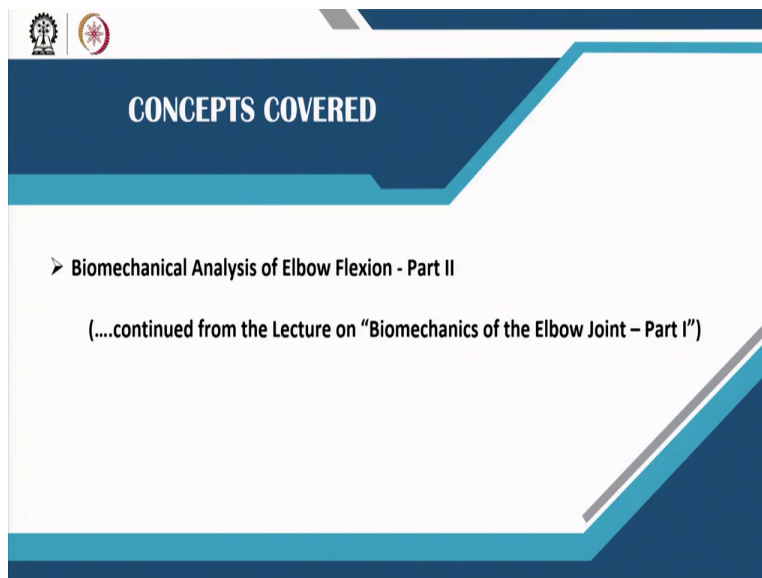


Biomechanics of Joints and Orthopaedic Implants  
Professor Sanjay Gupta  
Department of Mechanical Engineering  
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Lecture 12  
Biomechanics of the Elbow Joint Part-II

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**CONCEPTS COVERED**

➤ Biomechanical Analysis of Elbow Flexion - Part II

(....continued from the Lecture on “Biomechanics of the Elbow Joint – Part I”)


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**Biomechanical Analysis of Elbow Flexion – Part II**

As mentioned in the previous lecture, the aim of the calculation is to define the magnitudes and directions of the joint reaction forces.

- Based on geometry and given data on muscle origin and insertion, the moment arm of each muscle action about the joint axis was calculated.
- Using these moment arms about the joint axis, the muscle forces were estimated.
- Since the muscle forces have already been estimated, the joint reaction forces of humero-radial and humero-ulnar articulations need to be calculated.

First, we consider the humero-radial joint.



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Welcome to the second part of the lecture on the biomechanics of the elbow joint. This lecture is in continuation to the lecture on the biomechanics of the elbow joint part 1 discussed earlier.

Now, as mentioned in the previous lecture, the calculation aimed to define the magnitudes and directions of the joint reaction forces. Based on the geometry and the given data on muscle origin and insertion the moment arm of each muscle action about the joint axis was calculated. The muscle forces were estimated using the moment arm about the joint axis. Since the muscle forces have already been evaluated, the joint reaction forces of humeroradial and humeroulnar articulations need to be separately calculated.

In part one of the lectures, we had assumed that the radius and ulna to be one bone articulating with the humerus and based on that assumption, we had calculated the muscle forces. Now, we will be separately calculating the joint reaction forces corresponding to humeroradial articulation and humeroulnar articulations. So, we consider the humeroradial joint.

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### Humero-radial Joint Force( $R_R$ )

For the calculation of the joint reaction force, a further assumption is that the two bones carry an equal share of the limb's own weight.

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Now for the calculation of joint reaction forces, the humeral radial joint reaction force, we consider the assumption that the two bones carry an equal share of limbs on weight. The slide depicts the free body diagram consisting of the muscle forces and the limb weight, and humeroradial joint reaction force.

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**Humero-radial Joint Force ( $R_R$ )**

Now, moment applied by loading = moment applied by muscles about A.

Moment applied by muscles =  $M_{Bi} + M_{BR}$

$M_{Bi} = L_{Bi} \times F_{Bi} = 0.038 \times 1343.53 = 51.05 Nm.$

Similarly,  $M_{BR} = L_{BR} \times F_{BR} = 0.063 \times 311.24 = 19.61 Nm$

Moment applied by half of limb weight =  $0.16 \times 16.25 = 2.6 Nm$  and Moment of load acts at 0.35 m from A.

$W_R \times 0.35 + 2.6 = 51.05 + 19.61, \text{ so } W_R = 194.46 N.$

Remainder,  $311.25 - 194.46 N$  is taken by the ulna:  $W_U = 116.79 N$ , Resolving vertically,

$W_R + w/2 + R_R \cos(\alpha) = F_{BR} \sin(\gamma) + F_{Bi} \sin(\beta)$

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Now, we had already determined the angles at which these muscle forces were acting. So, we have already the values of gamma and beta. The moment applied by the external loads is equal to the moment applied by the muscles about the joint axis at A. So, the moment applied by the muscles are the moment generated by the biceps and the moment generated by the muscle brachioradialis.

Now, let us come to the moment created by the limb weight and the weight carried by the radius. Now, we do not know the amount of weight carried by the radius. So, this needs to be first determined, but we can use the moment balance equation, the equilibrium equation and determine the value of  $W_R$ , which is the weight carried by the bone radius, which comes out to be 194.46.

$$\text{Moment applied by muscles} = M_{Bi} + M_{BR}$$

$$M_{Bi} = L_{Bi} \times F_{Bi} = 0.038 \times 1343.53 = 51.05 Nm.$$

$$\text{Similarly, } M_{BR} = L_{BR} \times F_{BR} = 0.063 \times 311.24 = 19.61 Nm$$

Moment applied by half of limb weight =  $0.16 \times 16.25 = 2.6 Nm$  and Moment of load acts at 0.35 m from A.

$$W_R \times 0.35 + 2.6 = 51.05 + 19.61, \text{ so } W_R = 194.46 N.$$

*Remainder,  $311.25 - 194.46\text{N}$  is taken by the ulna:  $W_U = 116.79\text{N}$ . Resolving vertically.*

Now, the total weight carried by the elbow joint at  $90^\circ$  flexion was  $311.25\text{ N}$  out of which  $194.46\text{ N}$  is taken up by the radius bone, the remaining part that is  $116.79\text{ N}$  is carried by the ulnar. So, now, we proceed with this data calculated data of the weight carried by the radius bone and we resolve the system of forces along the vertical direction and we can write down the equation based on the laws of equilibrium summation of the forces along the vertical direction.

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**Humero-radial Joint Force ( $R_R$ )**

resolving horizontally,

$$R_R \sin(\alpha) = F_{BR} \cos(\gamma) + F_{Bi} \cos(\beta)$$

By equating the above two equations, we get:

$$\tan(\alpha) = \frac{F_{BR} \cos(\gamma) + F_{Bi} \cos(\beta)}{F_{BR} \sin(\gamma) + F_{Bi} \sin(\beta) - W_R - w/2} = \frac{311.24 \cos(15.2) + 1343.53 \cos(86.8)}{311.24 \sin(15.2) + 1343.53 \sin(86.8) - 194.46 - 16.25}$$

$\tan(\alpha) = 0.3096, \text{ therefore } \alpha = 17.2^\circ$

Substituting the value this value into the horizontally resolved equation

$$R_R = \frac{F_{BR} \cos(\gamma) + F_{Bi} \cos(\beta)}{\sin(\alpha)} = \frac{300.35 + 74.99}{0.2957} = 1269.33 \text{ N}$$

$R_R = 1269.33 \text{ N}$

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Resolving horizontally, we can write down the equation the  $R_R$ , the component of  $R_R \sin(\alpha)$  is equal to the brachioradialis muscle force's component along the horizontal direction and the horizontal component of the muscle biceps. The  $\gamma$  and  $\beta$  are the inclination angles of these forces. By equating the above two equations, we can calculate the  $\tan(\alpha)$ , where alpha is the angle of inclination of the humeroradial joint reaction force  $R_R$ . So,  $\alpha$  can be determined as  $17.2^\circ$ , substituting this value in the equation of horizontally resolved forces, we can determine the  $R_R$  to be 1269.33 N.

Resolving vertically,

$$W_R + w/2 + R_R \cos(\alpha) = F_{BR} \sin(\gamma) + F_{Bi} \sin(\beta)$$

resolving horizontally,

$$R_R \sin(\alpha) = F_{BR} \cos(\gamma) + F_{Bi} \cos(\beta)$$

By equating the above two equations, we get:

$$\tan(\alpha) = \frac{F_{BR} \cos(\gamma) + F_{Bi} \cos(\beta)}{F_{BR} \sin(\gamma) + F_{Bi} \sin(\beta) - W_R - w/2}$$

$$\tan(\alpha) = \frac{311.24 \cos(15.2) + 1343.53 \cos(86.8)}{311.24 \sin(15.2) + 1343.53 \sin(86.8) - 194.46 - 16.25}$$

$$\tan(\alpha) = 0.3096, \text{ therefore } \alpha = 17.2^\circ$$

Substituting the value this value into the horizontally resolved equation

$$R_R = \frac{F_{BR} \cos(\gamma) + F_{Bi} \cos(\beta)}{\sin(\alpha)} = \frac{300.35 + 74.99}{0.2957} = 1269.33N$$

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### Humero-radial Joint Force ( $R_R$ )

Now that  $R_R$  has been calculated, its effect upon the humero-radial contact can be considered. Resolving  $R_R$  into normal and transverse components,  $R_N$  and  $R_T$

Normal force:  $R_N = 1269.33 \cos(42.8) = 931.35\text{N}$

Tangential force:  $R_T = 1269.33 \sin(42.8) = 862.44\text{N}$

Note: The normal component  $R_N$  makes an angle of  $60^\circ$  with the humeral shaft axis.

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In the earlier slide, we calculated the angle  $\alpha$  is equal to  $17.20^\circ$ ; that is the angle at which the humeroradial joint reaction force is inclined. Now that we have calculated the magnitude of the resultant humeroradial joint reaction force  $R_R$  and its inclination  $17.20^\circ$ ; its effect upon humeroradial contact can be considered, resolving  $R_R$  into the normal and transverse component.

So,  $R_R$  can be resolved into normal component  $R_N$  and  $R_T$ , the transverse or the tangential components. We can find out the normal and the transverse or tangential force as indicated in the slide. In this calculation, we need to note that the normal component  $R_N$  makes an angle of  $60^\circ$  with the humeral shaft. So, the normal component  $R_N$  as indicated here,  $R_N$  actually makes  $60^\circ$  with the humeral shaft axis. We have calculated  $R_R$  making an angle  $17.20^\circ$  with the humeral shaft axis, then the remaining angle is  $42.80^\circ$ . So, with this angle  $42.80^\circ$ , we can calculate  $R_N$  and



$R_T$  by resolving  $R_R$  in the normal direction and the tangential or transverse direction. So, the values of  $R_N = 931.35 \text{ N}$  and  $R_T = 862.44 \text{ N}$ . Normal force:

$$R_N = 1269.33 \cos(42.8) = 931.35 \text{ N}$$

Tangential force:

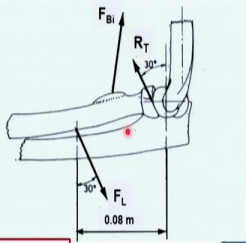
$$R_T = 1269.33 \sin(42.8) = 862.44 \text{ N}$$

The figure on the right presents a sagittal section of the humeroradial joint.

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**Calculation of the Ligamentous force**

Now, if we assume the interface friction coefficient = 0.02, the normal force will enable a tangential force of:  
 $0.02 \times 931.35 = 18.63 \text{ N}$  as the frictional force at the contact point.



- The remainder,  $862.44 - 18.63 = 843.81 \text{ N}$ , will cause sliding, and the radial head will be pulled sideways across the capitulum.
- However, that is not the case in reality, because the force is taken up by the ligamentous system, which restores the radial contact to equilibrium. It will be assumed that the forces are coplanar.

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Now comes a critical consideration in the problem that is on the calculation of the ligamentous force. On the right, we can see a figure which presents an arrangement of the articulation, the elbow joint articulation and if we assume an interface friction coefficient of 0.02 we can find out the frictional force at the point of contact as a function of the normal force that has been calculated as 931.35 N.

So, the frictional coefficient multiplied by the normal force will give you the frictional force that is actually being generated at the point of contact. Now, frictional force is along the tangential

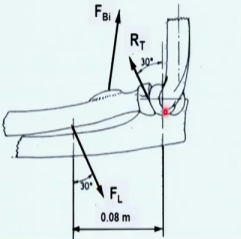
direction. Previously, the tangential component of the force was 862 N. The frictional force along the tangential direction gives rise to a force 843.81 N that will cause sliding and physically, what will happen?

This unbalanced force of 843.81 Newton along the transverse direction will move the radial head sideways across the capitulum. So, the radial head will be pulled sideways across the capitulum due to the action of this unbalanced force of 843.81 N. However, this is not the case in reality, because the force is taken up by the ligamentous system, which restores the radial contact to equilibrium.

So, it will be further assumed that the forces:  $F_L$  and  $R_T$  are coplanar.


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**Calculation of the Ligamentous force**



- The force imposed by the interosseous ligaments,  $F_L$  is assumed to act as shown in figure.
- It is equal in magnitude, and opposite in direction, to the sliding force set up at the contact point.
- As these two forces are not collinear, they impose an extension moment on the radius.

• It is assumed that the combined component of the ligaments acts at 0.08 m from the joint axis A along the radial shaft and 30° to the humeral axis.



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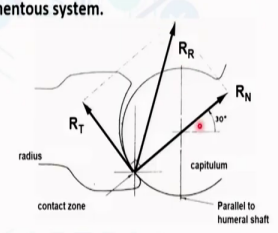
Now, let's further consider the action of the ligamentous force. The force imposed by the ligament  $F_L$  is assumed to act, as shown in the figure. It's equal in magnitude but opposite in direction to the sliding force set up at the point of contact. Sliding force is the remnant force that we had calculated earlier.

Now, as these two forces (Ligamentous force and the sliding force) are not collinear, they will impose an extension moment on the radius. Now, it is assumed that the combined component of the ligament act at a distance of 0.08 meter from the joint axis at A and along the radial shaft.

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**Recalculation of the Humero-radial Joint Force ( $R_R$ )**

- Assuming that the combined component of the ligaments acts at 0.08 m from the joint axis A along the radial shaft, the moment imposed upon radius =  $0.08 \cos 30^\circ \times 843.81 = 58.46 \text{ Nm}$ .
- The moment opposes the flexion muscle arrangement, and therefore reduces the load that can be carried.
- The resultant has to be calculated once again, since a portion of the transverse component of the reaction force is taken up by the ligamentous system.



The diagram illustrates the humero-radial joint. It shows the radius and capitulum bones. A contact zone is indicated between the radius and the capitulum. A line is drawn parallel to the humeral shaft. Three force vectors are shown:  $R_T$  (transverse component),  $R_N$  (normal component), and  $R_R$  (resultant force). A 30-degree angle is marked between the line parallel to the humeral shaft and the  $R_N$  vector.

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Now, we should recalculate the humeral radial joint reaction force considering the effect of the ligamentous force. So, assuming the combined component of the ligaments act at a distance 0.08 m from the joint axis along the radial shaft, the moment imposed upon the radius is calculated as 58.46 Nm. This moment opposes the flexion muscle arrangement and, therefore, reduces the load carried.

The resultant has to be calculated once again since the ligamentous system takes up a portion of the transverse component of the reaction force.

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**Recalculation of the Humero-radial Joint Force( $R_R$ )**

- The normal component of force,  $R_N$ , is unchanged and is 931.35 N, at  $60^\circ$  to the humeral axis.
- The transverse component,  $R_T$ , has its direction unchanged, but is now equal to 18.63 N (see Slide 8).

Thus  $R_R = \sqrt{R_N^2 + R_T^2} = \sqrt{931.35^2 + 18.63^2} = 931.54N$ .

$\tan(60^\circ - x) = 18.63/931.35$ ;  $x = 58.85^\circ$

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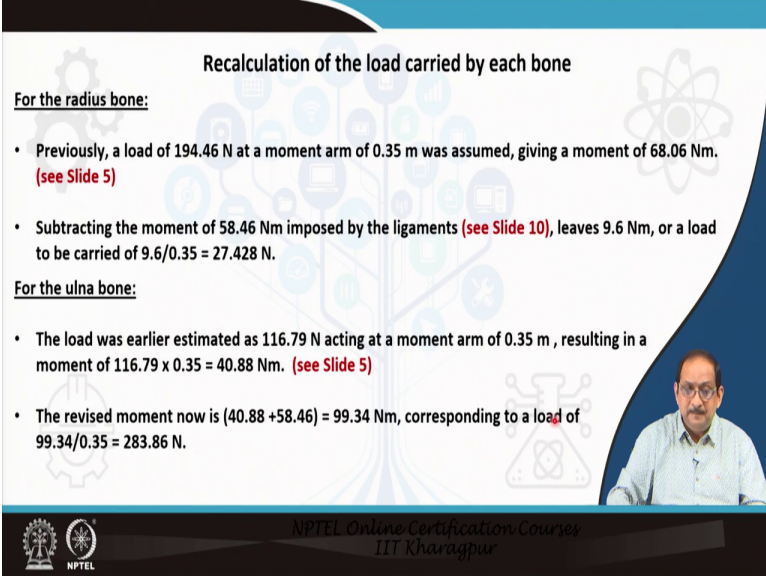
Now, the normal component of the force  $R_N$  as shown earlier in the figure. it remains unchanged and is calculated as 931.35 N acting at an angle  $60^\circ$  to the humeral axis. So, the normal component of the joint reaction force remains unchanged in direction and magnitude. However, the transverse component or the tangential component  $R_T$  has its direction intact, but now, the magnitude is equal to the frictional force that has been calculated earlier in slide 8. Please visit slide 8 for calculation on the frictional force that is 18.63 N and this frictional force is the tangential component of the joint reaction force.

So, once we have these two data, we can recalculate the revised humeroradial joint reaction force as 931.54 N and the angle  $x$ , inclination of this resultant force with the humeral axis can also be calculated, which is  $58.85^\circ$ .

$$R_R = \sqrt{R_N^2 + R_T^2} = \sqrt{931.35^2 + 18.63^2} = 931.54N.$$

$$\tan(60^\circ - x) = 18.63/931.35; x = 58.85^\circ$$

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**Recalculation of the load carried by each bone**

For the radius bone:

- Previously, a load of 194.46 N at a moment arm of 0.35 m was assumed, giving a moment of 68.06 Nm. (see Slide 5)
- Subtracting the moment of 58.46 Nm imposed by the ligaments (see Slide 10), leaves 9.6 Nm, or a load to be carried of  $9.6/0.35 = 27.428$  N.

For the ulna bone:

- The load was earlier estimated as 116.79 N acting at a moment arm of 0.35 m, resulting in a moment of  $116.79 \times 0.35 = 40.88$  Nm. (see Slide 5)
- The revised moment now is  $(40.88 + 58.46) = 99.34$  Nm, corresponding to a load of  $99.34/0.35 = 283.86$  N.

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The next important step is recalculation of the load carried by each bone because now, we have the ligaments acting in the system. So, separately we will consider the radius bone and the ulnar bone. Previously, external load of 194.46 N at a moment arm of 0.35 was assumed at giving rise to a moment of 68.06 Nm. So, for the detailed calculation you can refer back to slide 5.

Now, if we subtract the moment of 58.46 Newton meter imposed by the ligament, see calculation in slide number 10, then we are left with an unbalanced moment of 9.6 Nm. If we divide this moment by the distance 0.35m, then we recalculate the load carried by the radial segment of the bone which is 27.428 N.

For the ulna bone, the load was earlier estimated to be 116.8 N acting at a moment arm of 0.35 m resulting in a moment of 40.88 Nm. For detailed calculation, please see earlier slide number 5. Now, the revised moment can be calculated as 99.34 Nm corresponding to a load of 283.86 N.

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### Humero-ulnar Joint Force, $R_u$

The forces acting on the ulna are:

- A portion of the applied load taken by the ulna,
- Half the weight of the forearm
- Brachialis muscle ( $F_{Br}$ )
- Reaction force at joint
- Ligament forces, transferred from the radius

The diagram shows a horizontal line representing the ulna with points A, B, C, D, and E marked from right to left. At point A, the joint axis is shown with a vertical line. At point B, a force  $F_{Br}$  is applied upwards at an angle  $\beta$  to the vertical. At point C, a force  $F_L$  is applied upwards at an angle  $\gamma$  to the vertical. At point D, a weight  $w/2$  is applied downwards. At point E, a weight  $W_u$  is applied downwards. At point A, the joint reaction force  $R_u$  is shown acting along the joint axis. The angle  $\alpha$  is also indicated between the joint axis and the vertical.

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Now, let us consider the humeroulnar joint reaction force. We can see the free body diagram of the arrangement humeroulnar force. Here, we have a portion of the applied load taken by the ulnar that we have calculated just in the preceding slide, the half of the weight of the forearm as discussed earlier. We need to determine the reaction force,  $R_u$ .

But, one crucial thing included here is the ligament force transferred from the radius. So, the ligament acts between the radius and ulnar, and its line of action is indicated as  $F_L$ .

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### Humero-ulnar Joint Force, $R_U$

Resolving vertically,

$$W_U + w/2 + R_U \cos(\alpha) = F_{Br} \sin(\beta) + F_L \cos(\gamma)$$

Resolving horizontally,

$$F_{Br} \cos(\beta) = R_U \sin(\alpha) + F_L \sin(\gamma)$$

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### Humero-ulnar Joint Force, $R_U$

$$\tan(\alpha) = \frac{F_{Br} \cos(\beta) + F_L \sin(\gamma)}{F_{Br} \sin(\beta) + F_L \cos(\gamma) - W_U - w/2} = \frac{1343.53 \cos(64.6) - 843.81 \sin(30)}{1343.53 \sin(64.6) + 843.81 \cos(30) - 283.86 - 16.25}$$

$\tan(\alpha) = 0.094$ , therefore  $\alpha = 5.36^\circ$ , i.e. the direction of the reaction force

Substituting  $\alpha$  into the horizontally resolved equation, we get:

$$R_U = \frac{F_{Br} \cos(\beta) - F_L \sin(\gamma)}{\sin(\alpha)} = \frac{1343.53 \cos(64.6) - 843.81 \sin(30)}{\sin(5.36)} = \frac{154.38}{0.0934} = 1652.68N$$

With both joint reactions calculated, the forces acting on the distal humerus can be determined.

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So, we can resolve the forces based on the free body diagram and apply the laws of equilibrium. So, thereafter, we can actually calculate the inclination of the angle of the humero ulnar joint reaction force, which can be calculated using the two equations and the data already available to us.

Resolving vertically,

$$W_U + w/2 + R_U \cos(\alpha) = F_{Br} \sin(\beta) + F_L \cos(\gamma)$$



Resolving horizontally,

$$F_{Br} \cos(\beta) = R_U \sin(\alpha) + F_L \sin(\gamma)$$

Equating both the equations and rearranging, we get

$$\tan(\alpha) = \frac{F_{BR} \cos(\beta) + F_L \sin(\gamma)}{F_{Br} \sin(\beta) + F_L \cos(\gamma) - W_U - w/2}$$
$$\tan(\alpha) = \frac{1343.53 \cos(64.6) - 843.81 \sin(30)}{1343.53 \sin(64.6) + 843.81 \cos(30) - 283.86 - 16.25}$$

$\tan(\alpha) = 0.094$ , therefore  $\alpha = 5.36^\circ$ , i. e. the direction of the reaction force

Substituting  $\alpha$  into the horizontally resolved equation, we get:

$$R_U = \frac{F_{Br} \cos(\beta) - F_L \sin(\gamma)}{\sin(\alpha)} = \frac{1343.53 \cos(64.6) - 843.81 \sin(30)}{\sin(5.36)} = \frac{154.38}{0.0934} = 1652.68N$$

You can see the updated load  $W_u$  has been considered, which is 283.86 N, and of course, the limb weight, half of the limb weight is 16.25 N. So, with this new data, we calculate the angle,  $\alpha$  as  $5.36^\circ$  and after that, we can calculate the magnitude of the reaction force  $R_u$  as 1652.68 N. Now with both reactions forces estimated, the forces acting on the distal humerus can also be determined.

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**Axial Loading of Distal Humerus**

Axial load is given by the vertical components of the two reaction forces,  $R_U$  and  $R_R$ .

$$F_{axial} = R_R \cos(x) + R_U \cos(\alpha) = 931.54 \cos(58.85) + 1652.68 \cos(5.36) = 2126.62 N.$$

See Slide 11, for calculation of angle  $x$ .

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We have come to a stage that we have two separate joint reaction forces; one is the humeroulnar joint reaction force, the other is the humeroradial joint reaction force. Now, if we want to calculate the load at the distal end of the humerus, we need the vertical components of the two joint reaction forces.

$$F_{axial} = R_R \cos(x) + R_U \cos(\alpha) = 931.54 \cos(58.85) + 1652.68 \cos(5.36) = 2126.62 N.$$

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**Axial Loading of Distal Humerus**

Axial loading on distal humerus = 2126.62N This is remarkably high load, being more than twice body weight. The cross sectional area of the cortical bone in the humeral shaft is about 200 mm<sup>2</sup>

$$\text{mean compressive stress} = \frac{2126.62 \times 10^6}{200} = 10.63 \times 10^6 \text{ N/m}^2.$$

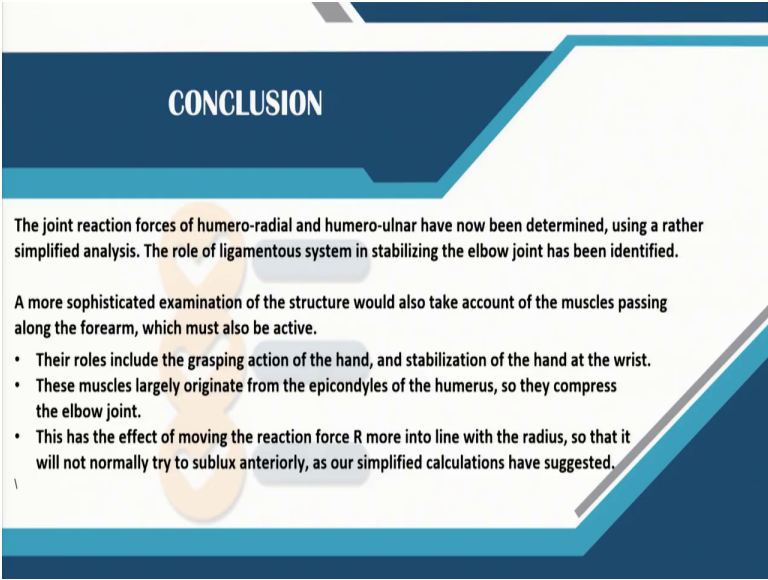
This stress is low compared with the compressive limit of elastic behaviour for humeral bone of 864 × 10<sup>6</sup> N/m<sup>2</sup>

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Now, if we consider the cross-sectional area of the cortical bone in the humeral shaft, the cross-sectional area is about 200 mm<sup>2</sup>. So, the mean compressive stress can be calculated as the axial force divided by the cross-sectional area, and it comes out to approximately 10.63 MPa. This stress is lower than the compressive strength of the humeral bone, which is about 864 MPa.

$$\text{mean compressive stress} = \frac{2126.62 \times 10^6}{200} = 10.63 \times 10^6 \text{ N/m}^2.$$

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## CONCLUSION

The joint reaction forces of humero-radial and humero-ulnar have now been determined, using a rather simplified analysis. The role of ligamentous system in stabilizing the elbow joint has been identified.

A more sophisticated examination of the structure would also take account of the muscles passing along the forearm, which must also be active.

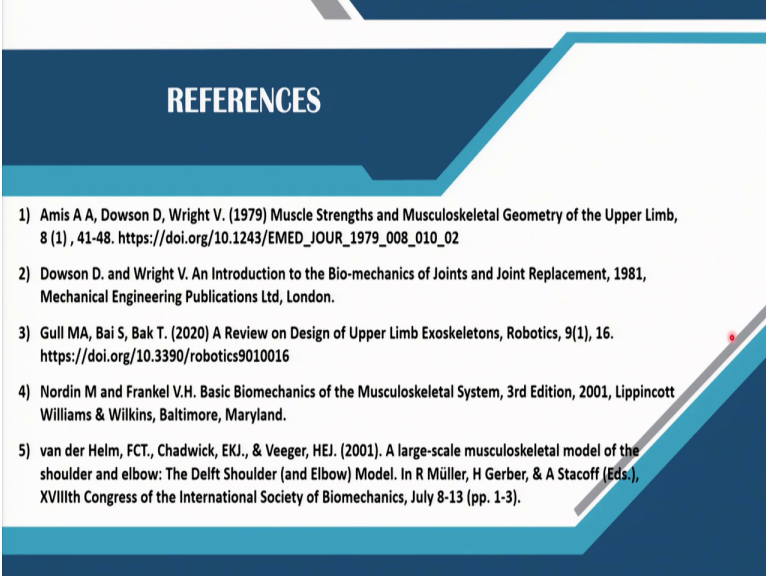
- Their roles include the grasping action of the hand, and stabilization of the hand at the wrist.
- These muscles largely originate from the epicondyles of the humerus, so they compress the elbow joint.
- This has the effect of moving the reaction force R more into line with the radius, so that it will not normally try to sublux anteriorly, as our simplified calculations have suggested.

So, let us come to the conclusion of this lecture, both part one and part two together. What did we learn from the biomechanical analysis of the elbow joint, the joint reaction force both humeroradial and humero ulnar separately has now been determined using a rather simplified analysis. The role of the ligamentous system most importantly, in stabilizing the elbow joint has been identified.

However, a more sophisticated examination of the structure would also take into account the muscles passing along the forearm even though we did not account for these muscles. Their role includes the hand's grasping action and stabilization at the wrist. These muscles originate from the epicondyles of the humerus, so they compress the elbow joint.

So, this has the effect of moving the reaction force  $R$  more in line with the radius bone so, that it will not normally try to subluc anteriorly as our simplified calculations have suggested.

(Refer Slide Time: 32:49)



## REFERENCES

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- 2) Dowson D. and Wright V. An Introduction to the Bio-mechanics of Joints and Joint Replacement, 1981, Mechanical Engineering Publications Ltd, London.
- 3) Gull MA, Bai S, Bak T. (2020) A Review on Design of Upper Limb Exoskeletons, Robotics, 9(1), 16. <https://doi.org/10.3390/robotics9010016>
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- 5) van der Helm, FCT., Chadwick, EKJ., & Veeger, HEJ. (2001). A large-scale musculoskeletal model of the shoulder and elbow: The Delft Shoulder (and Elbow) Model. In R Müller, H Gerber, & A Stacoff (Eds.), XVIIIth Congress of the International Society of Biomechanics, July 8-13 (pp. 1-3).

I hope you could follow the calculations presented in this lecture. The list of references are indicated in these slides. I would like to thank you for listening.