Biomechanics of Joints and Orthopaedic Implants
Professor Sanjay Gupta
Department of Mechanical Engineering
Indian Institute of Technology Kharagpur
Lecture 8
Biomechanics of the Hip Joint

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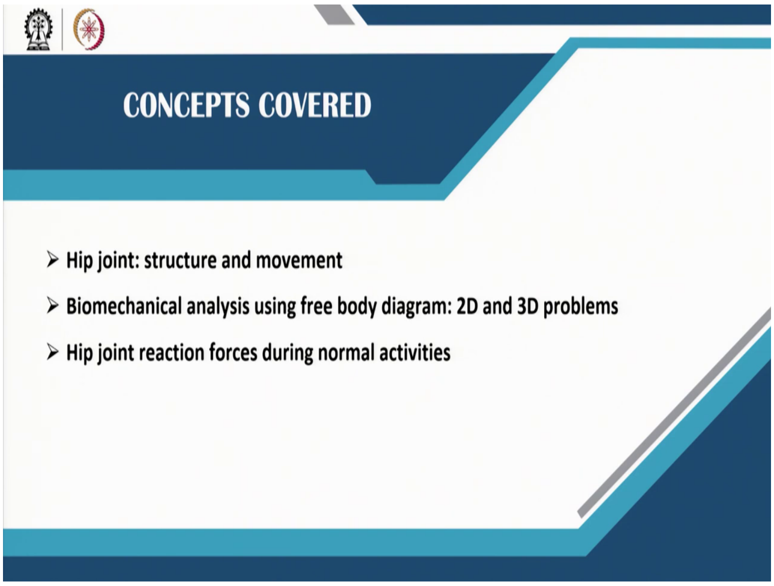

Good morning everybody, welcome to the first lecture of the second module on biomechanics of the hip joint. In this lecture, we will be discussing about the structure and movement of the hip joint in brief. Then we will be discussing about the biomechanical analysis of the hip joint using free-body diagrams based on 2D and 3D problems. And the third part of the lecture, we will cover the hip joint reaction forces during normal activities.

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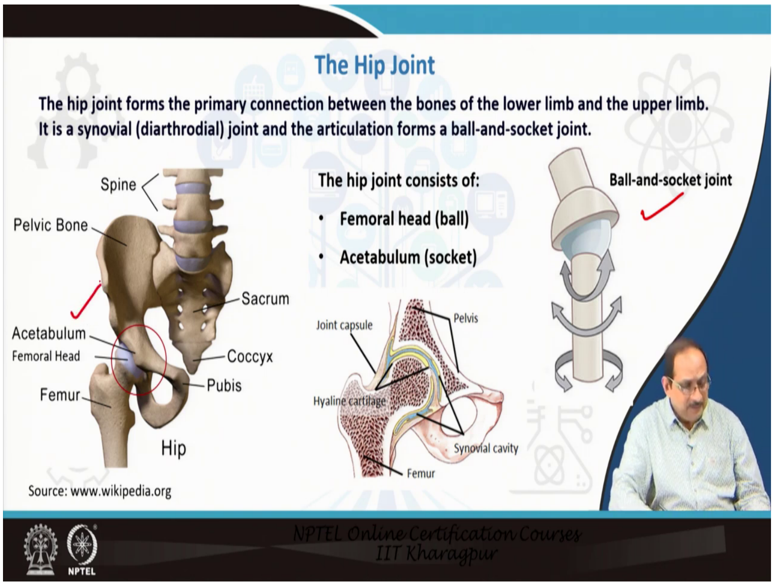

The hip joint forms the primary connection between the bones of the lower limb and the upper limb. It is a synovial joint, and the articulation forms a ball and the socket joint. The hip joint consists of the femoral head, which is the ball, and the acetabulum, which is the socket, as indicated here in this diagram.

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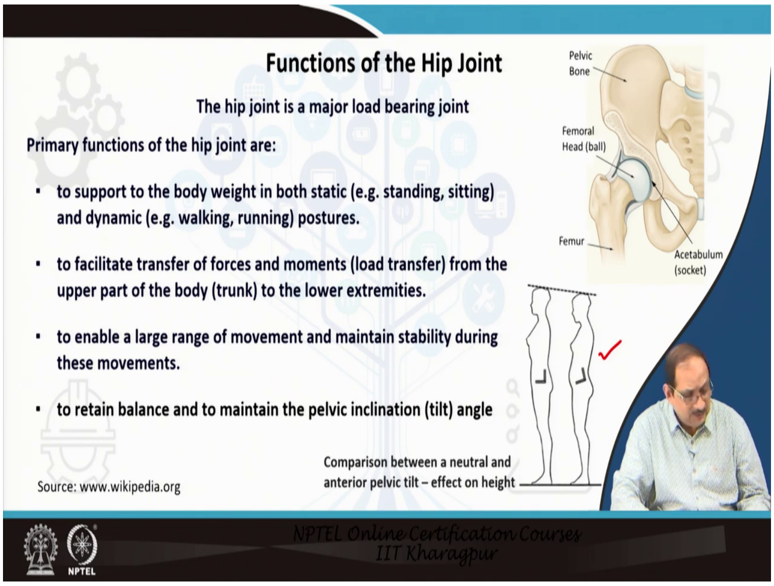

The hip joint is a major load bearing joints. The primary functions of the hip joint are to support the body weight in both static and dynamic posture, in static standing and sitting, in dynamic walking, running and other activities, to facilitate transfer of forces and moments, which is also called load transfer from the upper part of the body to the lower extremities.

The third function is to enable a large range of movement and maintain stability during these movements. The fourth point is to retain balance and to maintain the pelvic inclination tilt, as indicated here in the diagram. So, in this diagram, the effect of the anterior pelvic tilt on the height of a subject is indicated; with increase in pelvic tilt, we see that there is a decrease in the height of this object.

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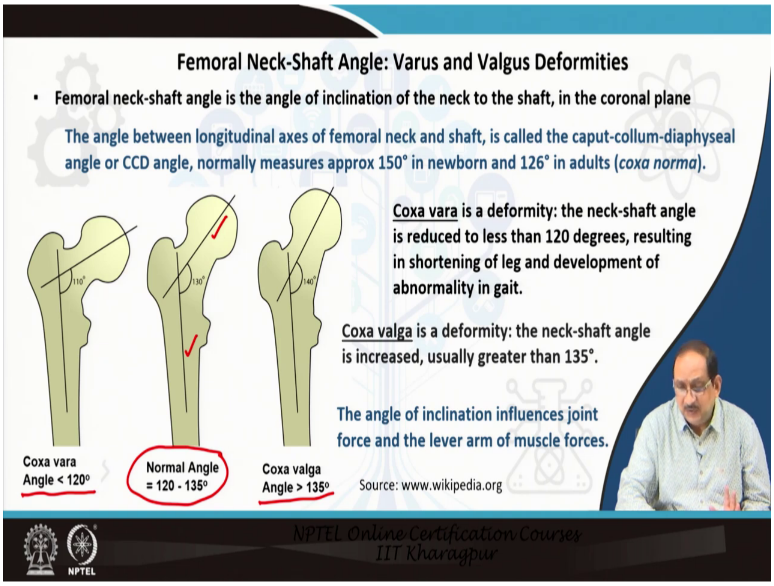

Now, there are few angles in the hip joint anatomy that needs to be defined. The foremost is the femoral neck shaft angle, which is basically required to measure the varus and valgus deformities. The femoral neck shaft angle is the angle of inclination of the neck to the shaft in the coronal plane. So, we define the angle as the angle between the longitudinal axis of the femur neck and the shaft.

So, this is the two axis, it is also called a CCD angle and normally measures 150 degrees in newborn and about 126 degrees in adults. So, the normal range is indicated here. The varus is a deformity, here the neck shaft angle is reduced to less than 120 degrees as indicated here in the figure, resulting in shortening of leg and development of abnormality in gait. The varus, on the other hand, is the case where the neck shaft angle is increased which is usually greater than 135 degrees. The angle of inclination influences joint forces and the lever arm of the muscle forces.

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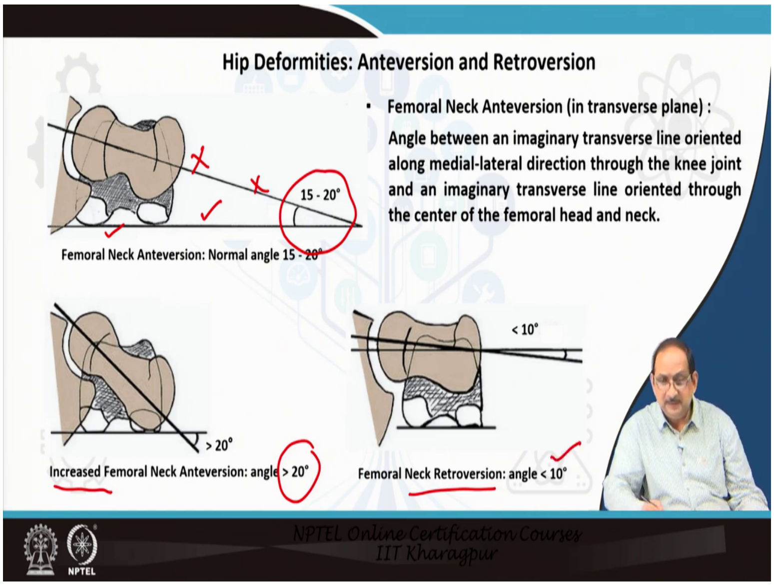

Let us, come to another angle angular measurement that is the femoral neck anteversion and retroversion, we define the femoral neck anteversion angle in the transverse plane and it is the angle between the imaginary transverse line oriented along the medial lateral direction through the knee joint as you can see here, and then imaginary transverse line oriented through the centre of the femoral neck, head and neck.

So, the angle between these two imaginary lines is the femoral neck anteversion angle. In normal case, it is about 15 to 20 degrees, the normal femoral neck anteversion angle and increased femoral neck anteversion angle is usually greater than 20 degrees, whereas the angle which is less than 10 degrees is usually called the neck retroversion angle and it is less than 10 degrees.

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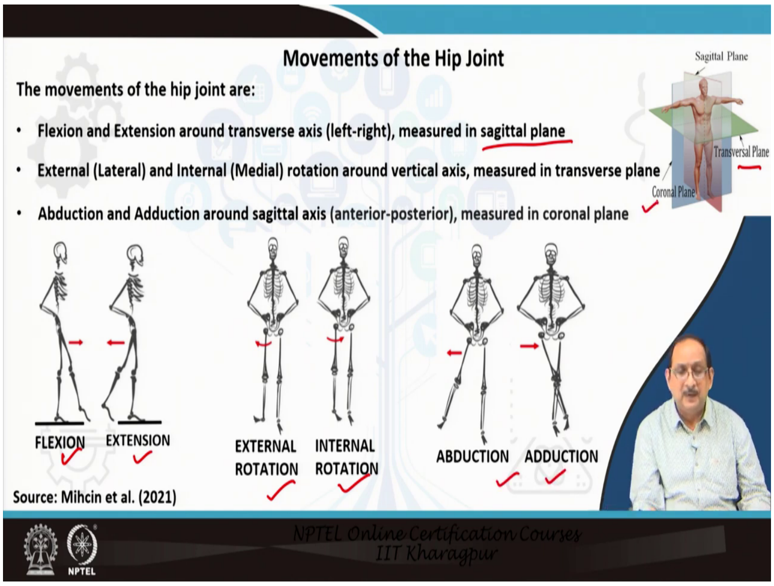

Let us come to the movements of the hip joint. The hip, the movements are flexion and extension as shown here, it is around the transverse axis, left to right, and measured in the sagittal plane. Then, we have the external and internal rotation, also known as lateral or medial rotation around the vertical axis, and it is measured in the transverse plane as indicated here. The abduction and adduction movements are around the sagittal axis that is anterior-posterior and measured in the coronal plane.

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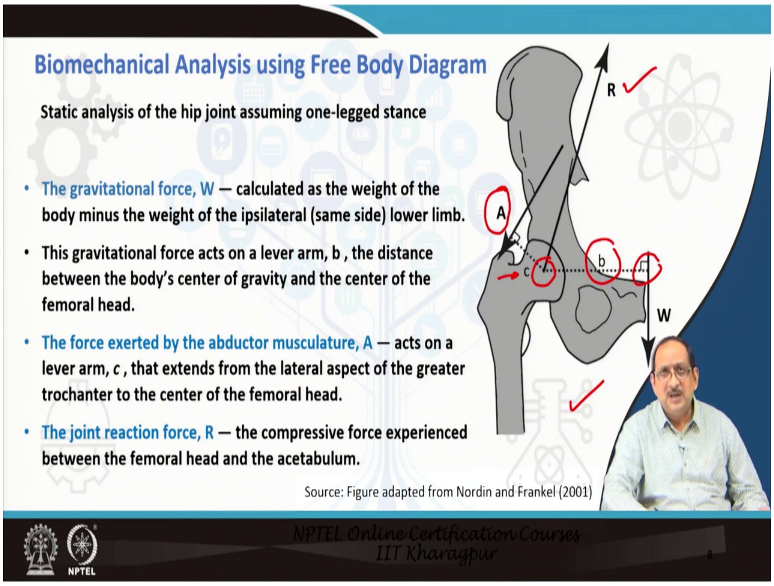

Now, let us move into the biomechanical analysis of the hip joint using free body diagram; this is the second main topic of the lecture. So, here we will be analysing the forces acting on the hip joint using free body diagrams, and this method has have traditionally been performed assuming a one legged stance under static conditions and evaluating forces that occur in the frontal or coronal plane.

While this scenario is somewhat artificial, it presents a powerful illustration of the impact, which even subtle changes in body position or hip anatomy can have on the hip biomechanics. So, referring to this figure, we define certain forces. The first one is the gravitational force W, calculated as the weight of the body minus the weight of the ipsilateral that is located on the same side of the lower limb.

This gravitational force acts on a lever arm b, as indicated here in the figure, which is the distance between the body's center of gravity and the center of the femoral head. The force exerted by the group of abductor muscle A is indicated here, it acts on a lever arm c that extends from the lateral aspect of the greater trochanter to the center of the femoral head. The joint reaction force is the compressive force experienced between the femoral head and the acetabulum and this actually passes to the center of the femoral head.

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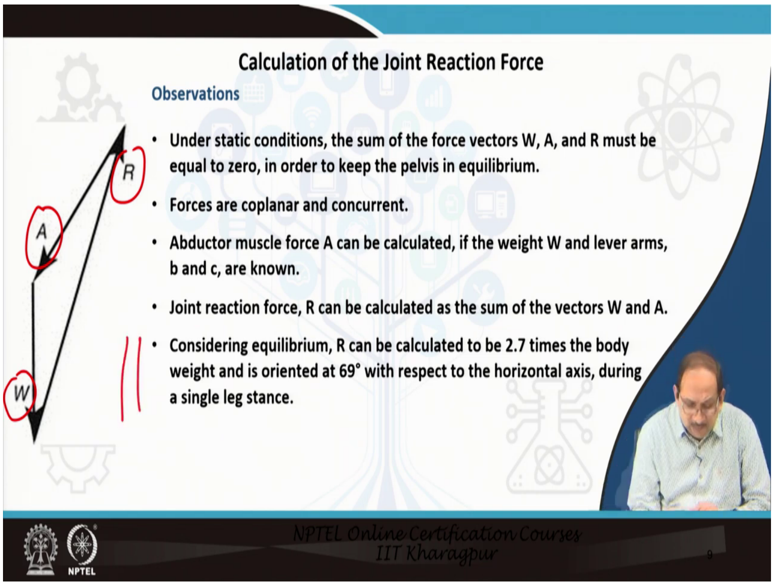

Now, let us move into the calculations of the joint reaction force and let me state few observations on it. Under static conditions, the sum of the force vectors W, A and R must be equal to zero in order to keep the pelvis in equilibrium. The forces are coplanar and concurrent. The abductor muscle force A can be calculated, if the weight W and the lever arms b and c are known. The joint reaction force can also be calculated as the sum of the vectors W and A. Considering equilibrium, the joint reaction force R can be calculated to be 2.7 times the body weight and is oriented at 69 degrees with respect to the horizontal axis during a single-legged stance, we will be actually calculating this in the subsequent slides.

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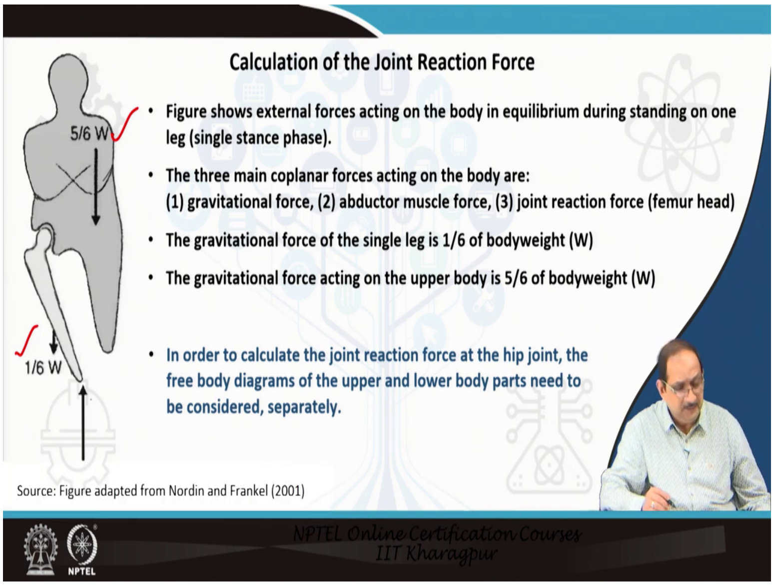

Now, let us move to the details of the calculation. We can see the figure on the left that shows the external forces acting on the body in equilibrium during standing on one leg, which is single stance phase. There are three main coplanar forces acting on the body: the gravitational force, the abductor muscle force, and the joint reaction force.

The gravitational force of the single leg is 1 /6 times or one-sixth of the body weight; the gravitational force acting on the upper part of the body is 5/6 times the body weight. In order to calculate the joint reaction forces at the hip joint, the free-body diagrams of the upper and lower body parts need to be considered separately.

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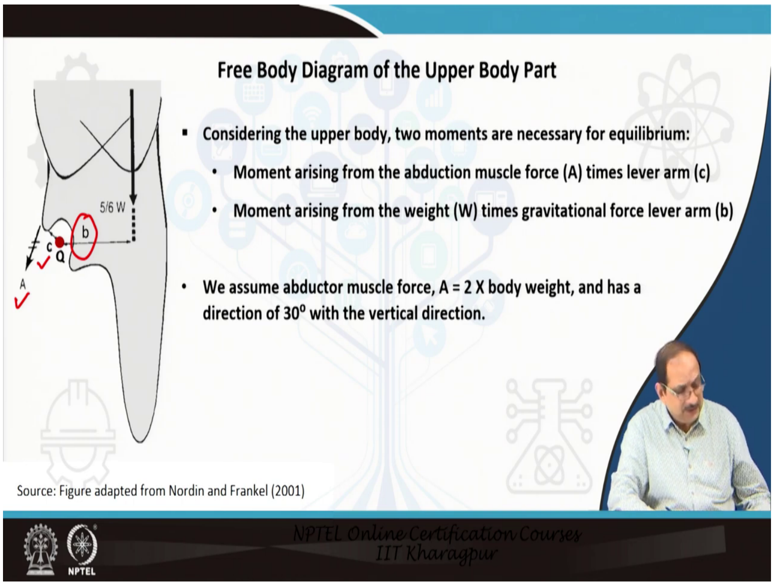

Let us first consider the free body diagram of the upper part of the body. Considering the upper part of the body, two moments are necessary for equilibrium. The first moment is arising from, due to the abductor muscle force A times the lever arm c, as indicated here. The second force is arising from the weight W times the gravitational force lever arm indicated by b. We assume that the abductor muscle force A, which is taken as 2 times bodyweight, acts in a direction of 30 degrees with the vertical direction.

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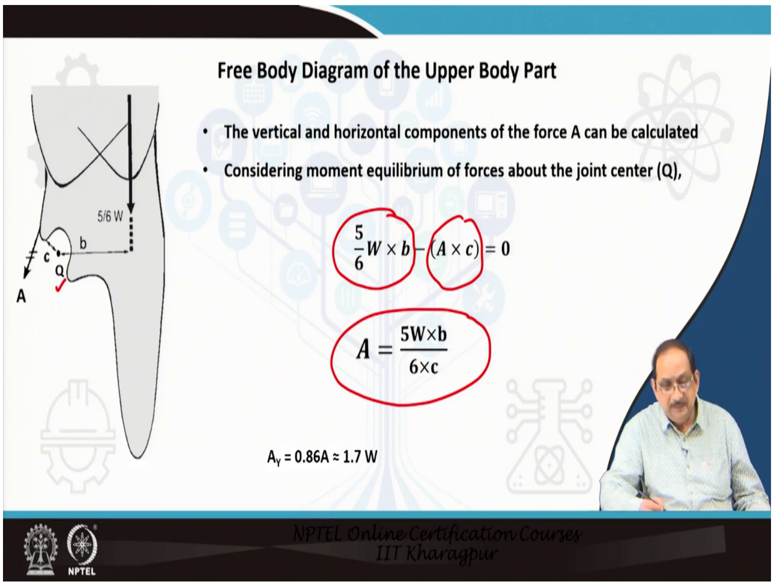

Now, considering the free body diagram of the upper part the body, the vertical and horizontal components of the force A can be calculated. Then considering the moment equilibrium of forces about the joint center Q, we can actually write the two moments: one due to the gravitational force, the other due to the abductor muscle force. So, A, abductor muscle force can be calculated in terms of body weight and the dimensions of the lever arm b and c.

$$\frac{5}{6}W\times b - (A\times c) = 0$$

$$A = \frac{5W\times b}{6\times c}$$

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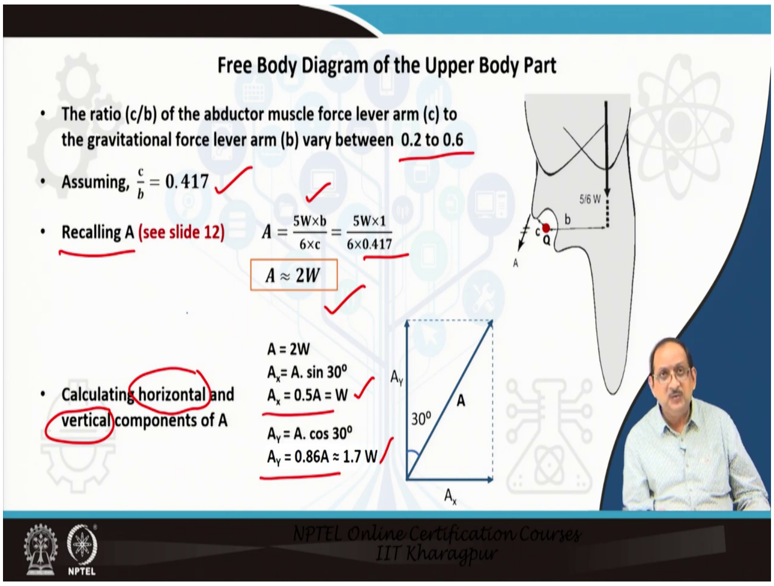

Now, considering still the upper part of the body, the ratio c/b, actually varies between 0.2 to 0.6. So, it is the ratio of the abductor muscle force lever arm to the gravitational force lever arm. Now, in this calculation, we will be assuming the c/b ratio as 0.417 and recalling the A which is given by 5W/6 x b/c, we can substitute the value of the ratio c/b here and we can calculate A, approximately equal to 2W. Once we have the abductor muscle force, we can calculate the horizontal as well as the vertical components of A, by resolving the force along X and Y direction. So, we obtain A_x and we obtain A_y, which we will use for the subsequent calculations.

$$A = \frac{5W\times b}{6\times c} = \frac{5W\times 1}{6\times 0.417}$$

$$A \approx 2W$$

Calculating horizontal and vertical components of A,

$$A = 2W$$

$$A_x = A.\ \sin 30^0$$

$$A_x = 0.5A = W$$

$$A_{Y} = A.\ \cos 30^0$$

$$A_Y = 0.8A = 1.7W$$

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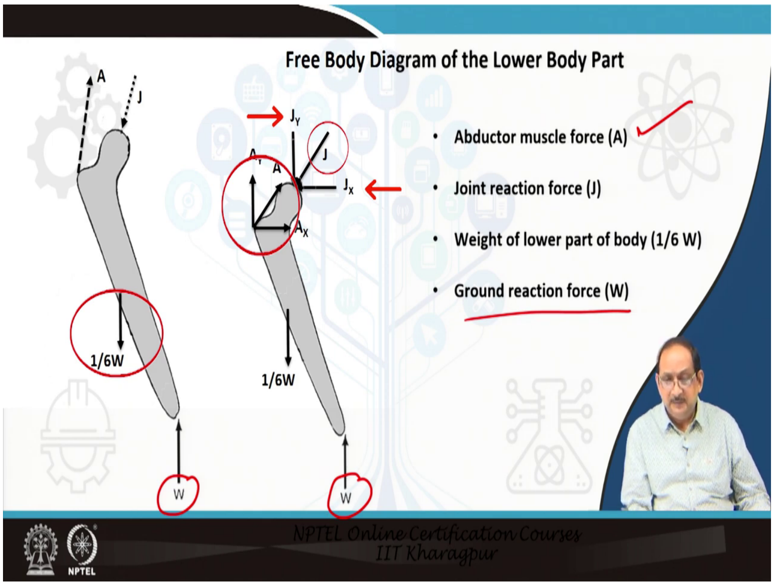

Now, let us go to the free body diagram of the lower part of the body. In this free body diagram, the forces that are taking part are the abductor muscle force which is given by here; the joint reaction force J, which can have two components along X and Y direction; the weight of the lower part of the body which is 1/6th of W and the ground reaction force which is given by W. The ground reaction force actually is the reactive force which is equal to the weight of the body.

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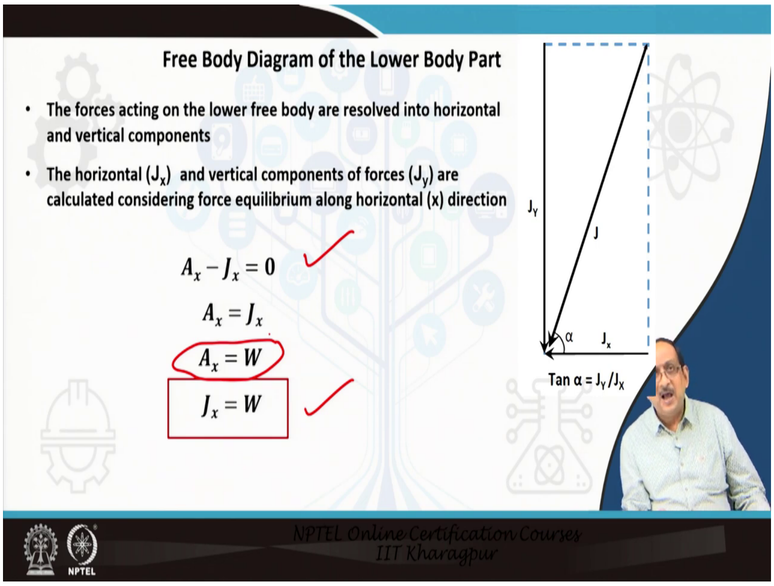

Considering the free body diagram of the lower part of the body, the forces acting on the lower free body diagram can be resolved along the horizontal and vertical directions. And thereafter, we can consider the force equilibrium along the X direction, and we can easily write down the mathematical relationship between the abductor muscle force along X direction and the joint reaction force along X direction. So, we get basically Jx equal to W, because Ax has been earlier calculated as W.

$$A_x - J_x = 0$$

$$A_x = J_x$$

$$A_x = W$$

$$J_x = W$$

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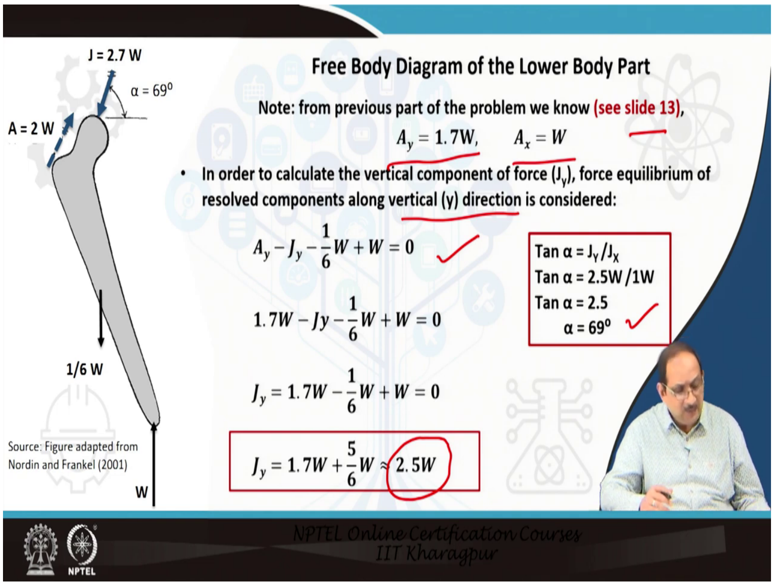

We further note that in the previous part of the problem, we have found out Ay and Ax, from slide number 13. Now, in order to calculate the vertical components of the force along the Y direction, the force equilibrium of resolve components around the vertical direction is considered. So we can write down the equation resolving the forces along the Y direction, and then we can easily find out the value of Jy, the vertical component of the joint reaction force as 2.5W.

Once we have found out Jx and Jy, we can find the inclination of the joint reaction force as 69 degrees, using the trigonometrical relation. So, we stated earlier that the joint reaction force of about 2.7 times the bodyweight will be acting which can be calculated to be acting along an inclination of 69 degrees and with this calculation, we can actually find the values which was stated earlier in the problem.

$$Ay - Jy - \frac{1}{6}W + W = 0$$

$$1.7W - Jy - \frac{1}{6}W + W = 0$$

$$Jy = 1.7W - \frac{1}{6}W + W = 0$$

$$Jy = 1.7W + \frac{5}{6}W \approx 2.5W$$

$$\text{Tan } \alpha = J_Y / J_X$$

$$\text{Tan } \alpha = 2.5W / 1W$$

$$\text{Tan } \alpha = 2.5$$

$$\alpha = 69^0$$

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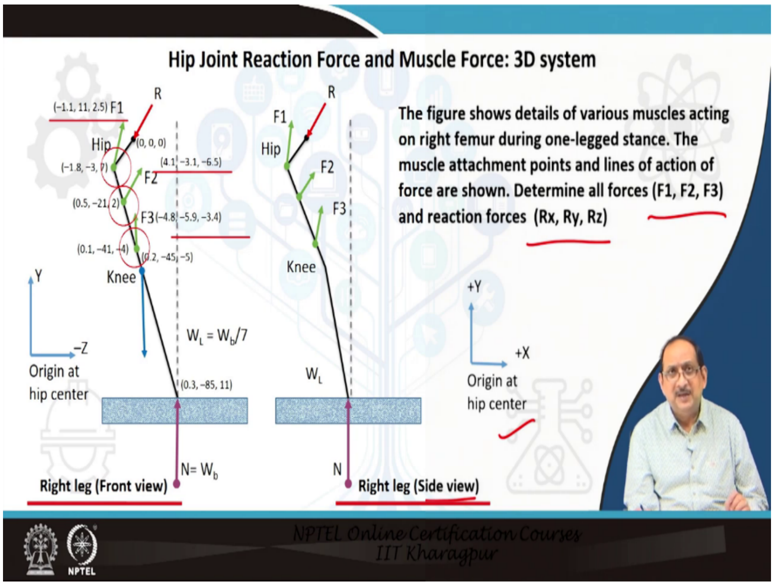

Let us now consider a 3D system. Now, we will consider the hip joint reaction force and muscle forces considering a 3D system. Earlier we have used a two dimensional system. Now, it is a 3D system, and we will be using the vector mechanics method to find out the forces muscle forces F1, F2, F3, and the joint reaction forces Rx, Ry, Rz.

So, the figure here shows the details of the muscle acting on the right femur during a one legged stance. The muscle attachment points F1, F2, F3 say, for instance, are marked here in two views; one is a front view, the other is a side view, and the lines of action of the forces are shown. So a point on the line of action of the force is shown so that we can actually calculate the unit vectors along the muscle force direction. The origin and the orientation of the coordinate system is indicated, the origin is at the hip at the center of the femoral head.

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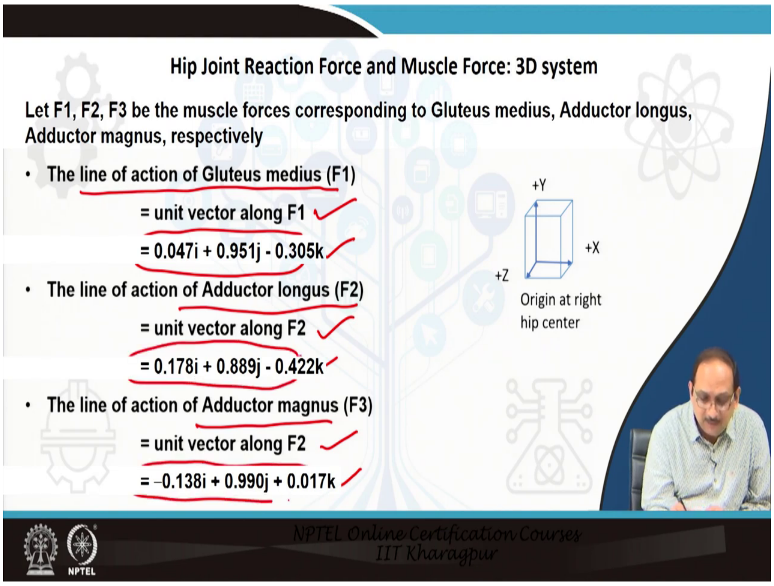

Now, considering the given figure and the coordinates of the muscle attachment and the line of action, we can calculate the line of action of gluteus medius, adductor longus, and adductor magnus. So, we first need to calculate the unit vector acting along F1, F2, and F3, considering the position vector of the coordinates. So, that can be easily done, and we can find the unit vectors as indicated in the figure. So, this is F1 unit vector, this is F2 unit vector and this is F3 unit vector as presented in the equations:

The line of action of Gluteus medius (F1)

= unit vector along F1

= 0.047i + 0.95j - 0.30k

The line of action of Adductor Longus (F2)

= unit vector along F2

= 0.17i + 0.88j - 0.42k

The line of action of Adductor magnus (F3)

= unit vector along F2

= -0.138i + 0.99j + 0.017k

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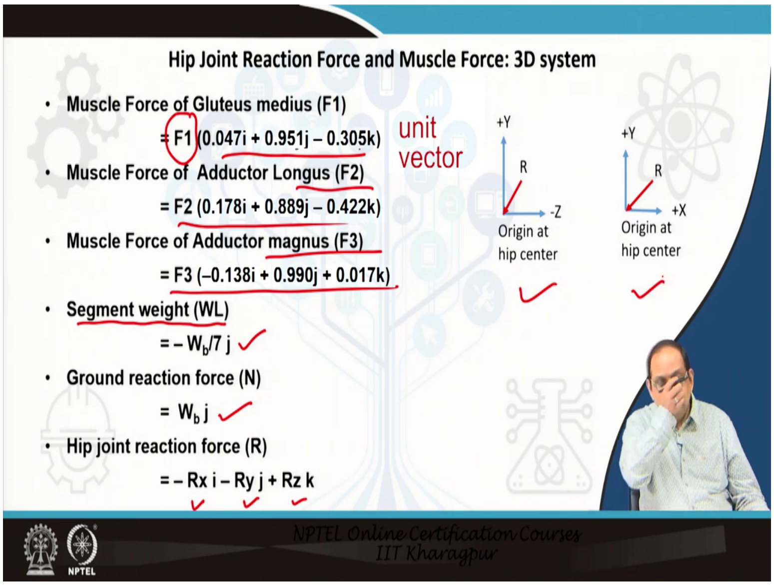

Now, we actually write the force vector, we just include the magnitude, say F1 and the unit vector here. So F1 multiplied by the unit vector gives the muscle force vector of F1, similarly we get for F2 and F3. Now, there are other forces that need to be considered, the segmental weight is acting downwards, so it is – Wb/7j.

The ground reaction force is the reactive force of the whole body weight, so it is purely the weight of the body multiplied by j. The hip joint reaction force, we will write it in the form of a generalized force vector that is Rx i, Ry j, Rz k depending on the definition of the coordinate system as indicated here.

Muscle Force of Gluteus medius (F1)

$$= F1\ (0.047i + 0.95j - 0.30k)$$

Muscle Force of Adductor Longus (F2)

$$= F2\ (0.17i + 0.88j - 0.42k)$$

Muscle Force of Adductor magnus (F3)

$$= F3\ (-0.138i + 0.99j + 0.017k)$$

Segment weight (WL)

$$= -W_b/7\ j$$

Ground reaction force (N)

$= W_b\, j$

Hip joint reaction force (R)

$= -Rxi - Ryj + Rzk$

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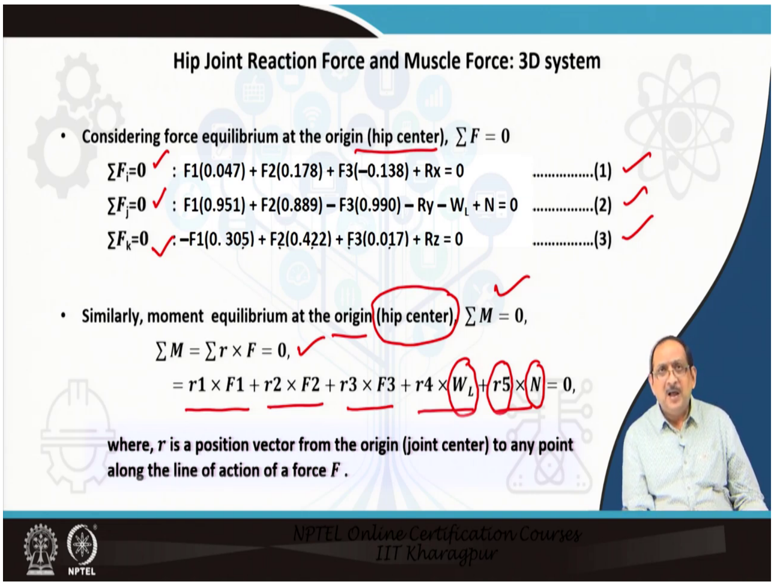

The hip joint reaction force and muscle forces will now be calculated using the force and moment equilibrium concepts of vector mechanics. So, considering force equilibrium at the origin of the hips center, we can resolve the forces along i, j, k directions by simply adding the force vectors. We can actually generate three equations connecting the forces.

Similarly, when we employ moment equilibrium at the center of the femoral head or the origin, we calculate the sum of the moments of individual forces and equate it to 0, so we will be calculating the cross product that is r x F for each muscle force F1, F2 and F3. So the corresponding r1, r2, r3, the cross product of r4 and the segmental weight WL is indicated here, and the cross product of r5 and the normal reaction force of the ground is also indicated here. So, we will add up all the moments to 0.

Considering Force equilibrium at the origin, $\sum F = 0$

$\sum \boldsymbol{F}_i = \mathbf{0}$: F1(0.047) + F2(0.17) + F3(-0.138) + Rx = 0 ....(1)

$\sum \boldsymbol{F}_j = \mathbf{0}$: $F1(0.95) + F2(0.88) - F3(0.99) - Ry - W_L + N = 0$ ....(2)

$\sum \boldsymbol{F}_k =$: $-F1(0.30) + F2(0.42) + F3(0.017) + Rz = 0$ ....(3)

Similarly, Moment equilibrium at the origin, $\sum M = 0,$

$$\sum M = \sum r \times F = 0,$$

$$= r1 \times F1 + r2 \times F2 + r3 \times F3 + r4 \times WL + r5 \times N = 0,$$

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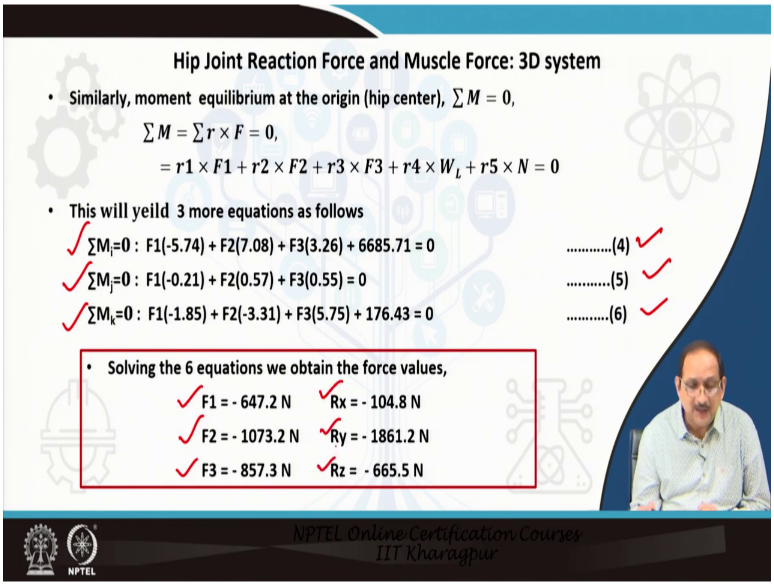

And we can actually from the equations 4, 5 and 6 considering the moments about i, j and k axis. Now, solving these 6 equations, we can finally find out F1, F2, F3 values as well as Rx, Ry and Rz.

$\sum M_i = \mathbf{0}$: $F1(-5.74) + F2(7.08) + F3(3.26) + 6685.71 = 0$ ....(4)

$\sum M_j = \mathbf{0}$: $F1(-0.21) + F2(0.57) + F3(0.55) = 0$ ....(5)

$\sum M_k = \mathbf{0}$: $F1(-1.85) + F2(-3.31) + F3(5.75) + 176.43 = 0$ ....(6)

Solving the equations we gets,

F1 = - 647.2 N; F2 = - 1073.2 N; F3 = - 857.3 N

$$R_x = -104.8\ N;\ R_y = -1861.2\ N;\ R_z = -665.5\ N$$

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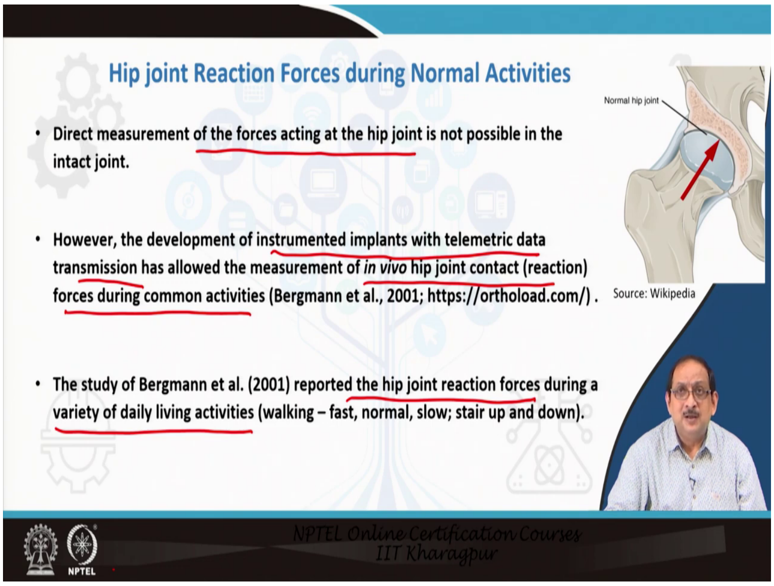

Let us now move to the third topic of this lecture on hip joint reaction force during normal activities. Direct measurement of the forces acting at the hip joint is not always possible in the intact joint. However, development of instrumented implants with telemetric data transmission has allowed the measurement of *in vivo* hip joint reaction forces during common activities. A pioneering study by Bergman group, published in journal of biomechanics in the year 2001, reported hip joint reaction forces during a variety of living activities such as fast walking, normal walking and slow walking, stair up and stair down.

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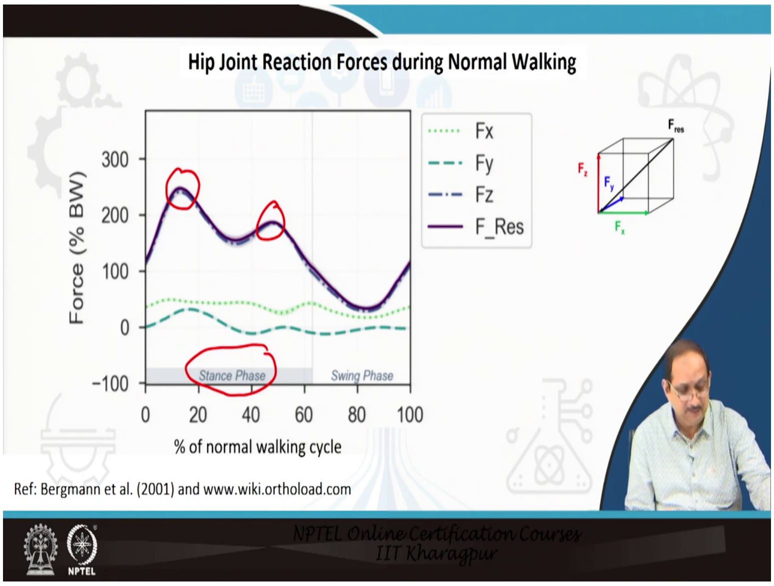
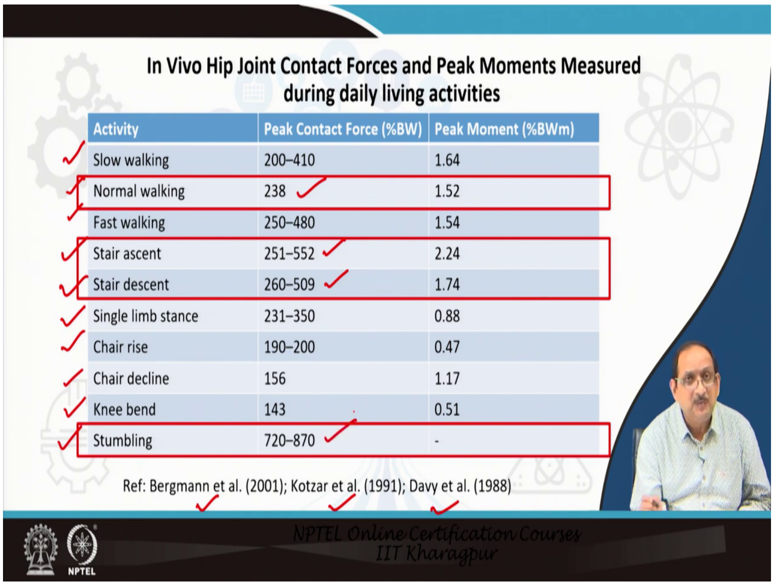


Now, when we plot the variation of the hip joint reaction forces during normal walking, the data we have received from the instrumented implant, we see that there is variation of hip joint forces during the normal walking cycle. The peak forces during walking have been reported to vary between 200 to 480 percent of body weight with increase in walking speed.

During normal walking, the first peak occurs around 15 percent of the gait cycle, whereas the second peak occurs around 45 to 50 percent of the gait cycle. Now, both these peaks occur during the stance phase of the gait cycle, as indicated in the figure. The magnitudes of these two peak forces is approximately similar and has been reported to be about 2.4 times of body weight for the first resultant peak and 2.1 times bodyweight for the second resultant peak. (Refer Slide Time: 30:37)



The magnitude of peak joint reaction force and peak moments, which is measured in vivo, during daily activities is summarized in this table and these data is based on different references. The references are indicated here below the table. The magnitude of the peak force and the moments actually vary considerably depending on the activity, the subject is performing.

So, we have a range of activities here starting from slow walking, normal walking, fast walking, stair climbing, stair up, stair down, single-limb stance, rising from a chair, declining in a chair, knee bend and stumbling. Now, the variation of the peak forces and moments are large, as I had already indicated. I can highlight a few activities like normal walking, where the peak joint reaction force is about 2.4 times the body weight. During stair climbing and stair down, the peak force can also go to about 5 times the body weight and maybe during stumbling, this can abnormally rise to 7 to almost 9 times the body weight.

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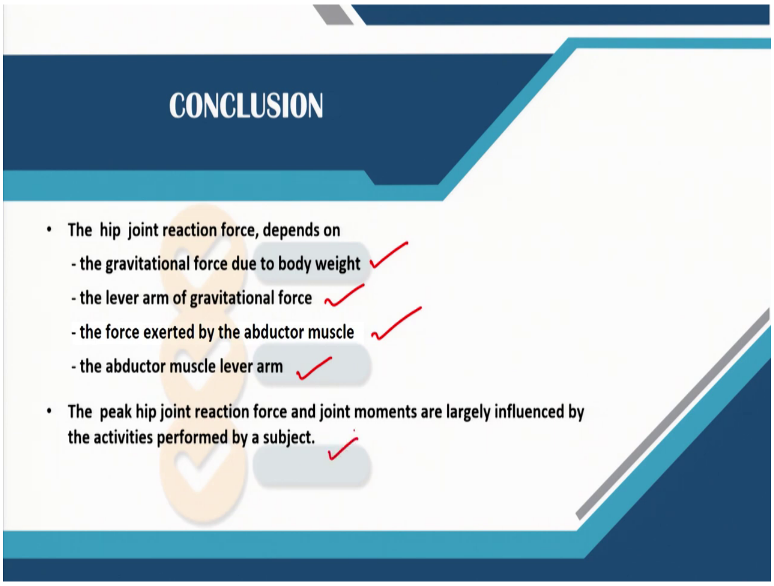

So, the conclusions of this lecture are: the hip joint reaction force depend on the gravitational force due to body weight, the lever arm of the gravitational force, the force exerted by the abductor muscles and the lever arm of the abductor muscle. The peak hip joint reaction force and the joint moments are largely influenced by the activities performed by a subject.

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The list of references are stated here, based on which the lecture has been prepared. Thank you for listening.