Biomechanics of Joints and Orthopaedic Implants
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Lecture 9
Biomechanics of the Knee Joint

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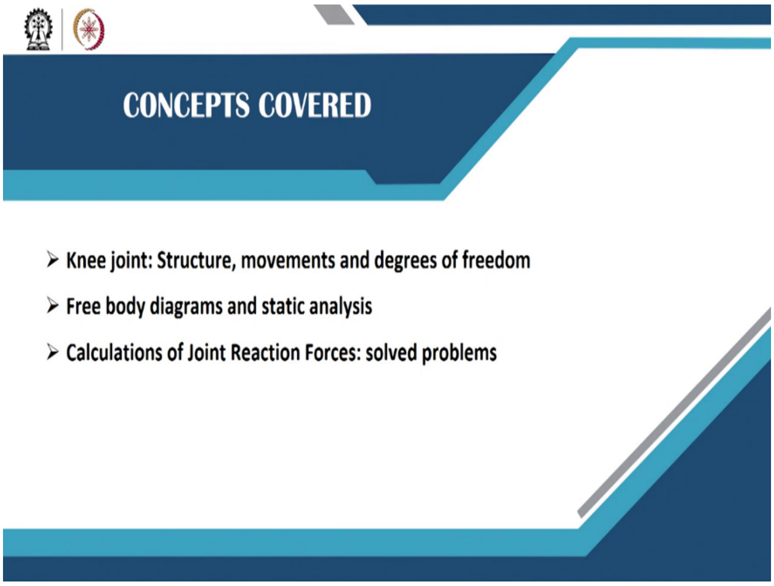

Good afternoon everybody, welcome to the lecture on the biomechanics of the knee joint. Now in this lecture, we will be discussing the structure movements and degrees of freedom of the knee joint followed by free body diagrams and static analysis. And the third topic is on calculations of joint reaction forces using solved problems.

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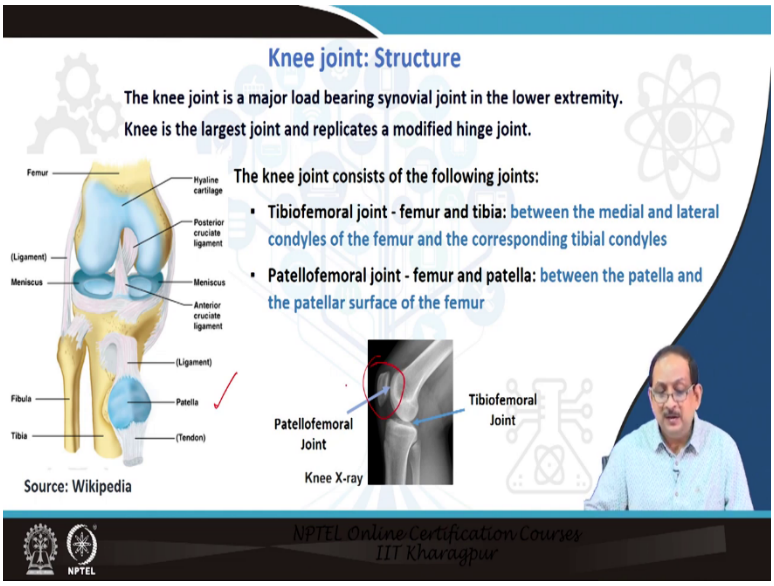

The knee joint is a major load-bearing joint in the lower extremity. The knee is the largest joint and replicates a modified hinge joint. The knee joint is an essential joint in the skeletal system responsible for human locomotion and is vulnerable to injuries during sports activity. The knee joint consists of the following joint: the tibiofemoral joint, articulation between femur and tibia i.e. between the medial and lateral condyles of the femur, and the corresponding tibial condyles as shown in the figure. The patellofemoral joint, which is an articulation between the patella and the patellar surface of the femur, is shown here in the X-ray image.

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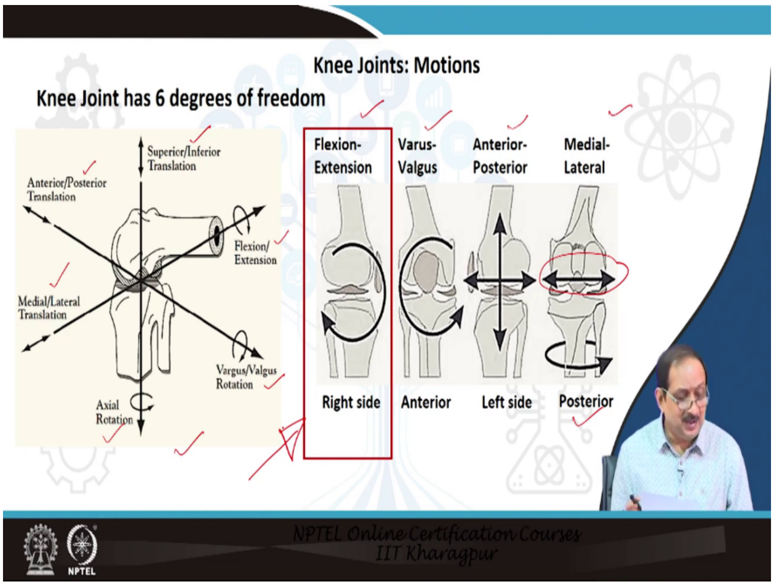

Now, the knee joint has 6 degrees of freedom. In the figure on the left, the three translational degrees of freedom are shown along with anterior-posterior, medial-lateral, and superior-inferior directions. The rotational degrees of freedom are the flexion-extension, Varus-valgus rotation, and axial rotation.

So, this is indicated here also in the slide. Here we see the flexion-extension, the rotational degrees of freedom, and the Varus-valgus rotation. The anterior-posterior translation is indicated here in this slide in this figure. The medial-lateral translation is indicated here, as well as the axial rotation about the vertical axis is also shown in this figure. However, the predominant movement of the knee joint is flexion-extension.

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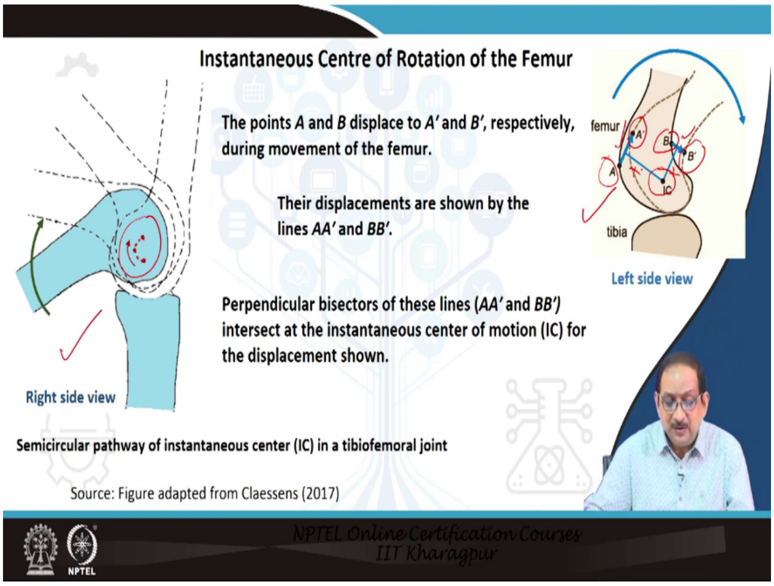

The instantaneous center of rotation of the femur is of prime importance because the location of this instantaneous center is very important for rigid body kinematics. The pathway of the instantaneous center of the femur throughout the range of knee flexion and extension is shown in this figure, the right side view; medial-lateral view.

In a normal knee, this pathway is semi-circular, so we see that with rotation of the femur that is flexion or extension, the instantaneous center of rotation is rotating along the semi-circular path. Now, how to find out this instantaneous center of rotation, we will take the help of the other figure that is presented on the right-hand side of the slide.

So, this is a left-side view of the femur and the tibia. Points A and B, as you can see here, are points on the femur. The femur is rotated through a small angle and these points are displaced from A to A` and B to B` dash during the movement of the femur. The displacement AA` and BB` are shown in the figure.

The perpendicular bisectors of these lines AA` and BB` intersect at the instantaneous center of rotation for the displacement shown. Now, clinically a pathway of the instantaneous center for a joint can be determined by taking successive radiograph images of the joint in different positions, usually in small intervals of around say 10 degrees throughout, but it has to be taken throughout the range of motion in one plane. Thereafter, we can apply such a method for locating the instantaneous center of rotation for each interval of rotation.

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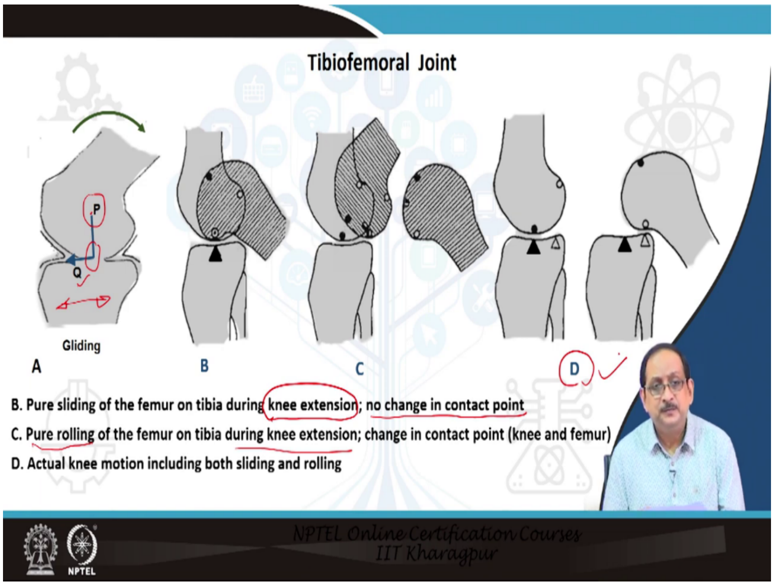

Now, let us consider the tibiofemoral joint. We consider the flexion movement in the tibiofemoral joint of a normal knee. So, in figure A as shown here, we will be discussing the instantaneous center of rotation of the tibiofemoral joint. So in a normal knee, a line is drawn from the instantaneous center of the tibiofemoral joint to the tibiofemoral contact point that is located here, so this line is designated by line P and is perpendicular with the line tangential to the tibial surface, which is line Q. The arrow indicates the direction of the displacement of the contact points. Line Q is tangential to the tibial surface, indicating that the femur glides on the tibial condyles during the measured interval of motion.

Now, in figure B, we see pure sliding of the femur on the tibia during knee extension. However, there is no change in the contact point between the tibia and femur. In figure C, which observed pure rolling of the femur on the tibia during knee extension, there is actually a change in the contact points of the femur and tibia while the femur rolls on the tibia. In figure D, the actual knee motion, including sliding and rolling is shown.

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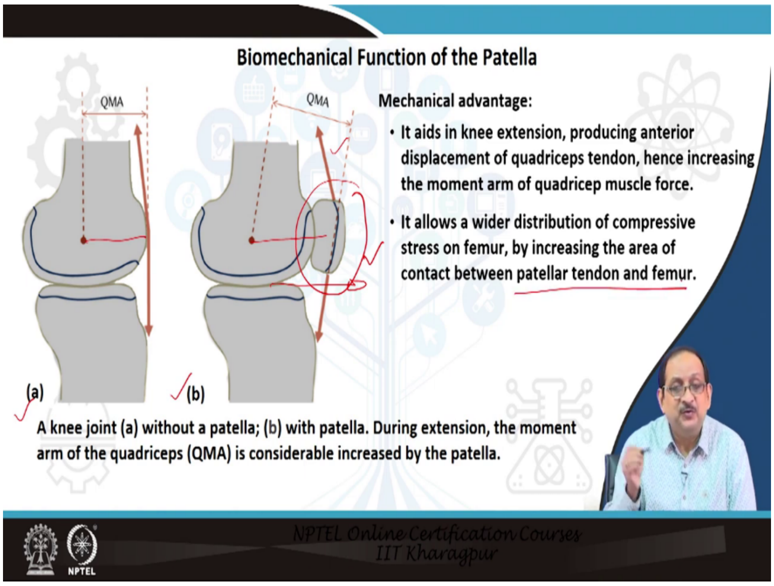

Now, let us consider the biomechanical function of the patella. On the left, we can see two figures A and B, the figure A shows the knee joint without a patella, and figure B shows the knee joint with the patella. Now, we can observe that there is a difference in this distance. So, during extension, the moment arm of the quadriceps tendon is considerably increased due to the presence of the patella.

So, the mechanical advantages of the patella are, it aids in knee extension producing anterior displacement of the quadriceps tendon, hence increasing the moment arm of quadriceps muscle force. It also allows wider distribution of compressive stress on the femur by increasing the area of contact between the femur between the patellar tendon and the femur.

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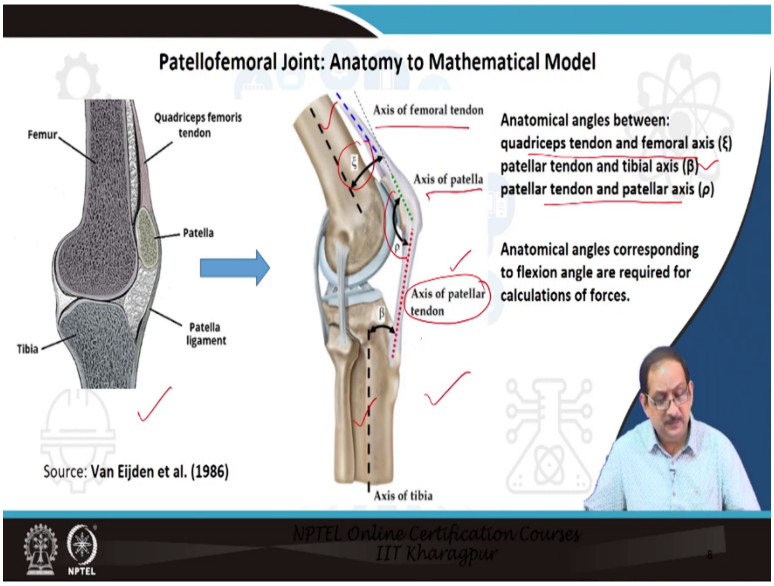

Let us look into more detail regarding the patellofemoral joint. So, on the left-hand side, we have a figure that represents the anatomy of the patellofemoral joint, and on the right, we have a mathematical model of the same joint. In this mathematical model, there are some important anatomical angles like the angle between the quadriceps tendon and the femoral axis indicated by ξ.

So, it is this angle between the femoral axis of the femoral tendon and the axis of the femur. The next angle is the angle between the patellar tendon and the tibial axis. So, this is the axis of the patellar tendon, and this is the tibial axis, so we need to find out β. The third angle is ρ and that is defined as the angle between the patellar tendon and the patellar axis. These anatomical angles corresponding to a flexion angle are necessary for calculations of forces in the knee joint.

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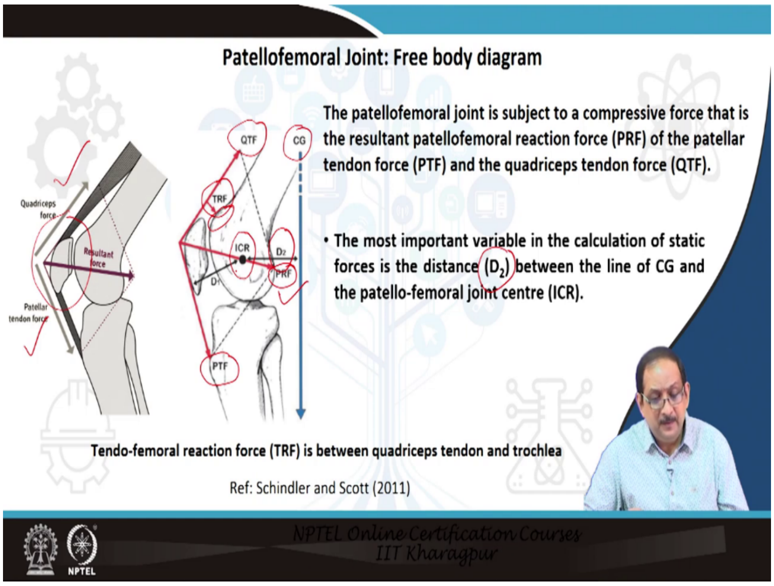

Now, let us consider the free body diagram of the patellofemoral joint. The patellofemoral joint is subjected to compressive forces as indicated here, which is the resultant patellofemoral reaction force due to the patella tendon force and the quadriceps tendon force. So, the resultant force is a resultant of these two forces.

The same thing is indicated here by the patellar tendon force PTF, quadriceps tendon force as QTF. The resultant force passes through the instantaneous center of rotation of the patellofemoral joint, so the resultant force is indicated here. There is another small force which is called TRF or tendo-femoral reaction force and that is between the quadriceps tendon and trochlea, as indicated in the figure.

Now, the weight of the body is acting through the center of gravity and vertically downwards. The most important variable in the calculation of static forces is the distance D2 which is indicated here, the distance between the line of the center of gravity and the patellofemoral instantaneous center that is ICR.

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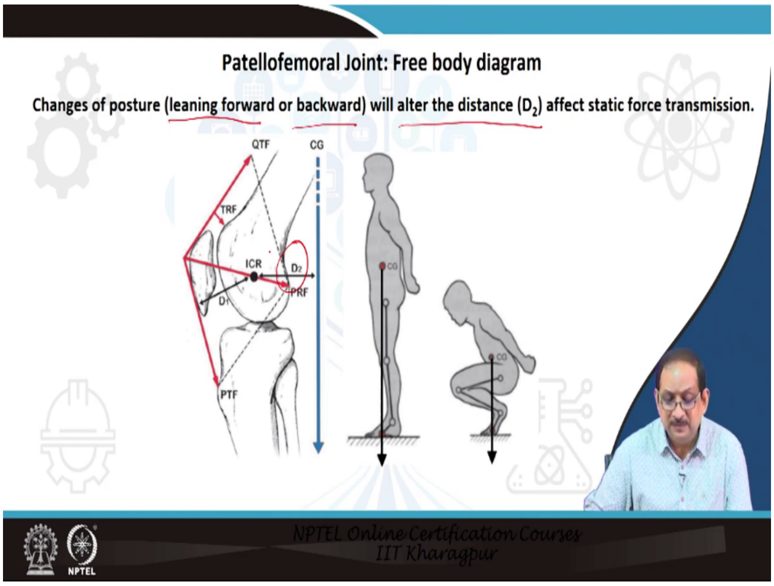

Changes in postures either leaning forward or leaning backwards will actually alter the distance D2, and it will significantly affect the calculations on static force transmission.

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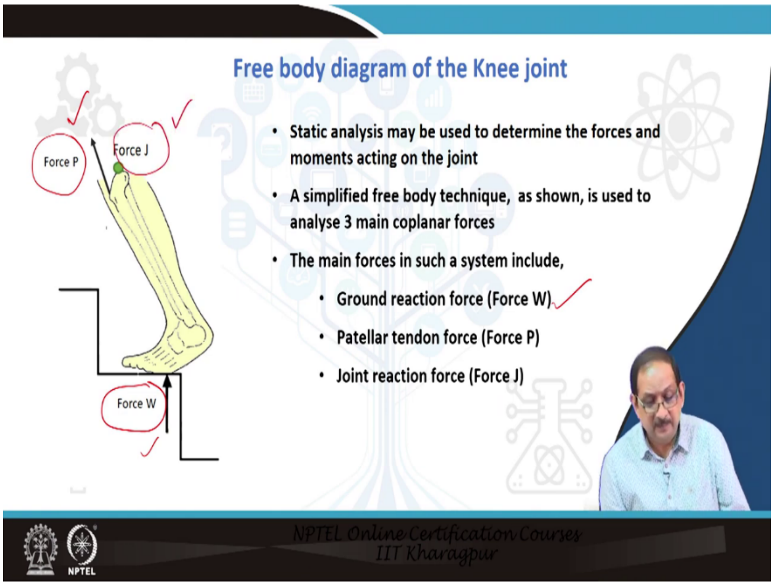

Let us now enter into the second topic, the free body diagram of the knee joint. Now, static analysis may be used to determine the forces and moments acting on the knee joint. So, on the left, we see a limb segment where the forces are indicated. So, simplified free body technique as shown in the figure is used to analyze 3 coplanar forces in a two-dimensional system. The main forces in such a 2D system include the ground reaction force W, the patellar tendon force P and the joint reaction force J.

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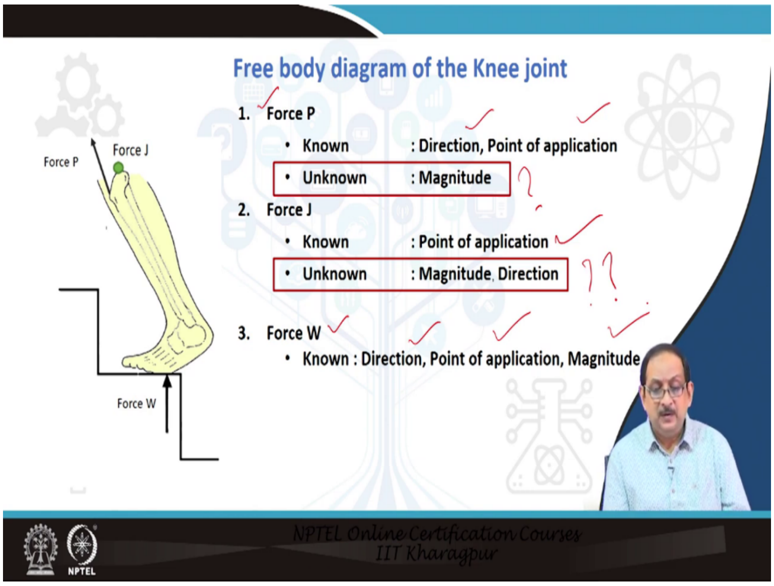

Now, when we consider the forces P individually, the forces P, J, and W, certain things are known and certain things are unknown. The known quantities are the direction and point of application of the force P; the magnitude is unknown. For force J joint reaction force, both magnitude and direction are unknown; only the point of application of this joint reaction force is known in the form of instantaneous center of rotation. For force W, which is the ground reaction force due to the bodyweight, the direction points or point of application and magnitude of the W force, all are known.

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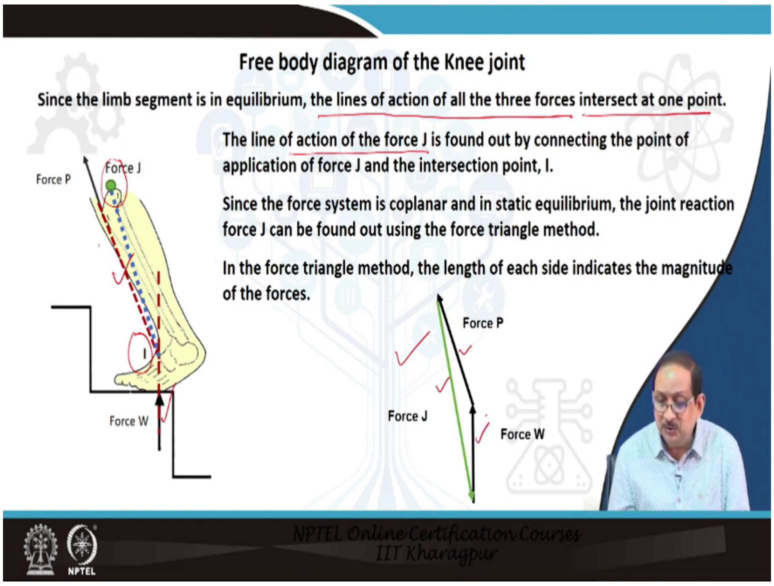

Now, since the limb segment is in equilibrium, the line of action of all the three forces intersect at one point. They have to intersect at one point, since the limb segment is in equilibrium. So, from this system of force, the line of action of the force J is found out by connecting the point of application of this force J and the intersection point I.

This intersection point I is found out by extending the lines of action of force forces P and W, as indicated in the figure. Since the force system is coplanar and in static equilibrium, the joint reaction force J can be found out using the force triangle, as indicated in the figure. In the force triangle method, the length of each side indicates the magnitude of the forces.

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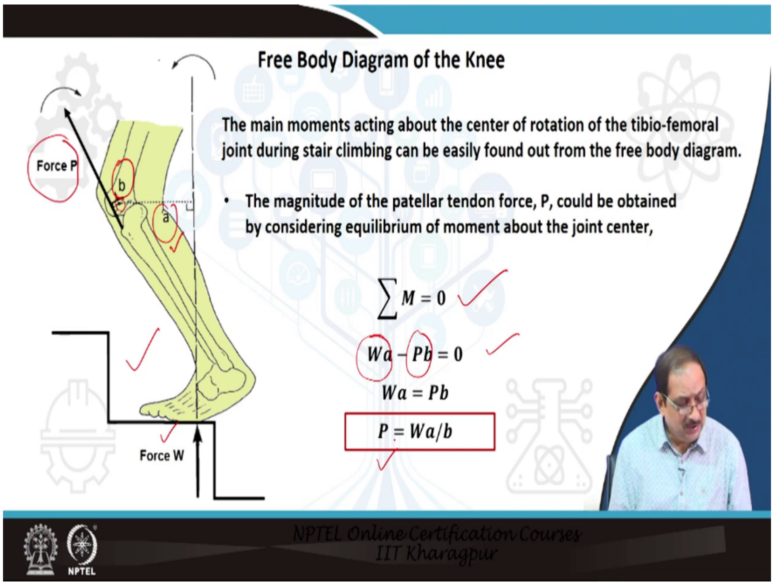

The moments acting around the center of rotation of the joint during stair climbing can be easily found out from the free body diagram shown here. The magnitude of the patellar tendon force P can be obtained by considering the equilibrium of moment about the joint center. So, we have the force W acting through a lever arm a, so that creates one moment around about the joint center here.

There is another force P which is acting through the lever arm b, which is creating a moment in the opposite direction. So, the two opposing moments Wa and Pb can be equated through the moment equilibrium equation, and we can find the P force in terms of the dimensions a b and the weight of the subject W.

$$\sum M = 0$$

$$Wa - Pb = 0$$

$$Wa = Pb$$

$$P = Wa/b$$

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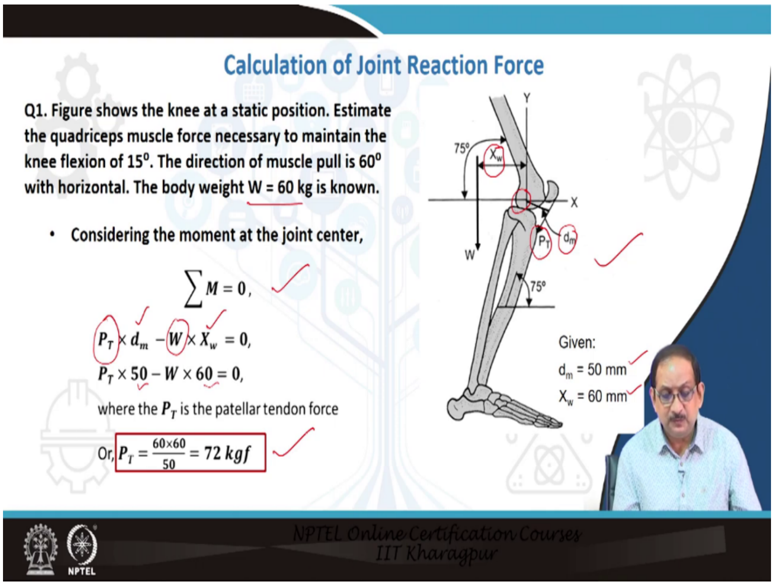

Let us now move into the calculation of joint reaction forces. The figure on the right shows the knee at a static position, so we need to estimate the quadriceps muscle force necessary to maintain the knee flexion at 15 degrees. The direction of the muscle pull P_T is at 60 degrees with horizontal and the bodyweight is 60 kg.

Considering the moment around the joint center and moment equilibrium, we can actually write down the equation connecting the patellar tendon force and the weight of the body or bodyweight W. Now, this force P_T is acting at a distance d_m from the joint center, indicated by d_m, whereas the bodyweight is acting through the lever arm X_w as indicated here.

So, X_w is the distance between the joint center and the line of action of the body weight. Now, if we consider the given data of 50 and 60 mm for d_m and X_w, respectively, we can substitute these values and find out the patellar tendon force of 72 kg force based on the data given for this problem.

$$\sum M = 0,$$

$$PT \times dm - W \times Xw = 0,$$

$$PT \times 50 - W \times 60 = 0,$$

where, PT is the patellar tendon force

$$\text{Or, } PT = \frac{60 \times 60}{50} = 72\ kgf$$

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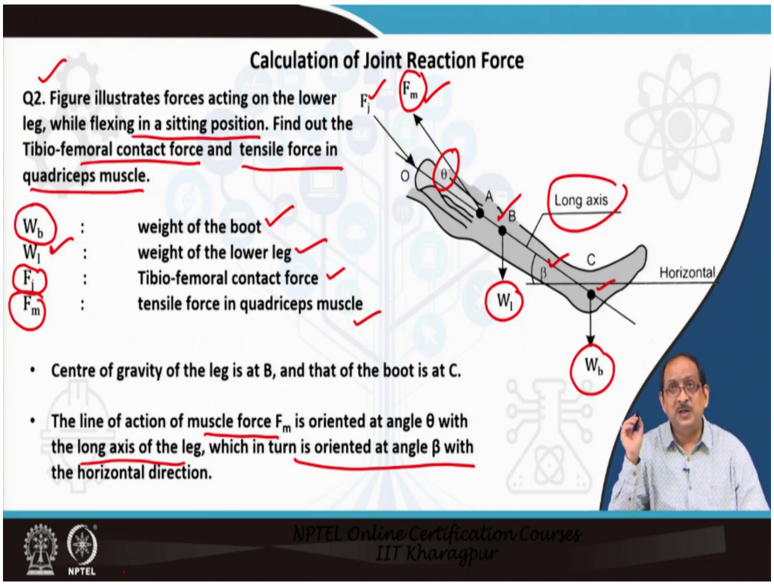

In the second problem, we consider a person in a sitting posture. This subject is actually wearing a boot of weight W_b. So, the figure illustrates forces acting on the lower leg while flexing in a sitting position. So, we need to find out for this instant the tibia-femoral joint contact force or joint reaction force and the tensile force in the quadriceps muscle.

So, the weight of the boot is indicated by W_b, and the weight of the lower leg is indicated by W_l. The tibiofemoral contact force F_j is indicated in the figure, and the tensile force in the quadriceps muscle is indicated by F_m. The center of gravity of the leg is located at B and that of the center of gravity of the boot is at C. The line of action of the muscle force F_m is oriented at an angle θ with the long axis of the leg, as shown in the figure. Now, this long axis, in turn, is oriented at an angle β with the horizontal direction.

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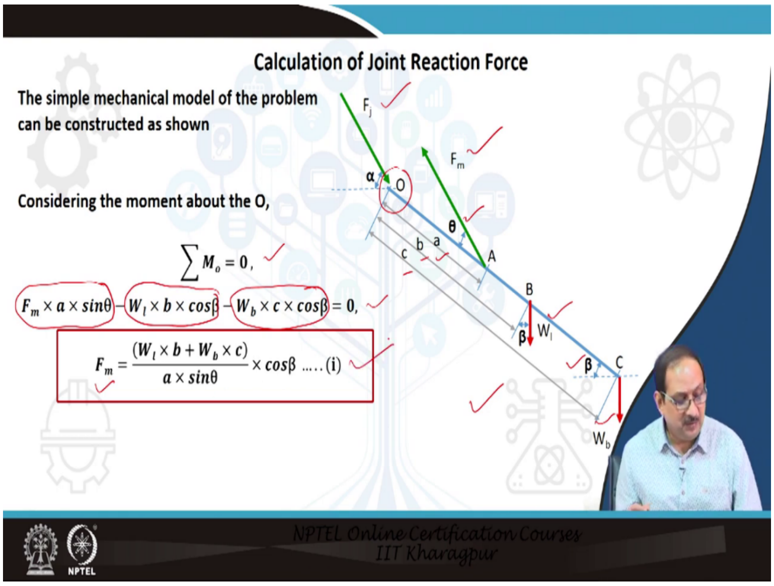

The simple mechanical model of the problem can be represented as shown in the free-body diagram here, where we have the muscle force with the joint reaction force, the weight of the lower limb, the weight of the boot and the angles θ, β, and the dimensions A, B, C. So, considering the moment about the joint center O and moment equilibrium, we can write down the equations of the moments.

So, the first term is the moment of the muscle force, the second term is the moment of the limb, and the third term is the moment created by the weight of the boot. So, these can be related through the moment equilibrium equation, from which we can actually express the muscle force in terms of the related variables as shown in equation (i).

$$\sum Mo = 0,$$

$$Fm \times a \times sin\theta - Wl \times b \times cos\beta - Wb \times c \times cos\beta = 0,$$

$$Fm = \frac{(Wl \times b + Wb \times c)}{a \times sin\theta} \times cos\beta \ldots\ldots\ldots\text{(i)}$$

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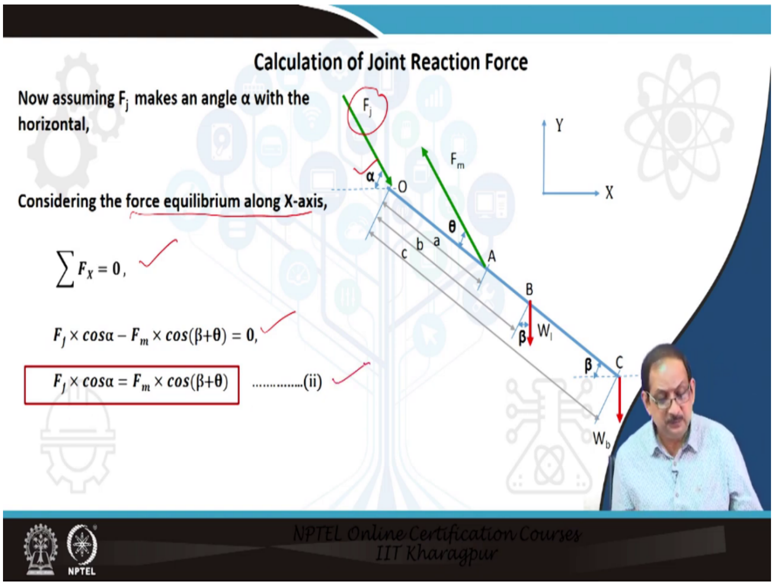

Now assuming the joint reaction force F_j makes an angle α with the horizontal, we can consider the force equilibrium along the X-axis that is the summation of the forces resolved along the X-axis, and we can write down the equation as shown in this figure. So, F_j can be related to F_m according to equation number (ii).

$$\sum FX = 0,$$

$$Fj \times cos\alpha - Fm \times cos(\beta + \theta) = 0,$$

$$Fj \times cos\alpha = Fm \times cos(\beta + \theta), \text{........(ii)}$$

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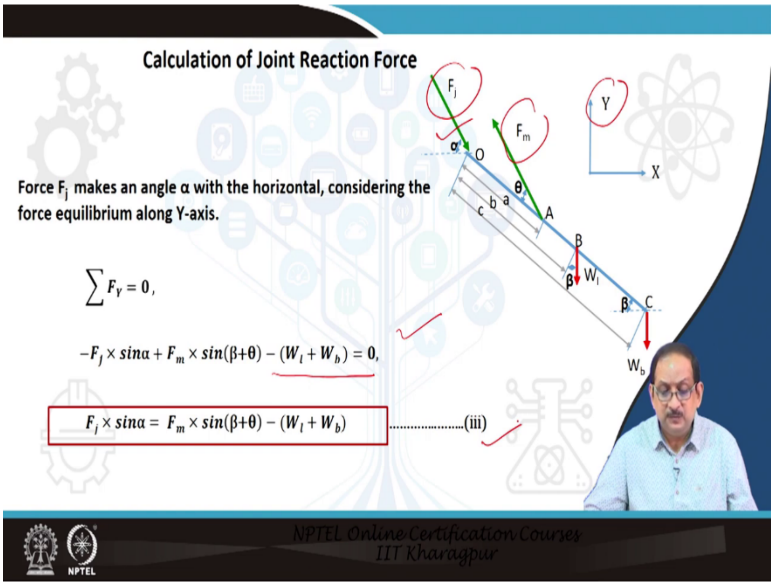

The force F_j makes an angle α with the horizontal, and we can also consider the vertical component along the Y direction. We can resolve the forces along the Y direction, so we can write down the equations relating the vertical components of F_j, F_m and the weight of the limb and the weight of the boot. So, we finally write down equation (iii) connecting the joint reaction force and the muscle force in terms of limb weight and the weight of the boot.

$$\sum FY = 0,$$

$$Fj \times sin\alpha - Fm \times sin(\beta + \theta) + Wl + Wb = 0,$$

$$Fj \times sin\alpha = Fm \times sin(\beta + \theta) - (Wl + Wb), \text{ ....(iii)}$$

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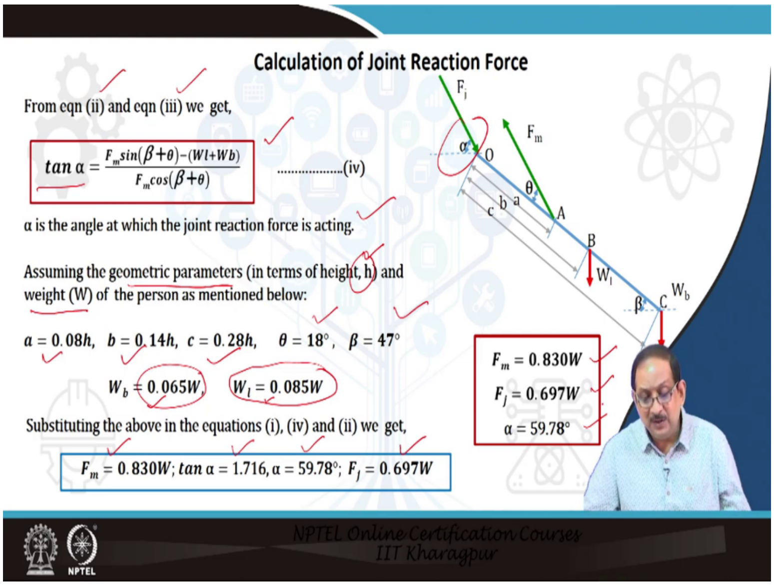

Now, from equations 2 and 3 that we had developed earlier, we can actually combine the two equations and find the expression for tan α, which is the angle at which the joint reaction force is acting. The angle α is the angle at which the joint reaction force is acting, indicated in this figure.

Assuming the geometric parameters (in terms of height h and weight W), that is a, b, and c, which are the dimensions expressed in terms of height. The weight of the limb and the weight of the boot are expressed as 0.085 W and 0.065 W, respectively. Assuming these two values and the angle θ has 18 degrees, and β has 47 degrees, we can substitute this in the equation and find out the quadriceps muscle forces, the tan α, the inclination angle of the joint reaction force, and the magnitude of the joint reaction force. So, these three important solutions of the problem can be obtained in the form of the muscle quadriceps muscle force, the joint reaction force, and the angle α, the inclination of the joint reaction force, as indicated below:

From eq (ii) and eq (iii) we get,

$$tan\propto = \frac{Fmsin(\beta+\theta)-(W1+W0)}{Fmcos(\beta+\theta)}, \ldots.(iv)$$

α is the angle which the joint reaction force is acting on

Assuming the geometric parameters (in terms of height,h) and weight (W) of the person as mentioned below

$$a = 0.08h, \quad b = 0.14h, \quad c = 0.28h, \qquad \theta = 18°, \quad \beta = 47°$$

$$Wb = 0.065W, \; Wl = 0.085W$$

Substituting the equations (i), (iv) and (ii), we get

$$Fm = 0.830W, \quad tan\propto = 1.716, \quad \propto = 59.78°, Fj = 0.697W$$

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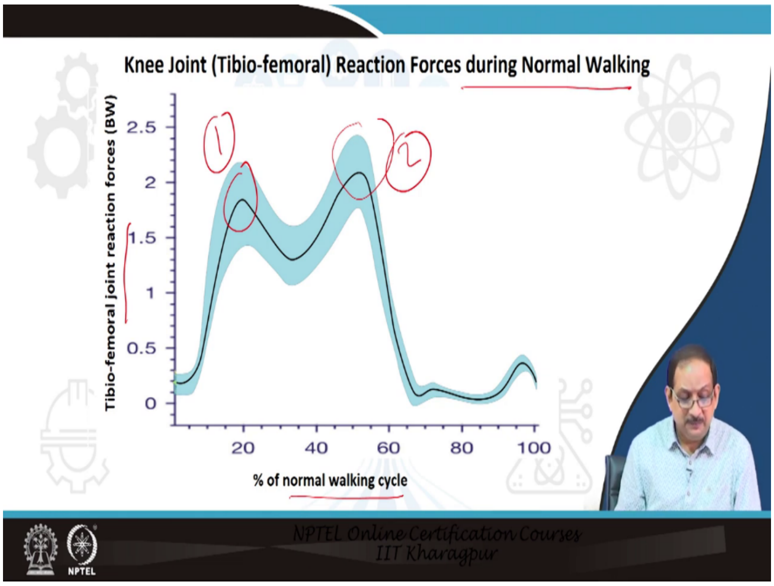

I would now like to present the variation of knee joint reaction force, the tibio-femoral reaction force during normal walking. So, this is on the X-axis we have the walking cycle, and on the Y-axis, we have the tibio-femoral joint reaction force; this is the resultant tibio-femoral joint reaction force.

So, here we see that the resultant peak, resultant joint reaction forces during walking that can vary between two times body weight to three times body weight. The first peak normally occurs at 18 percent of the gait cycle. The second peak normally occurs at 57 percent of the gait cycle. The magnitude of the two peaks is approximately similar and has been reported to be around two times bodyweight, 200 percent body weight for the first resultant, and around 240 percent of body weight or 2.4 times bodyweight for the second resultant peak.

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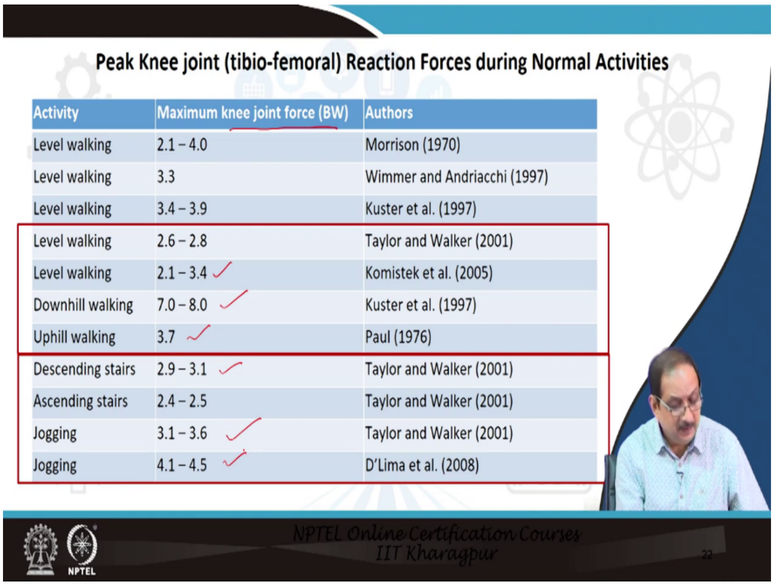

Now, in this table, the peak joint reaction force, the tibio-femoral joint reaction force during different activities, have been listed, wherein we can get the maximum knee joint reaction force. So it can be observed that the range of peak values of knee joint reaction force varies considerably with the activity.

So, during level walking, we can see that it can vary from 2.6 to about 3.4; during downhill it goes to about 7 to 8 times body weight; during uphill it goes to a peak of 3.7 times body weight. During descending stairs, it varies around three times body weight; during jogging, it may vary from 3.1 times body weight to 4.5 times the body weight.

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The patellofemoral joint reaction force is listed here for different types of activity. As you can see, it is the reaction force between the patella and the femur joint. During walking and cycling, this force is quite less because these activities do not involve too much flexion; that is the reason the patellofemoral joint reaction force is still low as compared to the other activities like stair ascent, stair descent; it abnormally rises from 3.3 times bodyweight to 5 times body weight.

In jogging, the patellofemoral joint reaction force is predominantly high; 7 times bodyweight. Normal squatting is also seven times body weight. Deep squatting, as all the squatting are actually high flexions movement, so, in these squatting (movement), the patellofemoral joint reaction force can rise up to 20 times the body weight.

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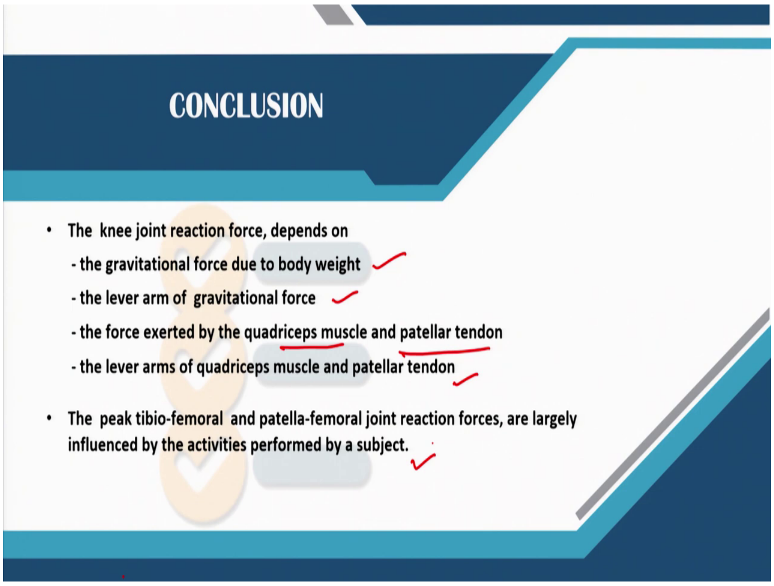

Let us now come to the conclusions of this lecture on knee joint biomechanics. The knee joint reaction force depends on the gravitational force due to body weight, the lever arm of the gravitational force, the force exerted by the quadriceps muscle and the patellar tendon, the lever arms of the quadriceps muscle, and also the lever arm of the patellar tendon. The peak tibio-femoral and patella-femoral joint reaction forces are largely influenced by the activities performed by a subject.

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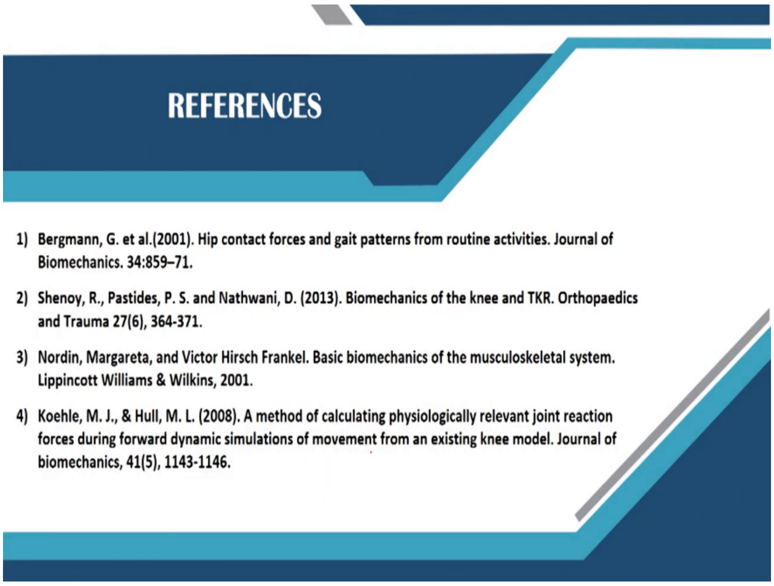

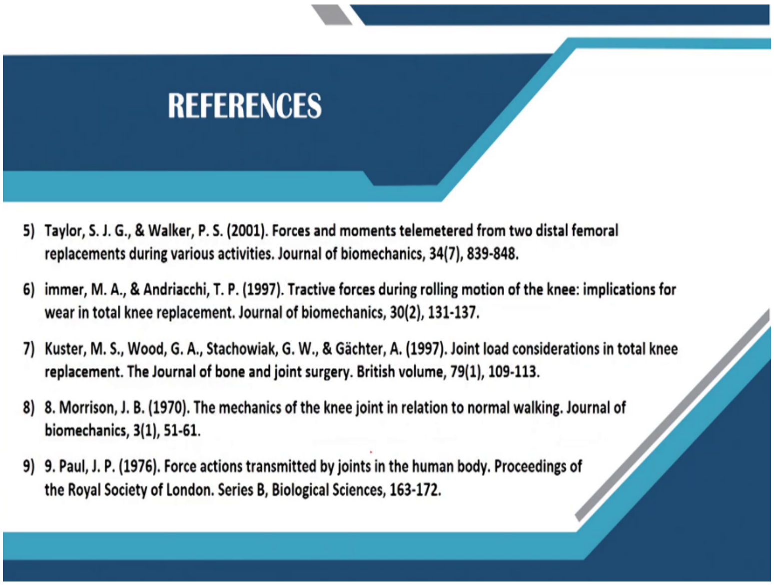

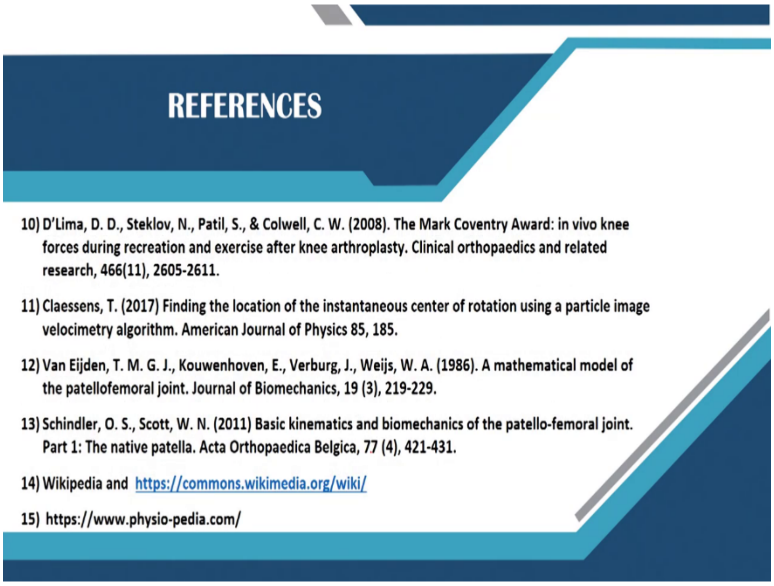

The list of references is indicated here. It is a long list of 3 slides. You can refer to these references, and thank you for listening.