Biomechanics of Joints and Orthopaedic Implants
Professor Sanjay Gupta
Department of Mechanical Engineering
Indian Institute of Technology Kharagpur
Lecture 10
Biomechanics of the Shoulder Joint

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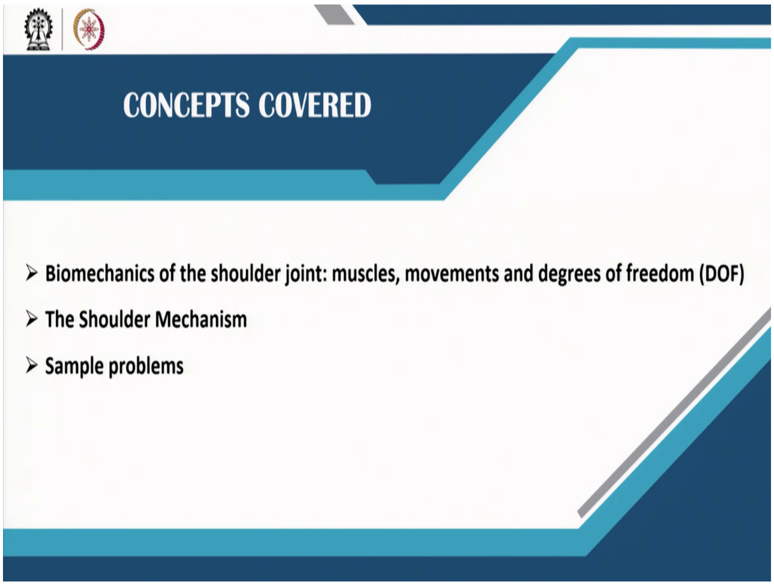

Good morning everybody, welcome to the lecture on biomechanics of the shoulder joint in module 2. In this lecture we will be discussing about the muscles movements and degrees of freedom of the shoulder joint in relation to the biomechanics of the joint, the shoulder mechanism and a few sample problems.

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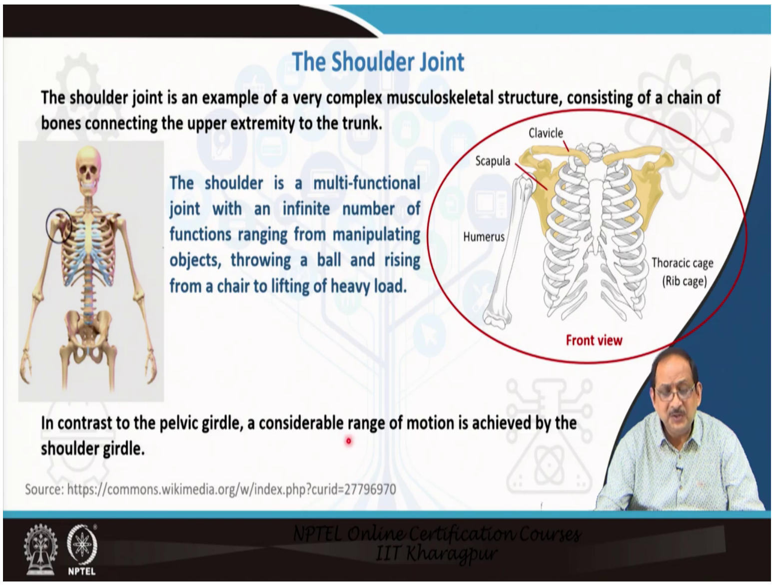

The shoulder joint is an example of a very complex muscular skeletal system, as already discussed earlier. And it consists of a chain of bones connecting the upper extremity to the trunk. The shoulder is a multi-functional joint with an infinite number of functions, ranging from manipulating objects, throwing a ball, and rising from a chair to lifting of heavy loads. In contrast to the pelvic girdle, the shoulder girdle actually offers a considerable range of motion.

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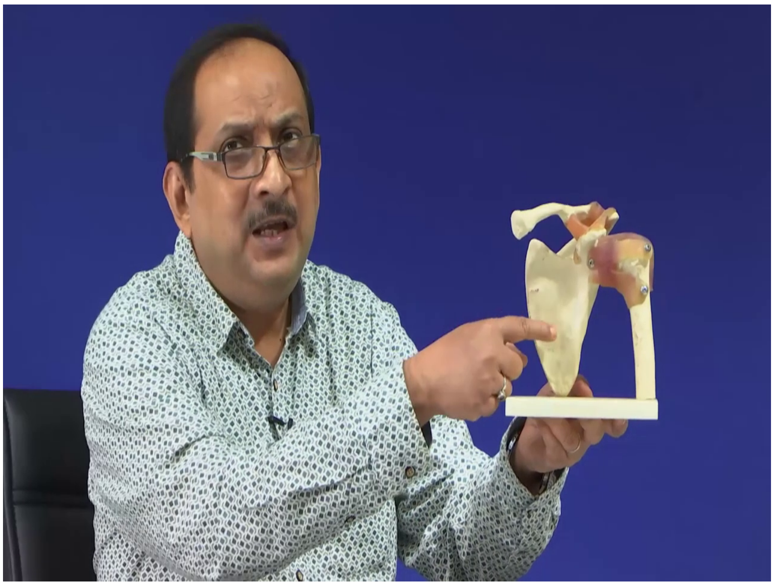

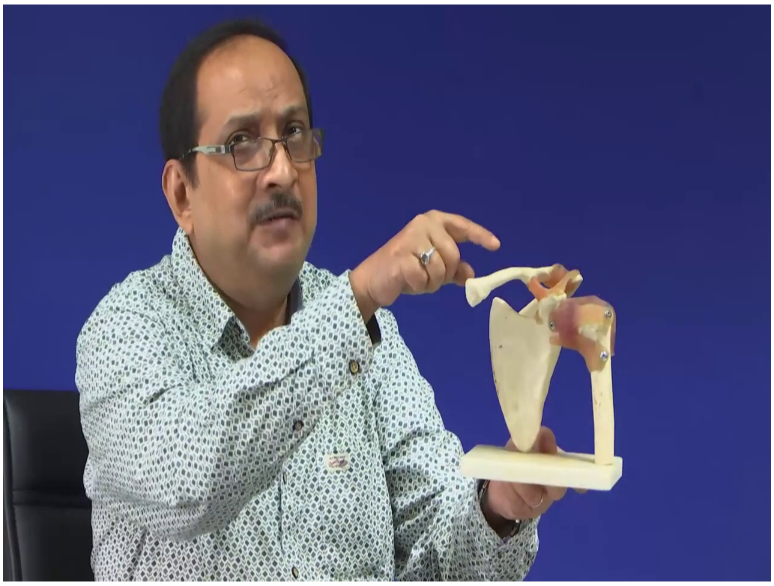
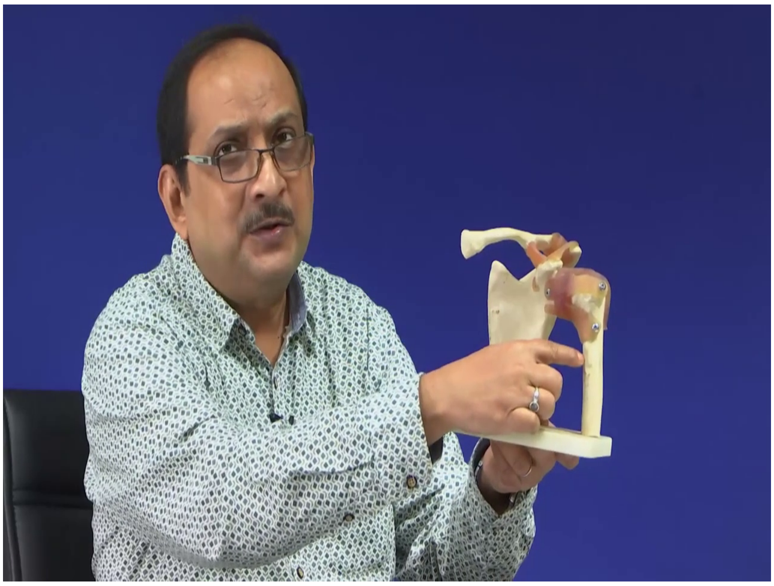
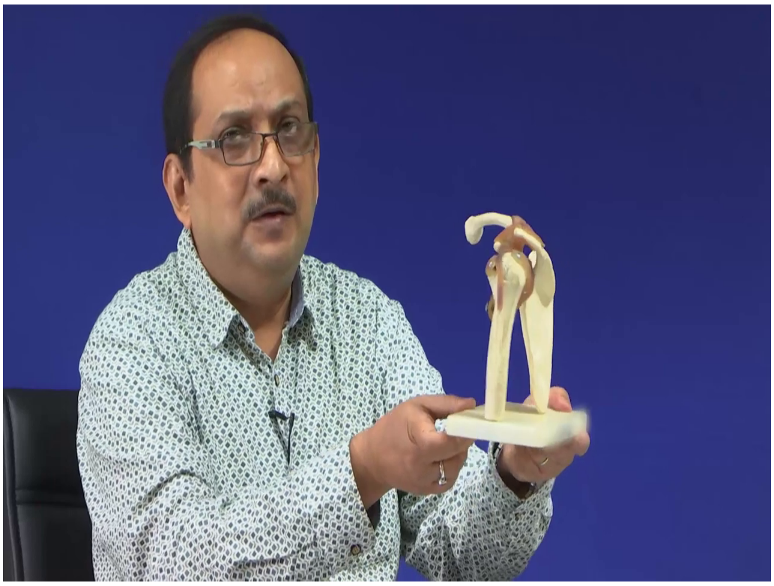

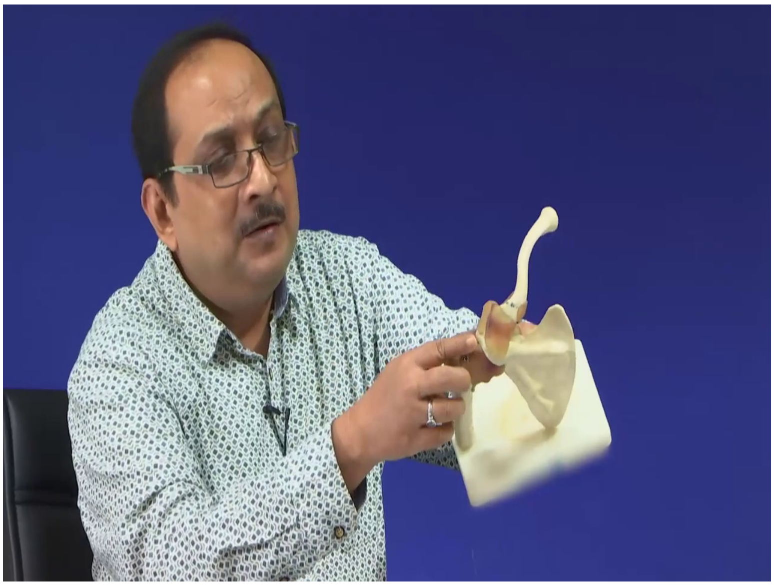

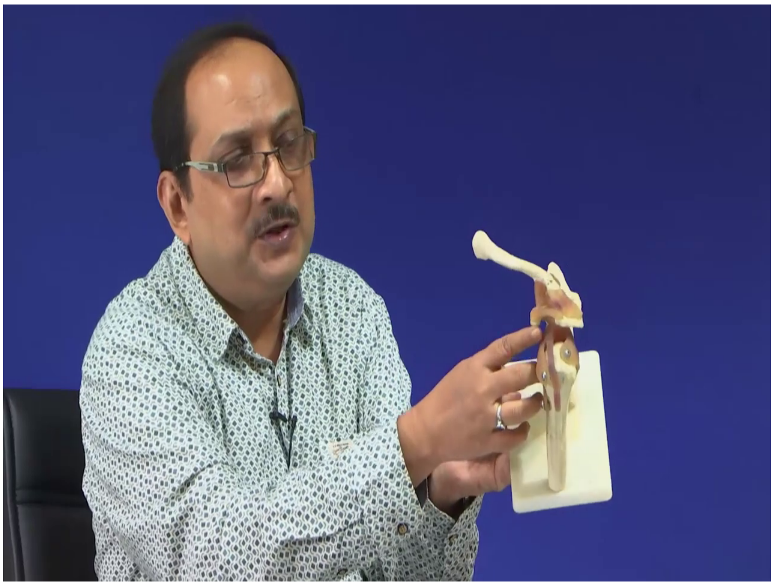

Let me present to you a plastic model of the shoulder complex. So, we have the scapula, the clavicle, and the humerus, which essentially forms the shoulder joint. This is the anterior view of the shoulder, and you can see that the scapula is an extremely thin bone, and there are also solid bony ridges. This is the glenoid part of the scapula, which forms the glenohumeral joint with the humerus.

If I rotate the shoulder joint, you can see the posterior part of the shoulder joint. This is the scapular spine, a very thick solid bone originating from the thin Fossa area, and this is acromial. If I look from the top, you can see how it branches out the whole structure, this is acromial, and this is the coracoid process.

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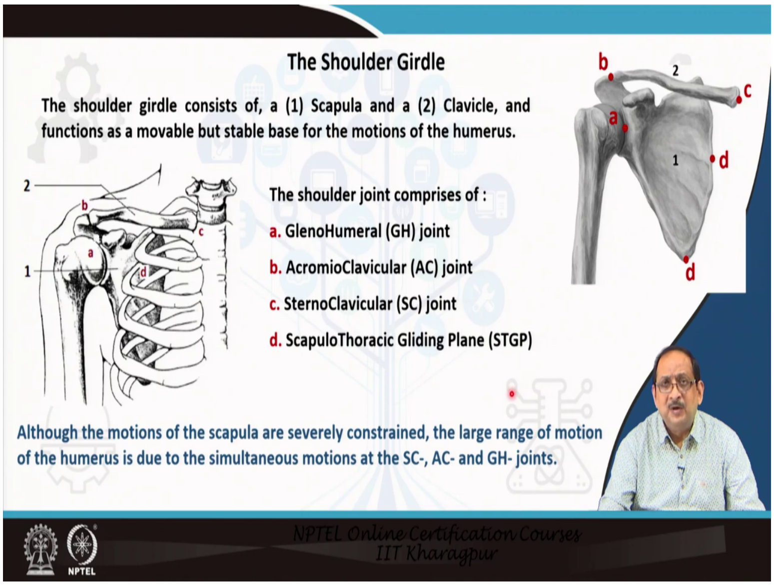

So, the shoulder girdle will consist of a scapula and a clavicle and functions as a movable but stable base for the motions of the humerus. The shoulder joint comprises the glenohumeral joint, acromioclavicular joint, sternoclavicular joint, and the scapulothoracic gliding plane, which is represented here in this figure by two points on the medial border. Although the motions of the scapula are severely constrained, the large range of motion of the humerus is due to the simultaneous motions of the sternoclavicular, acromioclavicular, and the glenohumeral joints.

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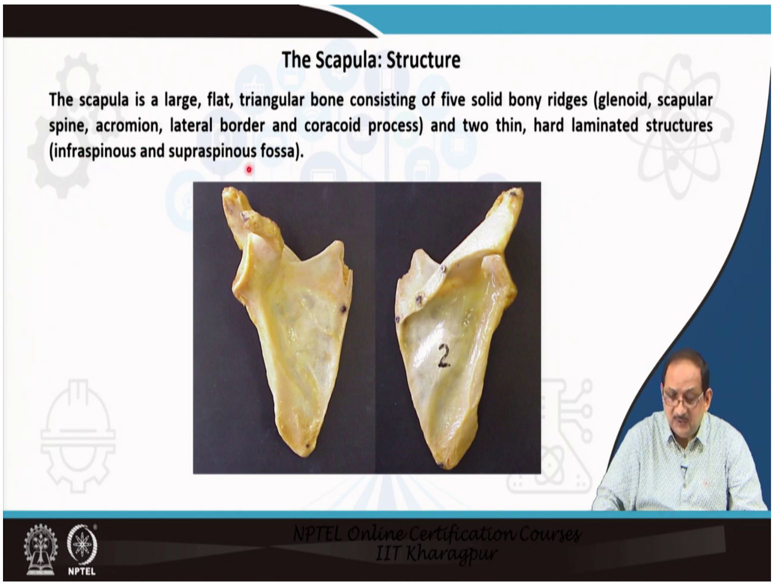

The structure of the scapula is quite complex. The scapula is a large, flat, triangular bone, as you can see here in the figure consisting of five solid bony ridges (glenoid, scapular spine, acromial, lateral border, and coracoid process) and two thin, hard laminated structures (the infraspinous fossa and the supraspinous fossa).

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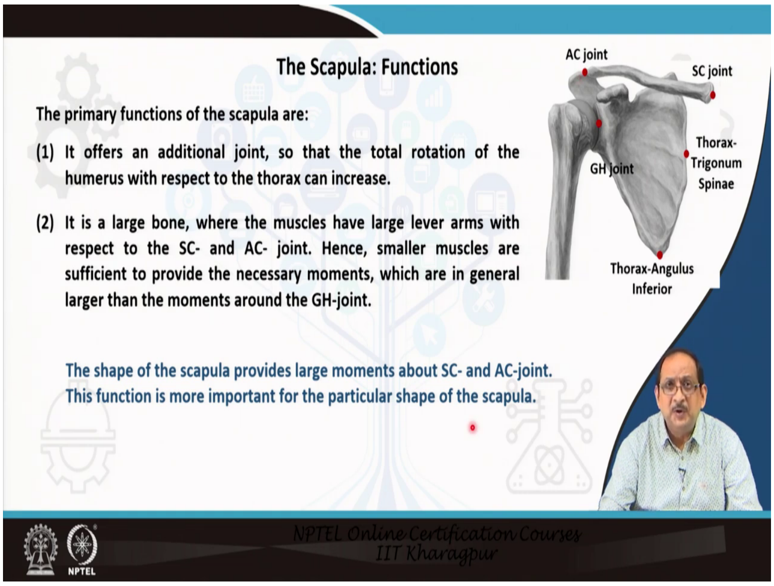

Let us look into the functions of the scapula. The functions of the scapula are; first, an important function is that it offers an additional joint, so that the total rotation of the humerus with respect to the thorax can increase. It is a large bone, as you can see already in the figure, where the muscles have large lever arms with respect to the SC sternoclavicular joint and the acromioclavicular joint.

Hence, smaller muscles are sufficient to provide necessary moments, which are in general larger than the moments around the glenohumeral joint. The shape of the scapula provides large moments about the sternoclavicular and the acromioclavicular joints. This function is more important for the particular shape of the scapula.

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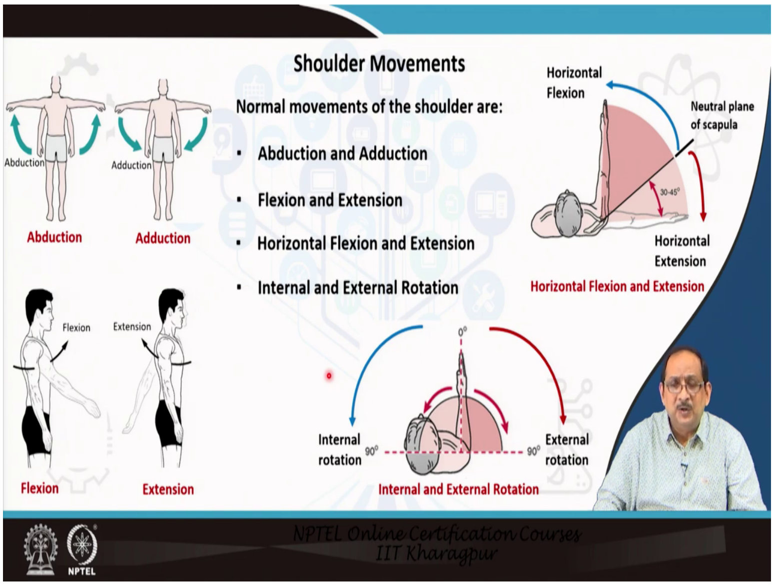

Let us now list the normal movements of the scapula, which are abduction and adduction opposite movements, flexion and extension, horizontal flexion and extension, internal and external rotation; these are very clearly shown in the figure. And we had discussed this earlier when we discussed the basic anatomy and movements of the shoulder.

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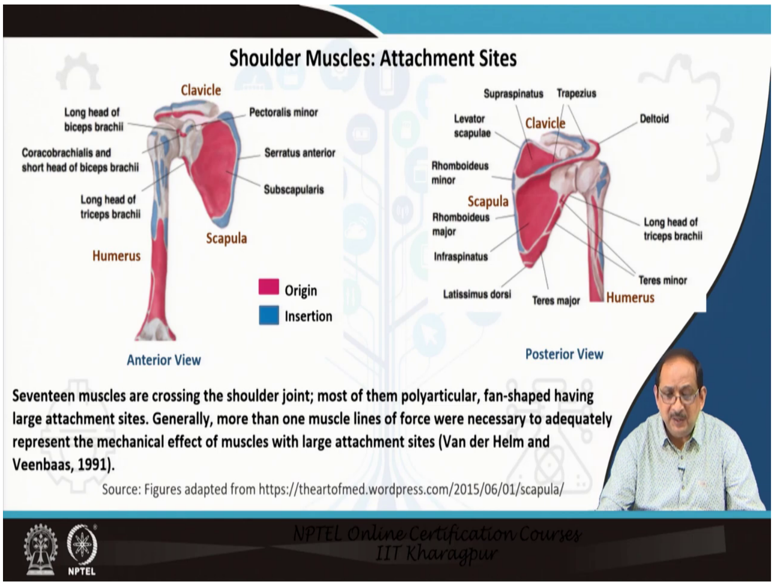

There are 17 muscles that are crossing this shoulder joint, most of them are polyarticular fan-shaped, having large attachment sizes, as seen in the image. Generally, more than one muscle lines of force are necessary to adequately represent the mechanical effect of the muscles with large attachment sites. So, you can see there are large muscles here on the posterior side of the scapula as well as on the anterior side of the scapula. And then, there are other muscles that we will be discussing more in detail.

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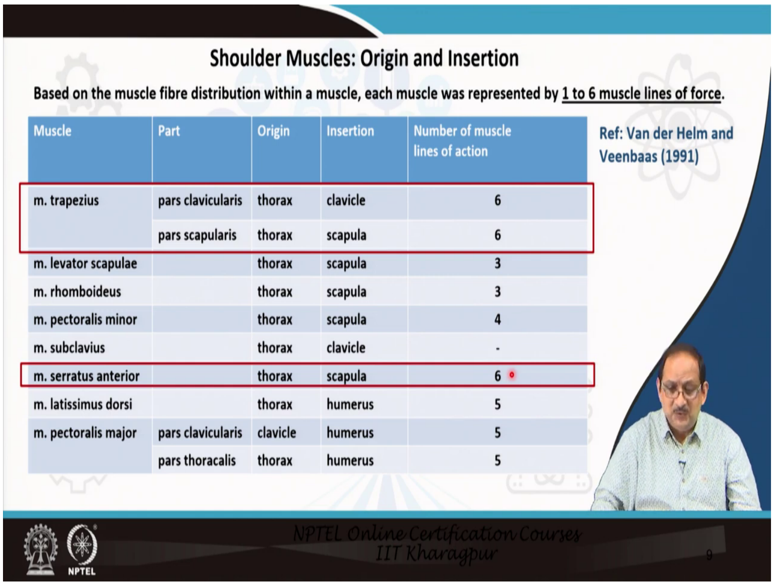

Muscle	Part	Origin	Insertion	Number of muscle lines of action
m. trapezius	pars clavicularis	thorax	clavicle	6
	pars scapularis	thorax	scapula	6
m. levator scapulae		thorax	scapula	3
m. rhomboideus		thorax	scapula	3
m. pectoralis minor		thorax	scapula	4
m. subclavius		thorax	clavicle	-
m. serratus anterior		thorax	scapula	6
m. latissimus dorsi		thorax	humerus	5
m. pectoralis major	pars clavicularis	clavicle	humerus	5
	pars thoracalis	thorax	humerus	5

So, the origin and insertion of these shoulder muscles are listed in the table. As you can see, we have the part for trapezius, there is a clavicularis part, and there is a scapular part. The origin of the muscle and the insertion of the muscle is indicated as well as the number of muscle lines of force.

Now, this number actually is based on the muscle fibre distribution within a muscle, so each muscle was represented by 1 to 6 muscle lines of force, where each element can be considered as a single independent muscle line of force. So, in this table, we highlight the muscle trapezius. As you can see for each part is represented by six lines of force. Muscle serratus anterior also has six muscle lines of force.

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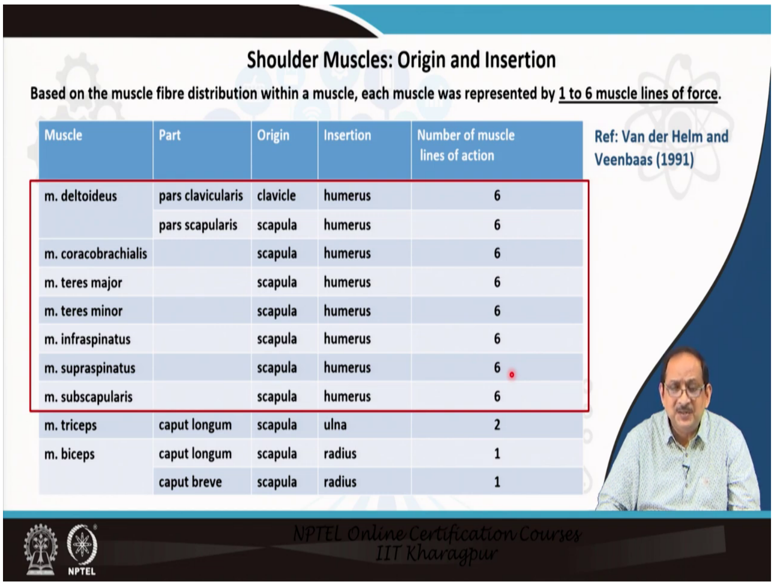

Muscle	Part	Origin	Insertion	Number of muscle lines of action
m. deltoideus	pars clavicularis	clavicle	humerus	6
	pars scapularis	scapula	humerus	6
m. coracobrachialis		scapula	humerus	6
m. teres major		scapula	humerus	6
m. teres minor		scapula	humerus	6
m. infraspinatus		scapula	humerus	6
m. supraspinatus		scapula	humerus	6
m. subscapularis		scapula	humerus	6
m. triceps	caput longum	scapula	ulna	2
m. biceps	caput longum	scapula	radius	1
	caput breve	scapula	radius	1

The table continues, where we see that the muscle deltoideus, coracobrachialis, teres major, teres minor, infraspinatus and supraspinatus, subscapularis, all have six lines of force. And they are major muscles with large attachment sites. The other muscles are also listed here, but they have fewer lines of force.

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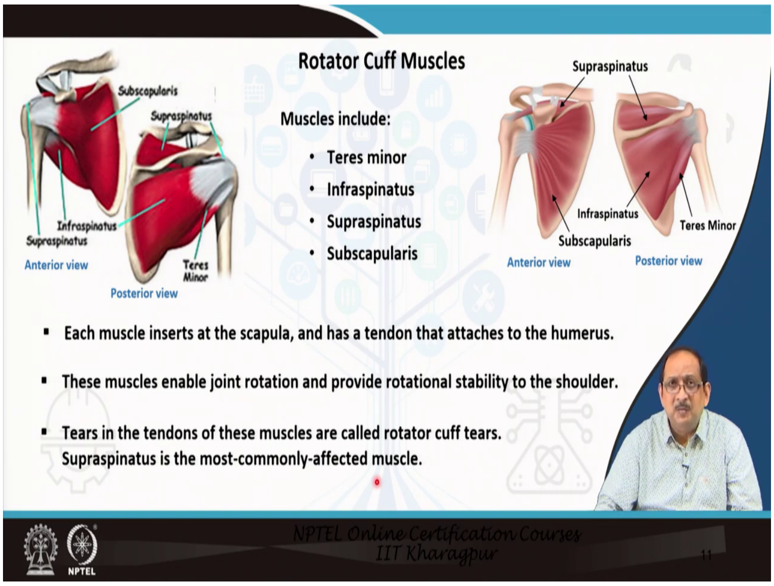

The rotator cuff muscles include four muscles: teres minor, infraspinatus, supraspinatus, and subscapularis. Each of these rotator cuff muscles inserts at the scapula, and has a tendon that attaches to the humerus. These muscles actually enable joint rotation and provide rotational stability to the shoulder. Tears in the tendons of these muscles are called rotator cuff tears; within this group of muscles supraspinatus is the most commonly affected muscle.

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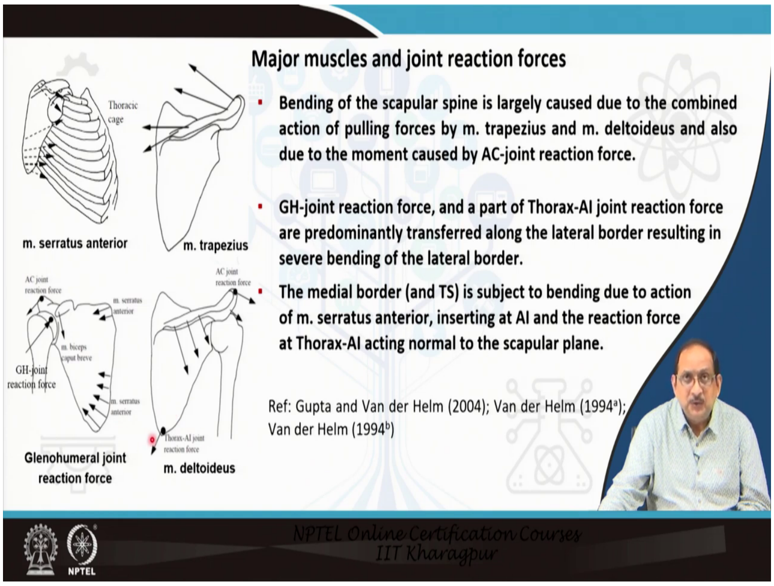

Let us figure out the action of the major muscles and joint reaction forces and their effect on the bony structures of the scapula. Muscle serratus anterior is pressing the medial border, as you can see in the figure on the top and also on the bottom. On the thorax, it is pressing the scapula on the thorax along with the muscle rhomboideus.

The reactive forces of the thorax on the scapula have been shown as two concentrated forces, one at the thorax AI, the other at the thorax trigonum spinae area. In reality, however the force is distributed along the medial border. The thorax-AI reaction force is acting normal to the scapular plane and has a large moment arm about the horizontal axis passing through the scapular spine.

Now, let us come to the action of two very important muscle, muscle trapezius and muscle deltoid. Each of these muscles is represented by six lines of force, and both these muscles are attached to the scapular spine, one on the superior side and the other on the inferior side, but the action of these muscles are opposite in direction. Around 90 degrees abduction, all parts of the muscle trapezius become active to counteract the protracting forces of muscle serratus anterior.

On the other hand, the muscle deltoid has the largest physiological cross-sectional area within all the muscles of the shoulder and exerts by far the largest moment around the glenohumeral joint. Let us now look into the effects on the bony structure of the scapula. Now, bending of the scapula spine is largely caused due to the combined action of pulling forces by muscle trapezius and muscle deltoid and also due to the moment caused by acromioclavicular AC joint reaction force.

The glenohumeral joint reaction force and a part of the thorax-AI joint reaction force is predominantly transferred along the lateral border resulting in severe bending of the lateral border, as shown in the figure. The medial border and the trigonum spinae are subject to bending action of muscle serratus anterior inserting at the annulus inferior and the reaction force at the thorax AI acting normal to the scapular plane.

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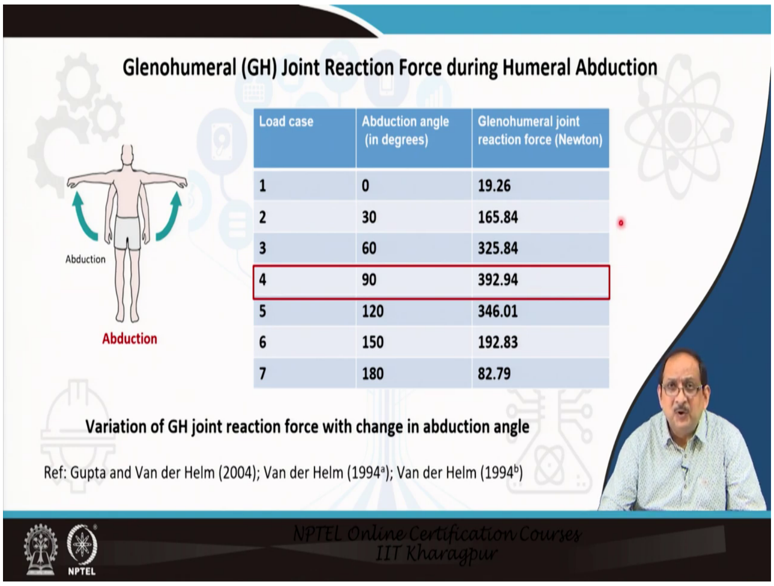

Now, in this slide, the variation of the glenohumeral joint reaction force with change in abduction angle has been presented. The glenohumeral joint reaction force is the major joint reaction force in the shoulder joint. So for different abduction angles starting from 0 degrees, 30 degrees, 60, 90, 120, till 180, we have the corresponding glenohumeral joint reaction forces. Out of this, it is clearly visible that for 90 degree abduction the glenohumeral joint reaction force is maximum, which is about 400 N, approximately 40 kg.

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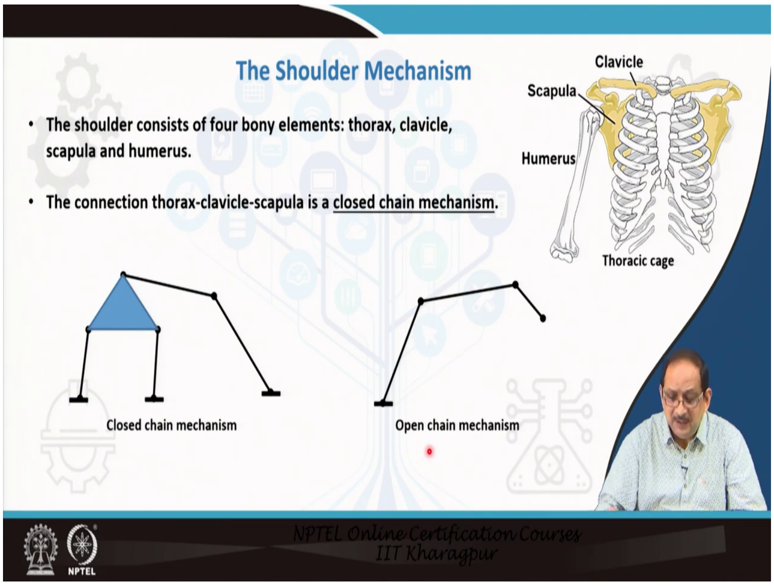

Let us come to the next topic, the shoulder mechanism. The shoulder consists of four bony element, as already discussed, the thorax or thoracic cage, the clavicle, the scapula and the humerus. The connection between the thorax, clavicle, scapula as well as thoracic is a closed chain mechanism. Now, what is this closed chain mechanism? There are two types of mechanisms one is closed chain, the other is the open chain as presented in the figure.

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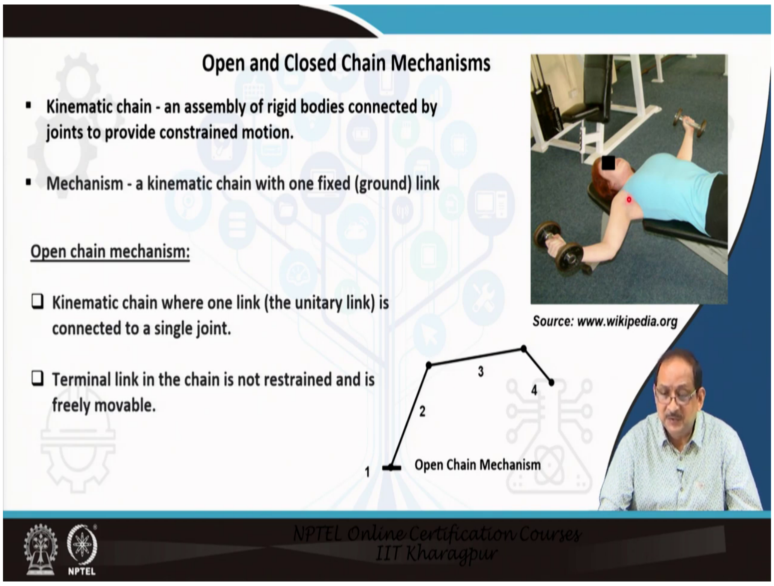

Let us briefly discuss the open and closed chain mechanisms. Now, what is a kinematic chain? A kinematic chain is an assembly of rigid bodies connected by joints to provide constrained motion, whereas a mechanism is a kinematic chain with one fixed link. Now, in case of open chain mechanism, the kinematic chain is where one link, the unitary link is connected to a single joint.

And the other important feature is the terminal link in the chain is not restrained and is freely movable, as shown in the figure. So, if I look in this example you can see the end of the arm forearm is free to move, whereas the other end at the shoulder is considered to be fixed. So, this is an example of an open chain mechanism.

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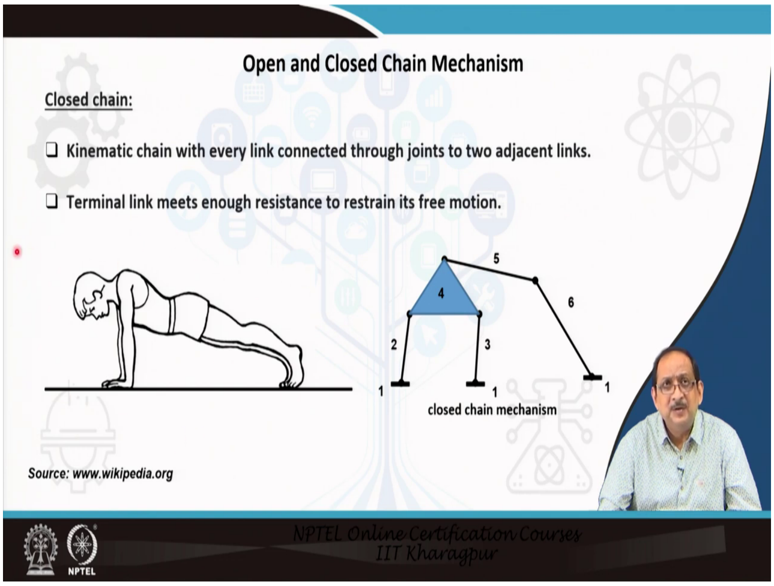

In closed chain mechanism, the kinematic chain with every link connected through joints to two adjacent links. The terminal link meets enough resistance to restrain its free motion. So, the terminal links are fixed, as also shown in a real life figure.

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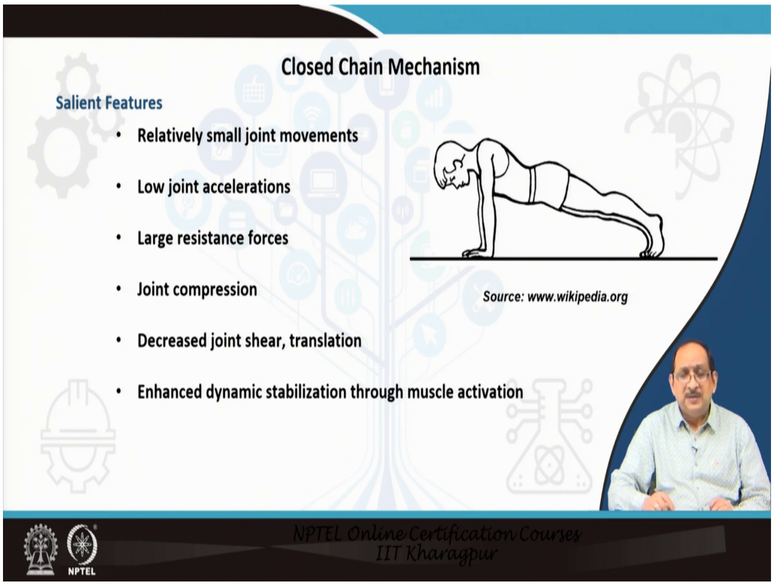

The salient features of the closed chain mechanism as encountered in the human body are: relatively small joint movements, low joint accelerations, large resistance forces, joint compression, decreased joint shear and translation, and enhanced dynamic stabilization through muscle activation.

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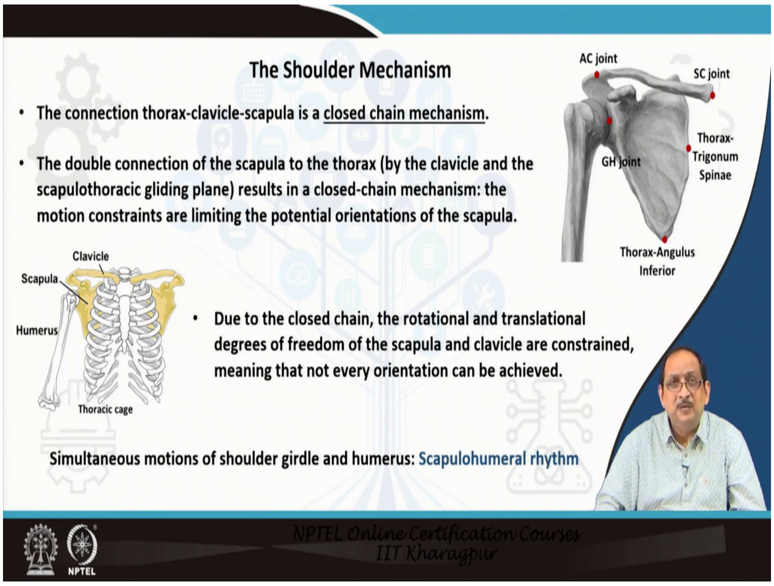

Now, let us come to the shoulder mechanism. As discussed earlier, the connection of the thorax clavicle and shoulder is a closed chain mechanism. The double connection of the scapula to the thorax, one by the clavicle, and the other by the scapula thoracic gliding plane, results in a closed chain mechanism. The motion constraints are limiting the potential orientation of the scapula.

Due to the closed chain, the rotational and translational degrees of freedom of the scapula and clavicle are constraint, meaning that not every orientation can be achieved for the scapula and the clavicle. Simultaneous motions of the shoulder girdle and humerus are actually called scapulohumeral rhythm.

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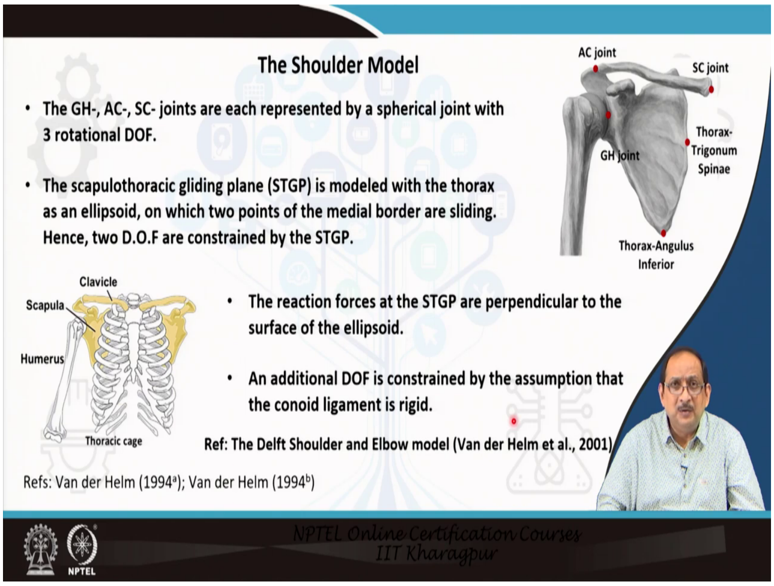

Let us come to the shoulder model. The glenohumeral, acromioclavicular, and sternoclavicular joints are represented by spherical joints with three rotational degrees of freedom. The scapulothoracic gliding plane is actually modeled with the thorax as an ellipsoid, on which two points on the medial border are sliding, hence two degrees of freedom are constrained by the scapulothoracic gliding plane.

The reaction forces at this scapula thoracic gliding plane are perpendicular to the surface of the ellipsoid at these two points, so it applies constraints at these two points along the perpendicular direction to the surface of the ellipsoid. And an additional degree of freedom is constrained by the assumption that the conoid ligament is rigid. So, this model was proposed by the Delft shoulder group, and it is popularly known as the Delft shoulder and elbow model.

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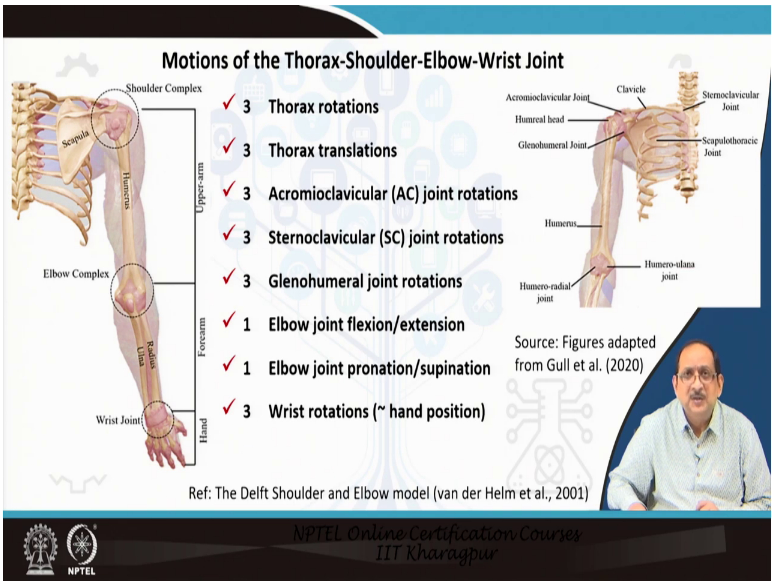

The motions of the upper extremity containing thorax, shoulder, elbow, and wrist joint may be summarized as follows. There are three rotations and three translation of the thorax. In the shoulder joint, three rotations each of acromioclavicular, sternoclavicular, and glenohumeral joints; they are all spherical joints. The elbow has one motion corresponding to flexion-extension, and the other movement is pronation-supination, so one each for these two movements. The wrist can have three rotations depending on the hand position.

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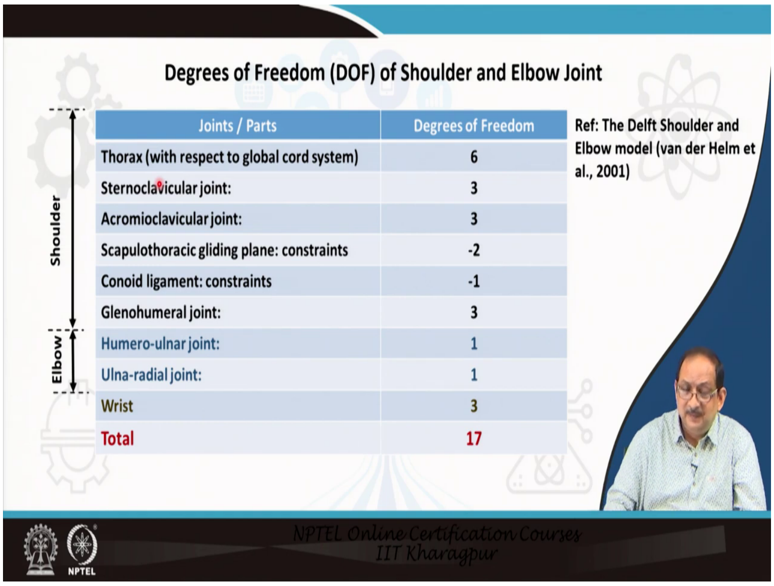

So, the degrees of freedom of the shoulder and elbow joints are listed here. So, if we consider thorax with respect to the global coordinate system, thorax has six degrees of freedom, three rotations and three translation. Sternoclavicular, acromioclavicular joint, as well as glenohumeral joint each, has three rotations. Now, these constraints are applied by the scapulothoracic gliding plane, so two constraints at the two points of contact, which is minus 2, and one by the conoid ligament, which is minus 1.

As discussed earlier, the humero-ulnar joint has one degree of freedom i.e. one rotation, and ulnar-radial joint also has one rotation i.e. 1 degree of freedom. The wrist has three degrees of freedom, so in total we have 17 degrees of freedom when we consider the thorax, the shoulder joint, and the elbow joint. If we consider the shoulder joint, shoulder, elbow and the wrist and at the same time consider the thorax to be fixed, then we would subtract the 6 degrees of freedom. Since if we try to calculate the degrees of freedom of the shoulder, elbow and wrist, excluding the thorax that is, we considered the thorax to be fixed, then we have 6 degrees of freedom less.

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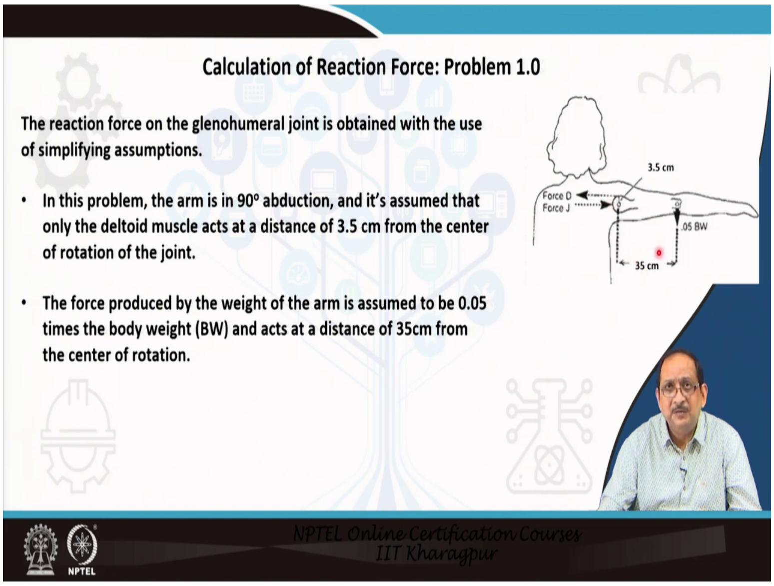

Let us now discuss two simple problems just to get an idea how to calculate the glenohumeral joint reaction force. So, the first problem as you can see, is that a subject is in the position of 90 degree abduction. So, we need to calculate the reaction force of the glenohumeral joint. There are certain simplifications in this problem.

It is assumed that only the deltoid muscle acts at a distance of 3.5 cm from the center of rotation, so as indicated here. The force produced by the weight of the arm is assumed to be

0.05 times the body weight and is acting at a distance of 35 cm from the center of rotation as indicated in the figure.

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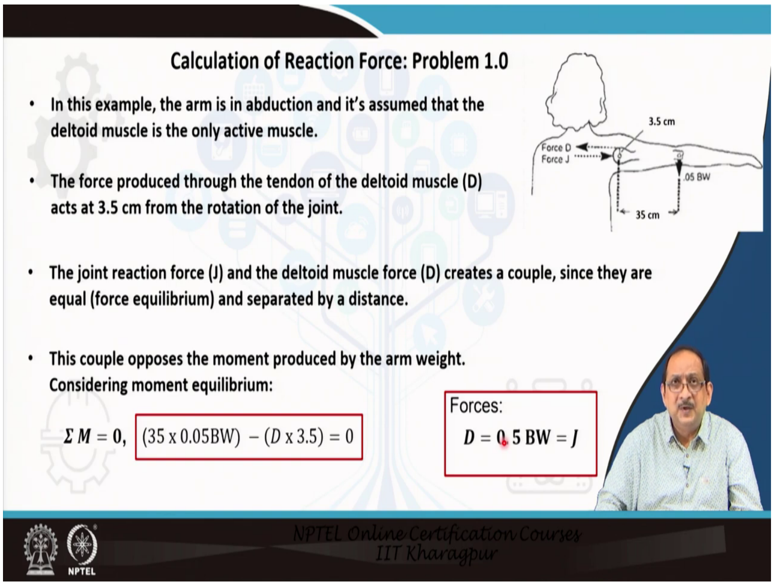

In this example, the arm is in 90 degree abduction, and it is assumed that the only the deltoid muscle is acting in this situation. So, we designate D as the force in the deltoid muscle, as indicated in the figure, the joint reaction force is indicated as J. So the joint reaction force and the deltoid muscle creates a couple since they are equal. If we consider the force equilibrium along the horizontal direction, and as a distance separates them, so this couple opposes the moment produced by the weight of the arm.

So, considering the moment equilibrium, at this center of rotation, we can form the equation which involves the weight of the arm and the deltoid muscle force, from which we can calculate the deltoid muscle force as 0.5 times the body weight. Since the deltoid muscle force is equal to the joint reaction force, glenohumeral joint reaction force, the reaction force has the same value as 0.5 times the body weight.

$$\sum M = 0$$

$$(35 \times 0.05BW) - (D \times 3.5) = 0$$

Forces: D = 0.5BW = J

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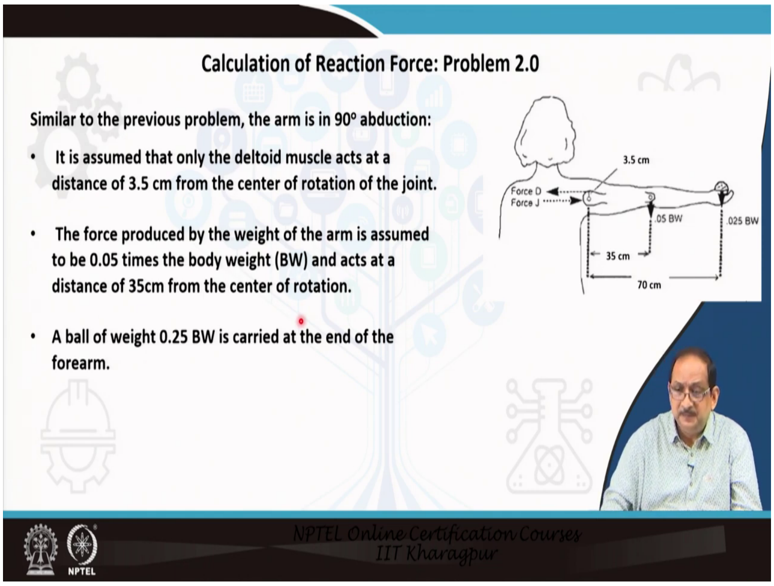

The next problem is slightly more complicated, where we have a weight or a ball at the end of the forearm. So, a ball of weight 0.25 times the body weight is carried at the end of the forearm. The rest remains the same, and we are continuing with the data in the earlier problem.

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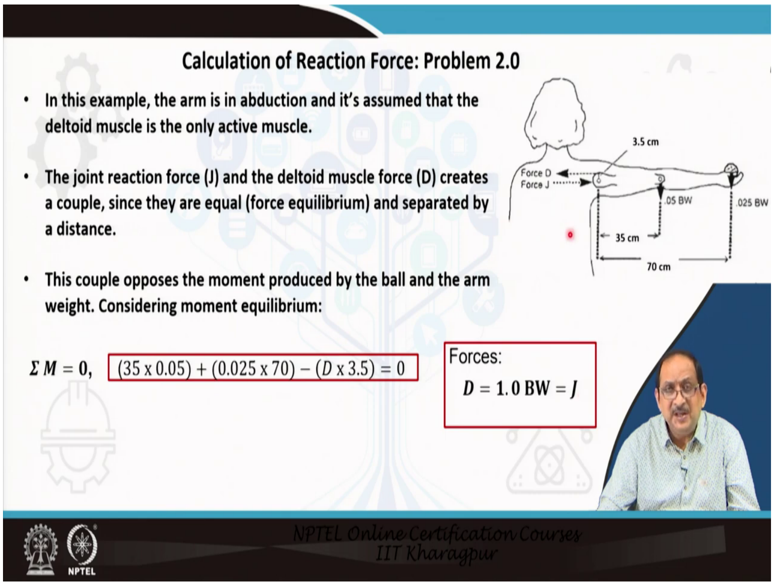

Now, the location of the ball carried at the end of the forearm is 70 cm from the center of rotation of the glenohumeral joint. So, in this case, as well, we will be considering the moment equilibrium because here also the couple opposes the moment produced by the ball and the arm. So, considering the moment equilibrium, we can actually write down the equation as indicated in the slide from which we can calculate a revised muscle force, deltoid muscle force, as one time body weight which is also equal to the glenohumeral joint reaction force as indicated in this problem.

$$\sum M = 0$$

$$(35 \times 0.05) + (0.025 \times 70) - (D \times 3.5) = 0$$

Forces: D = 1.0 BW = J

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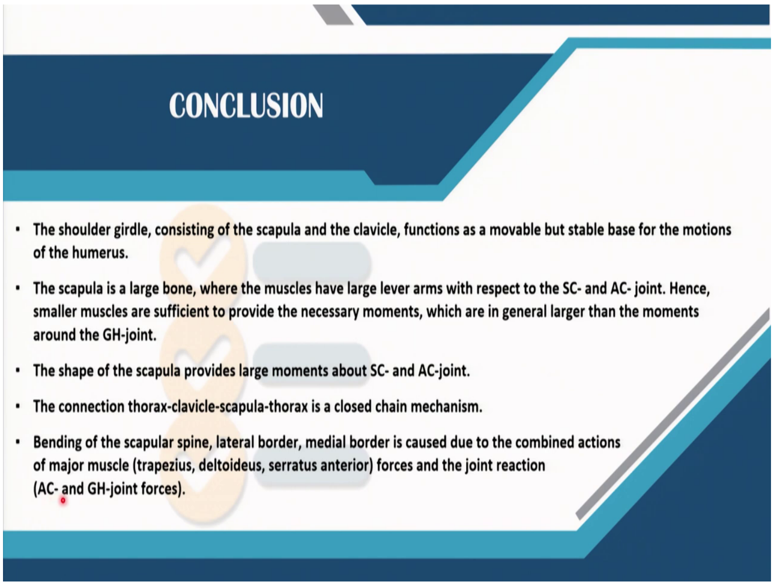

Let us come to the conclusions of this lecture. The shoulder girdle consisting of the scapula and the clavicle functions as a movable but stable base for the motions of the humerus. The scapula is a large bone where the muscles have large lever arms with respect to the sternoclavicular and the acromioclavicular joint.

Hence, the smaller muscles are sufficient to provide the necessary moments, which are in general larger than the moments around the glenohumeral joint. The shape of the scapula actually provides large moments about the sternoclavicular and acromioclavicular joints. The connection thorax-clavicle-scapula-thorax is a close chain mechanism and bending in the solid bony ridges scapular spine, lateral border, medial border is caused by the combined action of the major muscles like trapezius, deltoideus, muscle serratus anterior, muscle major muscle forces and the joint reaction forces like the glenohumeral joint reaction force and the acromioclavicular joint reaction force.

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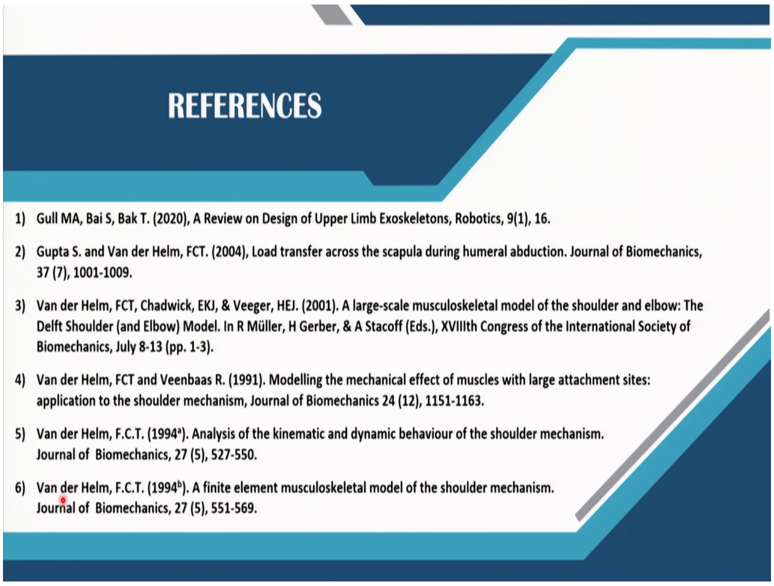

The references are listed here in this slide based on which the lecture has been prepared. Thank you for listening.