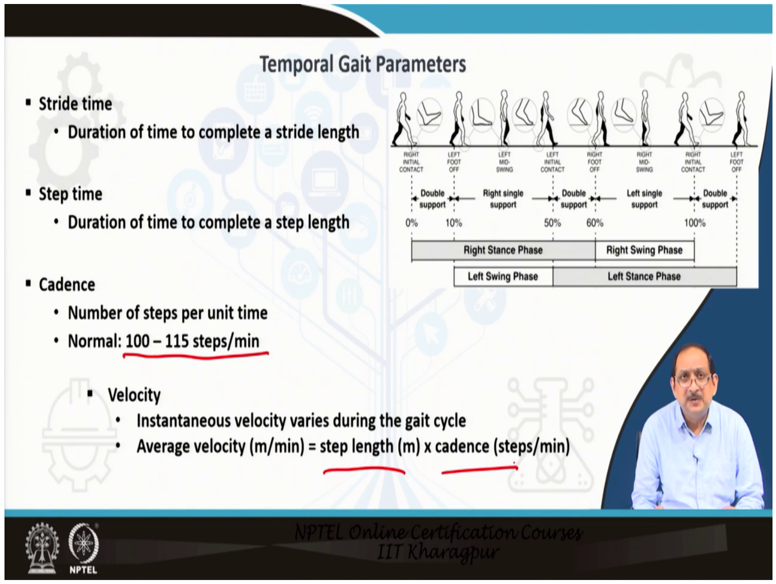

The temporal gait parameters can be defined as stride time, which is actually the duration of time to complete a stride length. The step time is the duration of time to complete a step length. Cadence is the number of steps per unit time. So, normally it is about 100 to 115 steps per minute. Now, the instantaneous velocity varies during the gait cycle and the average velocity can be calculated as step length times the cadence steps per minute.

$$\text{Average velocity } (m/min) = \text{steplength}(m) \times \text{cadence}(steps/min)$$

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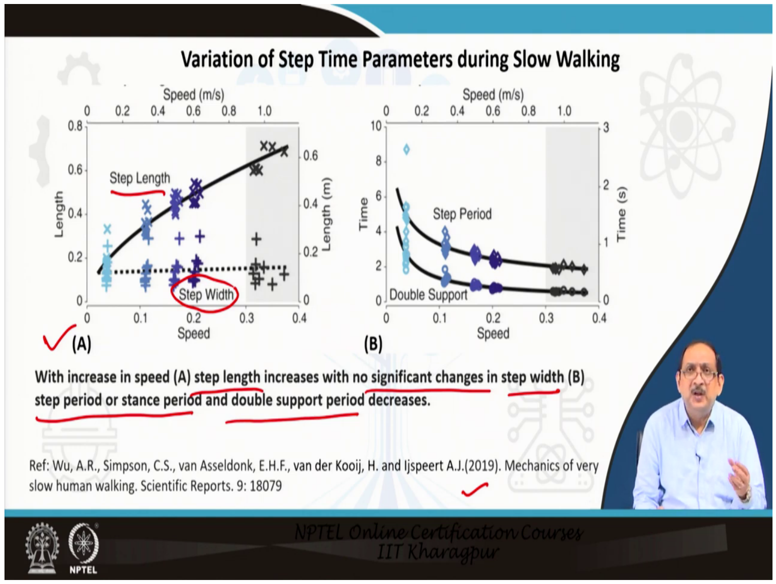

Now, the variation of step time parameters during slow walking has been investigated in detail quite recently and we would like to discuss briefly the effect of increase in speed on step length, step period, double support, and the various parameters that govern the gait cycle. Now, it is clear from figure A that with an increase in speed, the step length increases, but there is hardly any significant change in the step width.

But this conclusion is restricted to slow walking. Now, if I want to walk fast, then obviously, the step width has to reduce. Step width is actually the distance between the two feet. So, if the distance is more, it is, of course, providing more balance to the body, which is seen in elderly people that they walk with larger step width. But if somebody wants to move fast, he has to move with a reduced step width.

The step period or stance period and the double support period both decreases with increase in speed. If actually, if we can imagine if we want to increase the speed of walking, obviously, the time for these double support will have to reduce.

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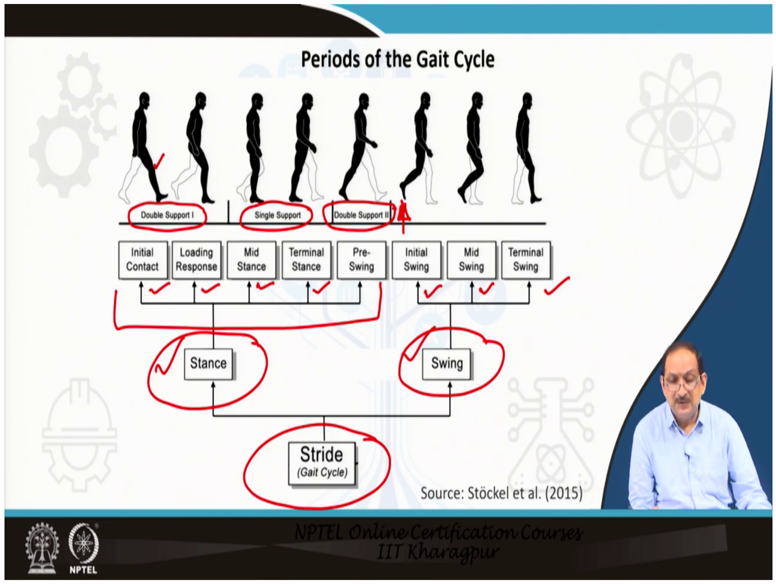

Let us discuss a little bit more in detail the periods of the gait cycle. During the double support first phase, we have the initial contact and then the loading response. In the single support phase, it is the mid stance and the terminal stance, and finally, in the double support 2, it is actually pre swing condition of the right leg, which is marked in black now.

So, the right leg you can see here, the start of the swing phase it is actually taken off the ground and it will be swinging further. So, from initial contact to the pre swing phase, it is collectively known as the stance phase. For the swing phase, the right leg goes through the initial swing, mid swing, and finally, the terminal swing before it is ready to strike the ground, and that is where the gait cycle ends.

So, together with these initial swing, mid swing, and terminal swing, it can be grouped together as the swing phase of the cycle. So, total stride or the gait cycle, as I indicated earlier, can be broadly classified into stance phase and swing phase and further into different phases as discussed in this figure.

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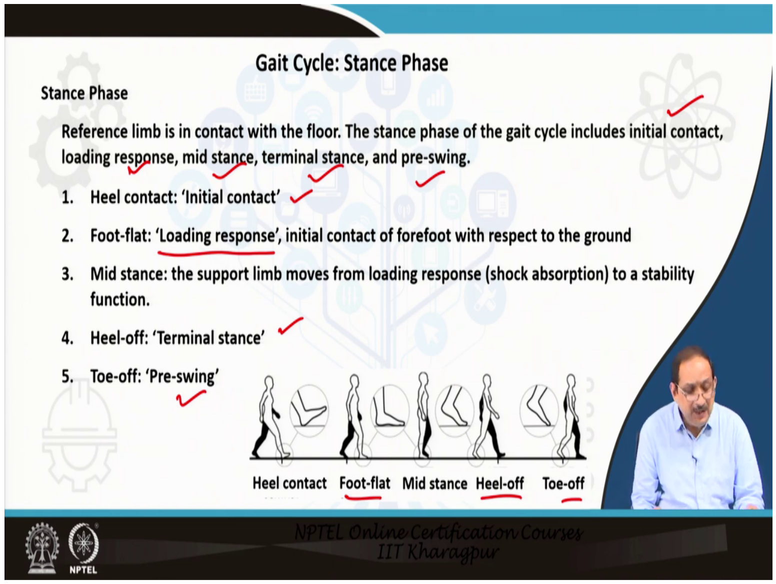

Now, in the stance phase of the gait cycle, the reference limb is in contact with the floor. The stance phase of the gait cycle includes initial contact, loading response, mid stance, terminal stance, and the pre swing. So, the heel strike is the initial contact. The foot flat is the loading response phase, the initial contact of the forefoot with respect to the ground. In the mid stance phase, the support limb moves from a loading response to a stability function. The mid stance is followed by the heel off and, finally, the toe off that completes the stance phase.

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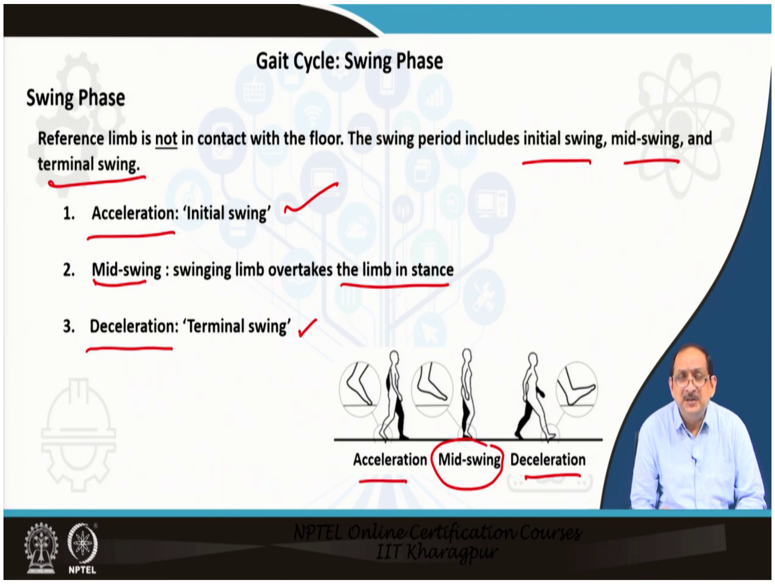

During the swing phase, the reference limb is not in contact with the ground or floor. The swing period includes initial swing, the mid swing, and the terminal swing. So, in the initial swing, the limb is actually accelerating. In the mid swing, the swinging leg overtakes the limb, which is executing stance phase. So, in the mid swing phase, the swinging leg overtakes the limb in the stance phase. Finally it is decelerating and is designated by the terminal swing phase.

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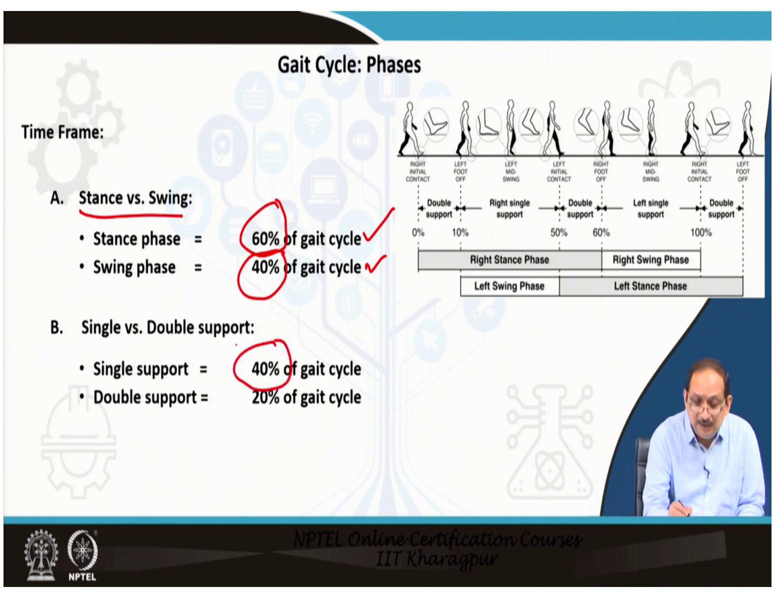

Now the timeframe corresponding to the phases of the gait cycle is presented here. So, the stance versus swing phase: the stance phase, as I indicated earlier, is 60 percent of the gait cycle, whereas the swing phase is 40 percent of the gait cycle. Single versus double support phases: In single support, there is only the single leg coming in i.e., only the single leg is in contact with the ground. So, the single support is about 40 percent of the gait cycle, and the double support is about 20 percent of the gait cycle.

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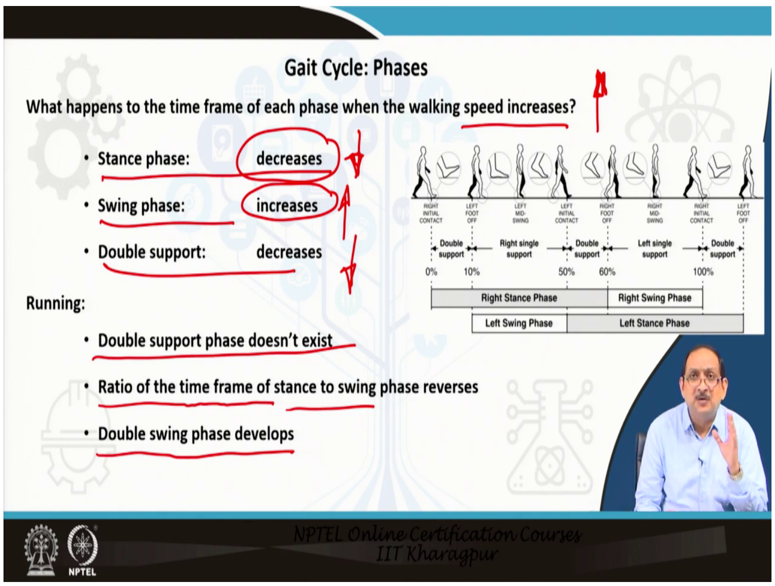

Now, what happens to the timeframe of each phase when the walking speed increases. So, with increase in walking speed, the stance phase decreases whereas the swing phase increases. The double support phase actually has to decrease because the speed is increasing. Running as compared to normal gait is slightly different. The double support phase does not exist in running because you do not need to have the two feet always on the ground.

Therefore, the double support phase is not existing in the case of running. The ratio of timeframe of stance to swing actually reverses and the double swing phase develops in case of running. So, running is different from walking. Walking can be slow walking, fast walking, but running is a completely different event as compared to walking.

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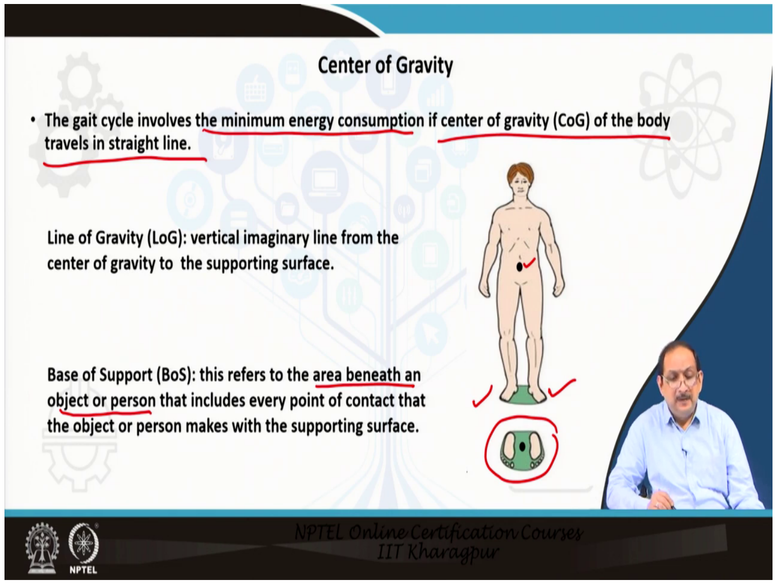

Let us now discuss the influence of the center of gravity. The gait cycle actually involves the minimum energy consumption if the center of gravity of the body travels in a straight line. Now here comes the role of the center of gravity of the body. If the center of gravity travels in a straight line then there will be minimum energy consumption involved in the gait cycle. So, the line of gravity is an imaginary vertical line from the center of gravity to the supporting surface.

The base of support is the area beneath an object or a person that includes every point of contact that the object or person makes with the supporting surface. Preferably it is preferred that the center of gravity remain within the base of support. During bending different types of postures like forward bending or bending backward, the center of gravity of the body actually is located outside sometimes depending on the degree of bending. It is located outside the base of support that is the area defined here.

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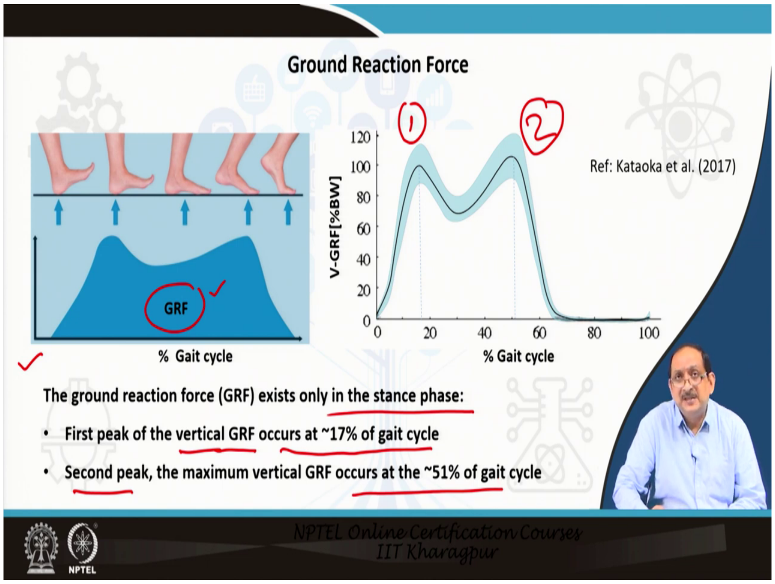

Now, let us come to the ground reaction forces generated during the gait cycle. The figure on the left presents the variation of ground reaction forces during the gait cycle and if we are considering, say the right leg. As long as the right leg is in contact with the ground that is during the stance phase only, we are actually getting a ground reaction force from the ground. So, the ground reaction force exists only in the stance phase.

The first peak of the vertical ground reaction force, the vertical component is the predominant force component and the first peak of the ground reaction force occurs at 17 percent of the gait cycle whereas, the second peak occurs around 51 percent of the gait cycle.

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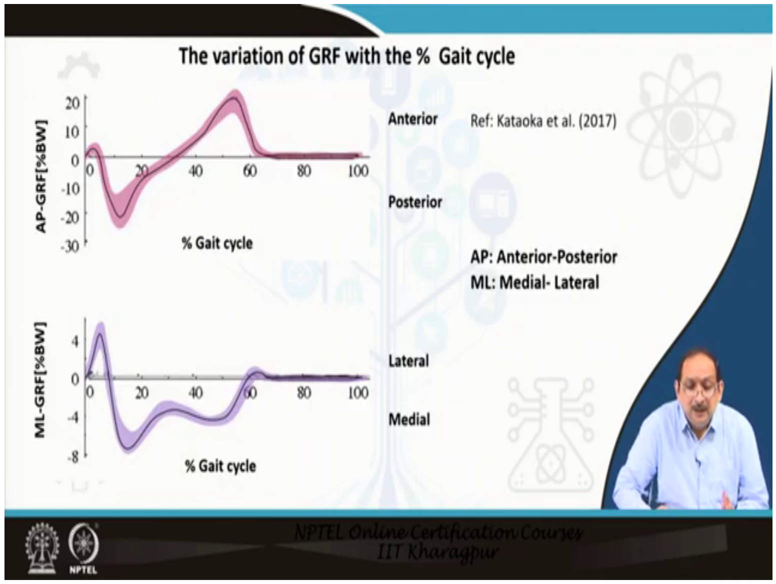

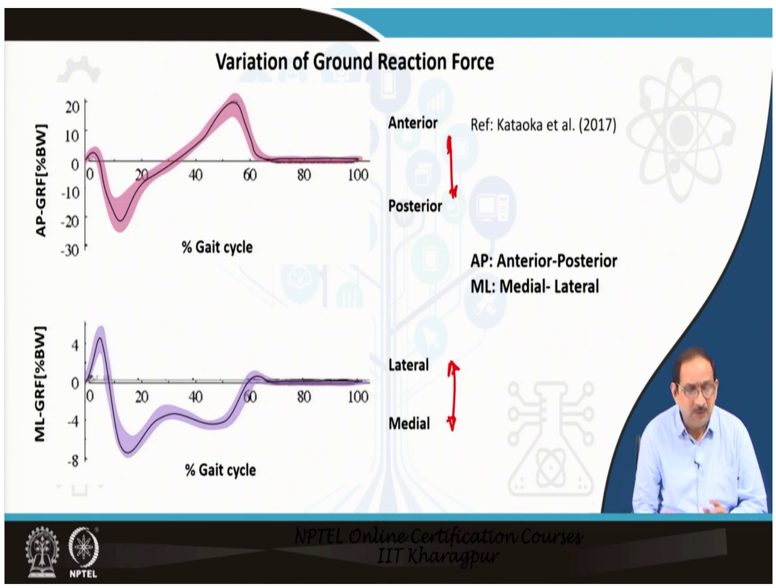

Now, the variation of the ground reaction force with the percentage of gait cycle along anterior-posterior direction and medial-lateral direction is presented here in this slide. However, the variation of forces is minimum as compared to the predominant vertical component of the ground reaction force.

The variation of the ground reaction force along the anterior-posterior direction and the medial-lateral direction is plotted in this slide. As you can see, that the magnitude of the force is far less as compared to the predominant vertical component of the ground reaction force.

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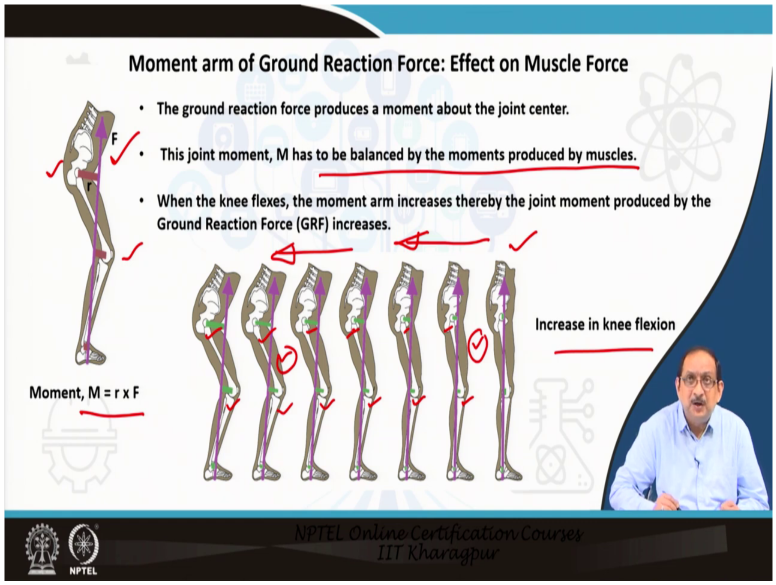

Now, let us discuss the moment arm of ground reaction force and its effect on the muscle force. So, we had discussed this earlier, but I will be brief in discussing the contribution of ground reaction forces in generating the muscle force for a particular posture. Now, the ground reaction force actually produces a moment about the joint center. So, here it is the direction of the ground reaction force, as indicated by F, and the moment of this ground reaction force about, say the hip joint or the knee joint can be calculated as a cross product of the moment arm and the ground reaction force vector.

Now, this joint moment actually has to be balanced by the counter moment of the muscle, as we had discussed in problems earlier in module two. Now, let us first look at the rightmost figure, which is a standing position. As you can see, when a person is standing, the ground reaction force is passing through the joint centers, the knee joint center and the hip joint center. As we go on increasing the flexion angle, we can observe that the moment arm is increasing.

This means that the net moment due to the ground reaction force is increasing, which needs to be counterbalanced by, say, the quadricep muscle forces, which will come into play to counterbalance the ground reaction force moments for particular knee flexion.

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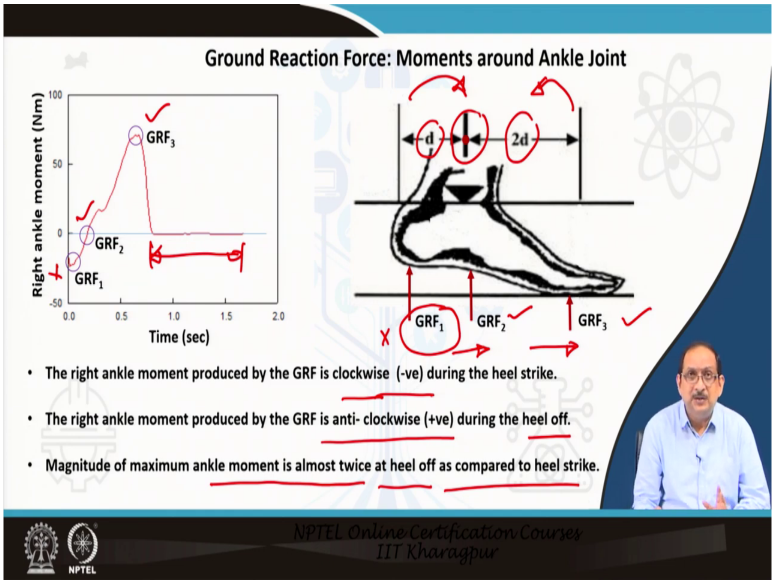

This can also be explained when we consider moments around the ankle joint. Let us consider the ground reaction force first position that is at heel strike. So, when it is striking the ground, the first ground reaction force is located along the line of action towards the left of the ankle joint center, as indicated in the figure. So, this actually produces a clockwise moment about the ankle joint center. As we move towards more foot flat, the ground reaction force actually passes through the ankle joint thereby reducing the distance d and the moment.

So, this position is about the ground reaction force 2; the moments is about 0. Whereas, for ground reaction force 1 position and since it is producing a clockwise moment, it is considered to be starting from a negative value of the ankle moment. As we move further towards the right of the ankle joint, the third position of the ground reaction force actually produces a counter-clockwise moment, thereby producing a positive ground reaction force at the position toe off almost at the end of the stance face.

Thereafter, you can see the ground reaction forces abruptly drops down to 0 during this phase, which means this is during the swing phase of the gait cycle. So, the right ankle moment produced by the ground reaction force is clockwise and that is negative during heel strike. The right ankle moment produced by the ground reaction force is positive during heel off. The magnitude of maximum ankle moment is almost twice at heel off as compared to the heel strike if we consider the distance d and 2d as indicated in the figure.

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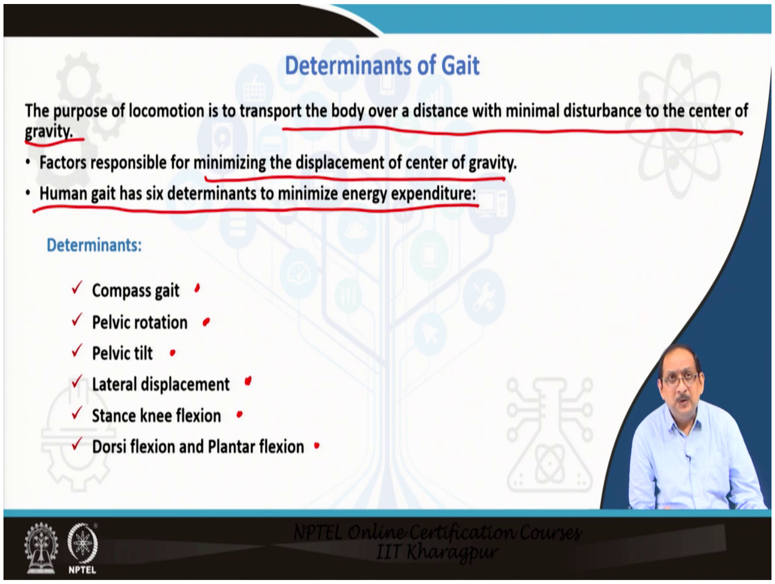

Now, the determinants of the gait cycle are the factors responsible for minimizing the displacement of the center of gravity. The purpose of the whole locomotion is to transport the body over a distance with minimal disturbance to the center of gravity.

Now, human gait has six determinants to minimize this energy expenditure. These are compass gait, pelvic rotation, pelvic tilt, lateral displacement, and stance knee flexion and finally, dorsi flexion and plantar flexion. I will quickly show you these six determinants.

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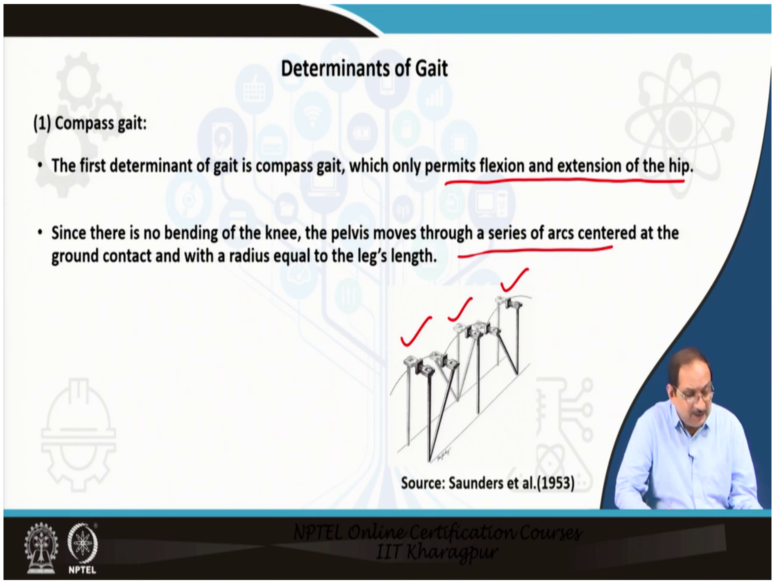

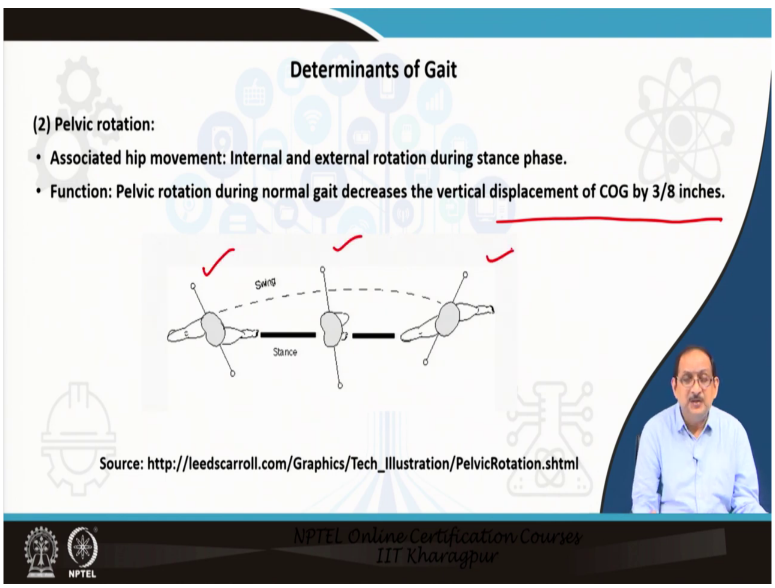

The compass gait actually permits only flexion and extension of the hip. Since there is no bending of the knee, the knee is more straight, the pelvis actually moves through a series of arches as indicated in the figure, centered at the ground contact and with the radius equal to the legs length.

The pelvic rotation is associated with the hip movement, internal and external rotation during the stance phase. The pelvic rotation during normal gait decreases the vertical displacement of the center of gravity by around 3/8 inches approximately. So the rotation of the pelvis is indicated in this figure.

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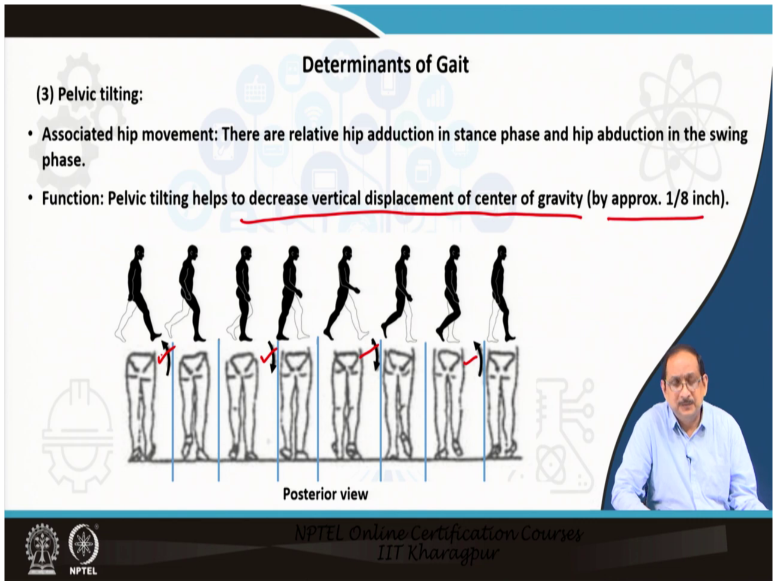

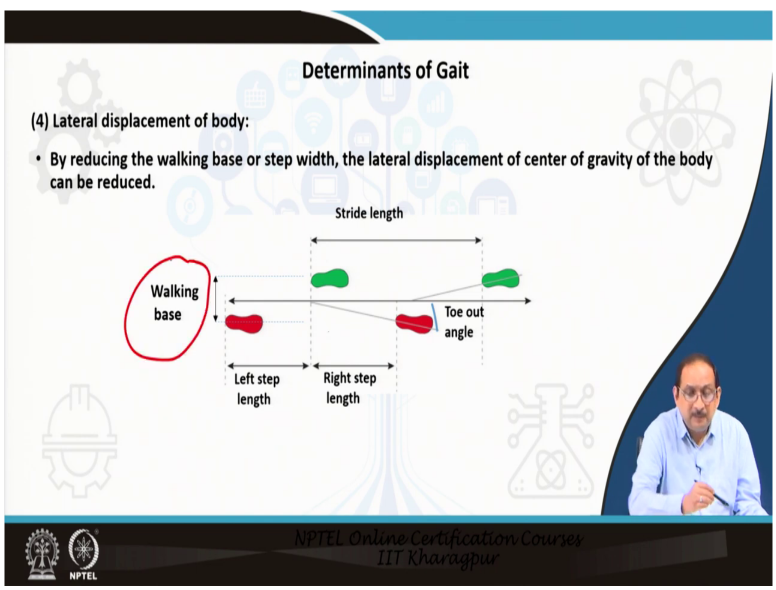

Pelvic tilting is associated with another hip movement. The pelvic tilting helps to decrease the vertical displacement of the center of gravity by approximately one-eighth inch. So, we can see that during the walking cycle, there is if we look from the posterior side, there is tilting of the pelvis at different positions which is arising due to hip abduction. The lateral displacement of the body can be explained in this figure. By reducing the walking base or step width, the lateral displacement of center of gravity of the body can be reduced.

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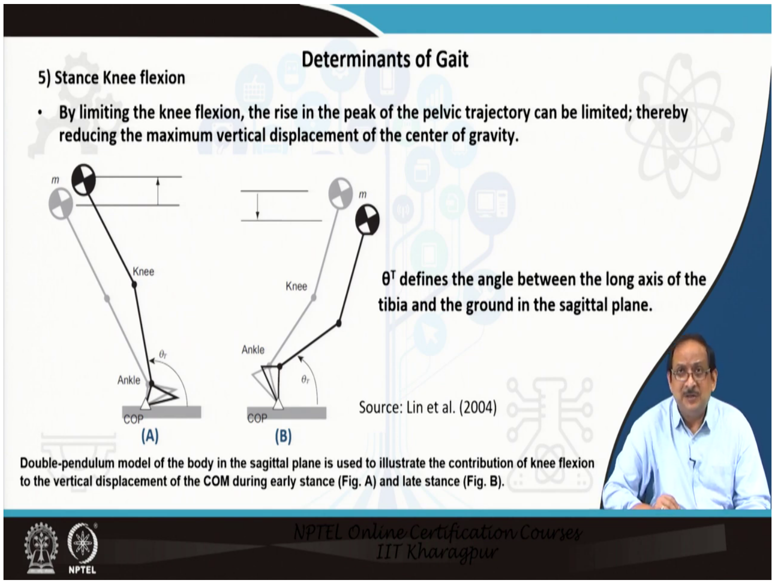

The fifth determinant is the stance knee flexion. Now, by limiting the knee flexion, the rise in the peak of the pelvic trajectory can be limited, thereby reducing the vertical displacement of the center of gravity, as shown in the figure. Now, a double pendulum model of the body in the sagittal plane is used to illustrate the contribution of knee flexion to the vertical displacement of the center of mass or center of gravity during early stance as represented by figure A and during late stance as represented by figure B.

Now, in this figure, the foot is hinged to the ground at the center of pressure and the mass of the whole body m as indicated in the figure, is assumed to be lumped at the hip joint. The body moves from the initial position as indicated by the gray stick in the figure to the final position indicated by the black stick in the figure when the flexion angle of the knee is perturbed, keeping all the remaining joint angles, as well as the location of the COP, held fixed.

This is applicable to the other figure that is figure B. The perturbation of the knee flexion angle has been exaggerated for clarity. Now, in this figure, the θ^T defines the angle between the long axis of the tibia and the ground in the sagittal plane.

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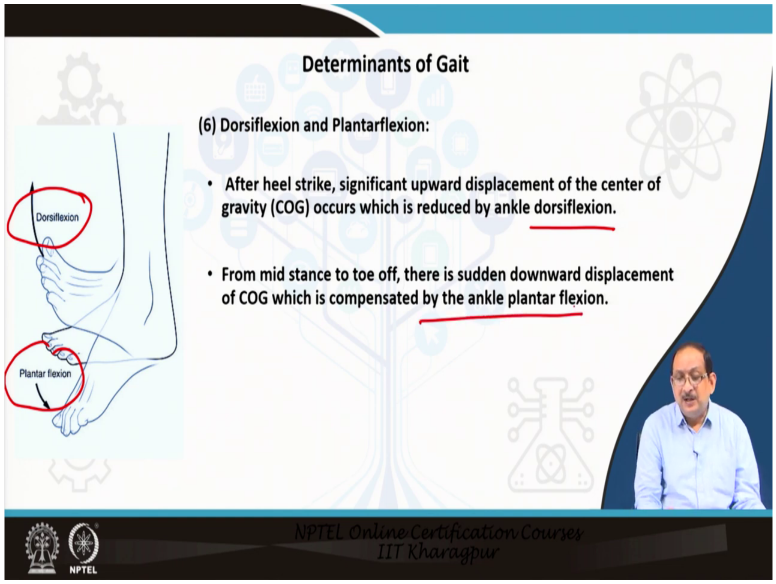

The final and the sixth determinant is the dorsiflexion and plantarflexion. After heel strike significant upward displacement of the center of gravity occurs, which is reduced by ankle dorsiflexion as indicated here in the figure. From mid stance to toe off, there is sudden downward displacement of this center of gravity, which is compensated by the ankle plantar flexion.

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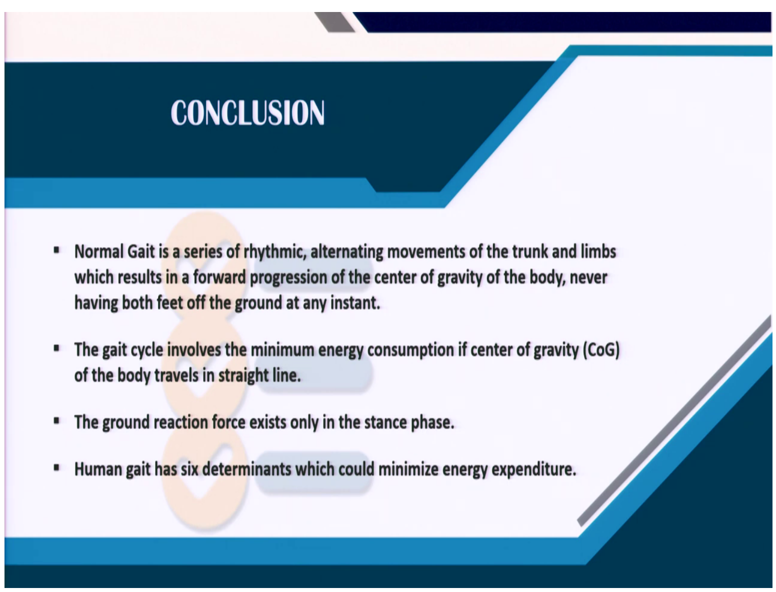

Let us come to the conclusions of this lecture. Normal gait is a series of rhythmic, alternating movements of the trunk and limbs, which result in a forward progression of the center of gravity of the body, never having both feet on the ground at any instant. The gait cycle involves the minimum energy consumption if the center of gravity of the body travels in a straight line. The ground reaction force exists only in the stance phase. The human gait has six determinants, which could minimize energy expenditure.

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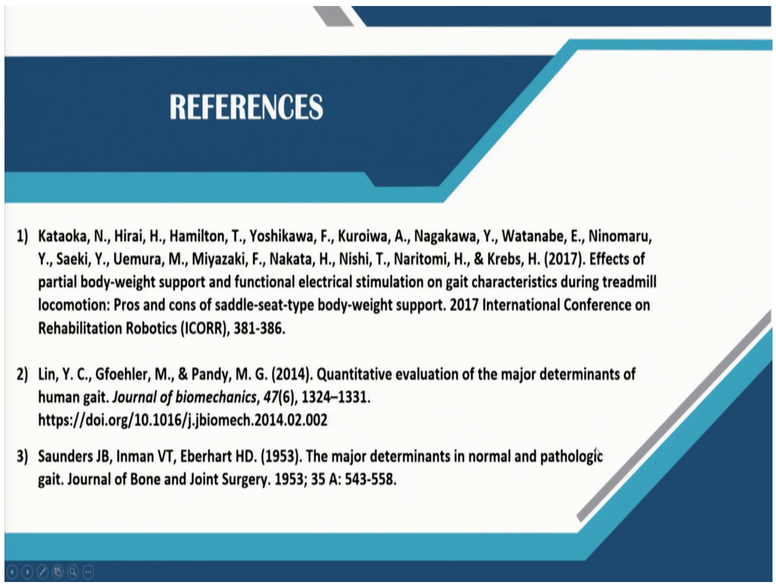

The list of references are listed here in two slides. And thank you for listening.