Biomechanics of the Human Upper Limb – The Shoulder Joint

1. Introduction

The **upper limb** of the human body demonstrates a remarkable range of movement and strength, allowing for complex actions such as throwing, lifting, typing, and swimming. Understanding its **biomechanical structure** is essential for the design of prosthetic and orthotic systems that can replicate or support natural movement.

2. Structure of the Shoulder

The **shoulder** is the most complex joint system in the human body, consisting of **five articulations** that work together to provide mobility and stability:

- **Sternoclavicular joint**
- **Acromioclavicular joint**
- **Coracoclavicular joint**
- **Glenohumeral joint**
- **Scapulothoracic joint**

2.1 Sternoclavicular Joint

This joint is a **modified ball-and-socket joint** between the proximal end of the clavicle and the **manubrium of the sternum**.

A **fibrocartilaginous disc** enhances the fit of the articular surfaces and serves as a **shock absorber**. It allows motion in the **frontal**, **transverse**, and limited **sagittal** planes. It is the major axis for **rotation of the clavicle and scapula**, and its close-packed position occurs with **maximal shoulder elevation**. **Fig.1:** The sternoclavicular joint.

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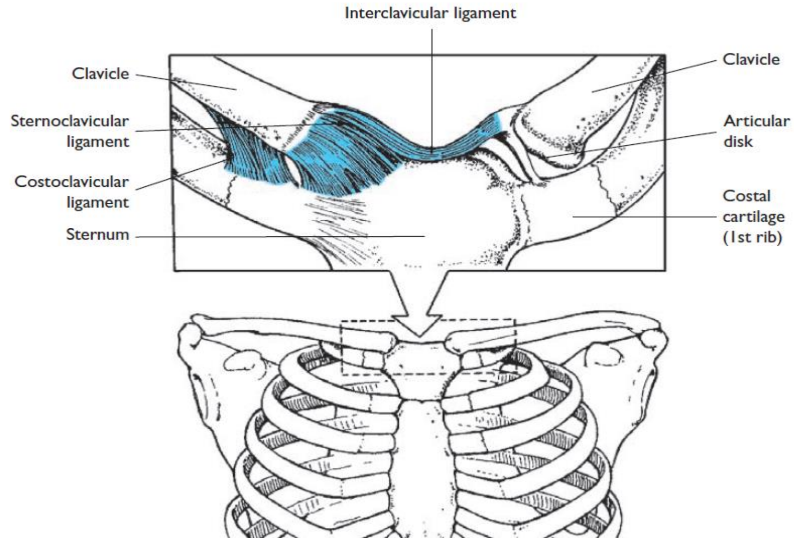
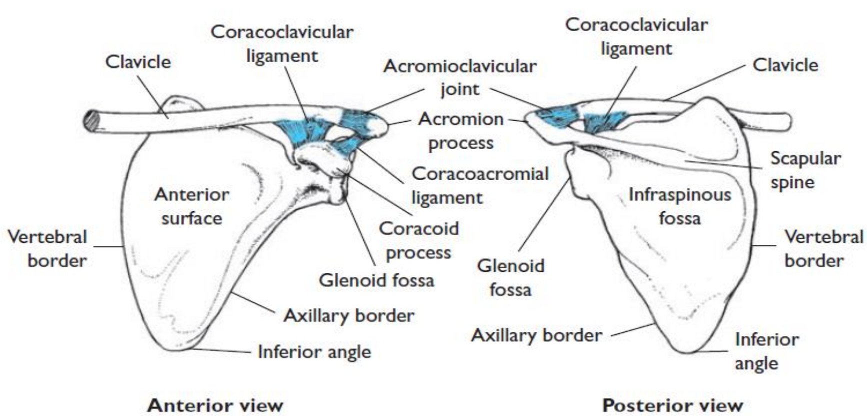


2.2 Acromioclavicular Joint

An **irregular diarthrodial joint** between the **acromion process** of the scapula and the **distal clavicle**. It allows limited motion in all planes and rotates during **arm elevation**. The joint is most stable when the humerus is **abducted to 90°**.

2.3 Coracoclavicular Joint

A **syndesmosis** where the **coracoid process** of the scapula is bound to the **inferior clavicle** by the **coracoclavicular ligament**. It allows very little movement but provides **stability** to the shoulder girdle. The coracoclavicular and acromioclavicular joints are shown in **Fig.2.**



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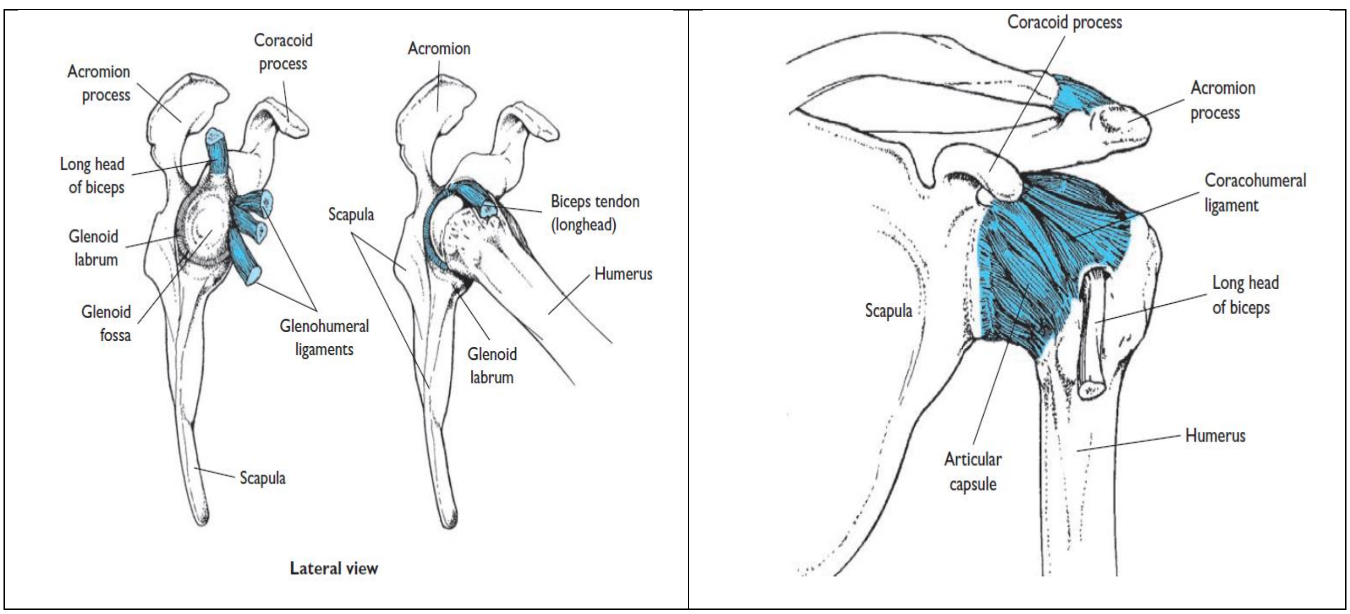
2.4 Glenohumeral Joint

This **ball-and-socket joint** is the most mobile articulation in the human body, allowing:

- **Flexion**, **extension**, **hyperextension**
- **Abduction**, **adduction**
- **Medial and lateral rotation**
- **Horizontal abduction/adduction**

Because the **humeral head** is much larger than the **glenoid fossa**, the shoulder sacrifices **stability** for **mobility**. The **glenoid labrum**, a rim of fibrocartilage, deepens the fossa and adds **stability**. The joint capsule is reinforced by **superior**, **middle**, and **inferior glenohumeral ligaments**, as well as the **coracohumeral ligament**. See **Fig.3.**



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Rotator Cuff Muscles (SITS Muscles)

Four muscles form the **rotator cuff**, which stabilizes and rotates the humerus:

- **Supraspinatus** – initiates abduction and assists in lateral rotation
- **Infraspinatus** – lateral rotation
- **Teres minor** – lateral rotation
- **Subscapularis** – medial rotation

Together, they form a **collagenous cuff** around the joint capsule and maintain **joint stability** by pulling the humeral head toward the glenoid fossa.

2.5 Scapulothoracic Joint

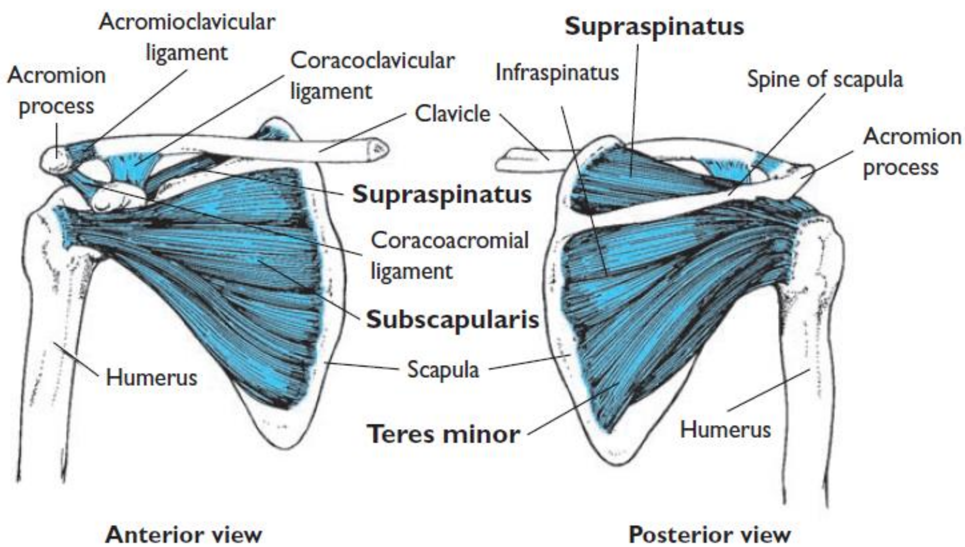
Not a true anatomical joint, but a **functional articulation** between the **anterior scapula** and the **posterior thoracic wall**. Muscles such as the **trapezius**, **levator scapulae**, and **rhomboids** stabilize or move the scapula, facilitating **upper limb movement**. During lifting or throwing, scapular motion ensures correct **positioning of the glenohumeral joint**.

Bursae of the Shoulder

Small sacs known as **bursae** reduce friction between soft tissues.
Important bursae in the shoulder region include:

- **Subscapularis bursa**
- **Subcoracoid bursa**
- **Subacromial bursa**

The **subacromial bursa** cushions the **supraspinatus tendon** beneath the **acromion** and **coracoacromial ligament**. (See **Fig. 4**)



3. Movements of the Shoulder Complex

The shoulder complex exhibits a **coordinated movement pattern** known as the **scapulohumeral rhythm**, where:

- For the first **30°** of humeral elevation, the scapula contributes about **1-5** of the total motion.
- Beyond 30°, the scapula rotates **1°** for every **2°** of humeral elevation. This rhythm allows smooth and efficient **arm elevation** (flexion and abduction).

4 Muscles Acting on the Shoulder

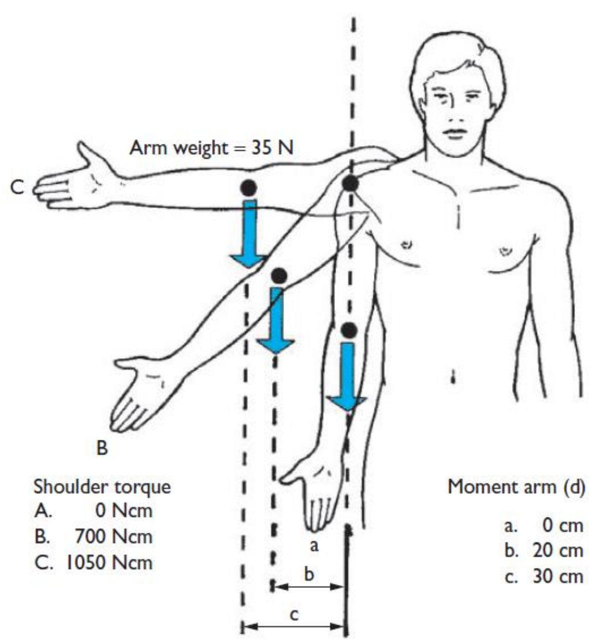
- **Flexion:** Anterior deltoid and clavicular pectoralis major are the main flexors.
- **Extension:** Latissimus dorsi, teres major, and posterior deltoid extend the arm.
- **Abduction:** Supraspinatus initiates, and middle deltoid continues abduction.
- **Adduction:** Latissimus dorsi, teres major, and sternal pectoralis major.

- **Medial Rotation:** Subscapularis and teres major.
- **Lateral Rotation:** Infraspinatus and teres minor.
- **Horizontal Movements:**
  - **Adduction:** Pectoralis major, anterior deltoid.
  - **Abduction:** Posterior deltoid, infraspinatus, teres minor.

5 Loads on the Shoulder

The **shoulder complex** supports the weight of the arm and any external load, making it one of the most mechanically stressed regions of the upper body. Because the **glenohumeral joint** is highly mobile, it experiences large **muscle and joint reaction forces**, even during simple arm elevation.

When the arm is raised or extended away from the body, its **weight acts at the center of gravity**, creating a **torque** around the shoulder joint. (see **Fig.5**).



As the arm moves farther from the trunk, the **moment arm** increases, and the **muscles—especially the deltoid—must produce greater tension** to balance that torque.

In **Fig. 6**, the arm is divided into two segments (upper arm and forearm/hand), each contributing to the total torque.

When the elbow is flexed, the total torque decreases slightly because the **forearm's moment arm shortens**, reducing the load on the shoulder.

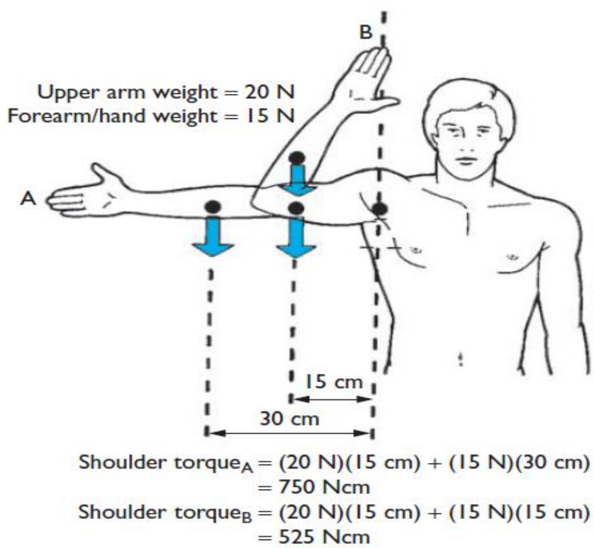
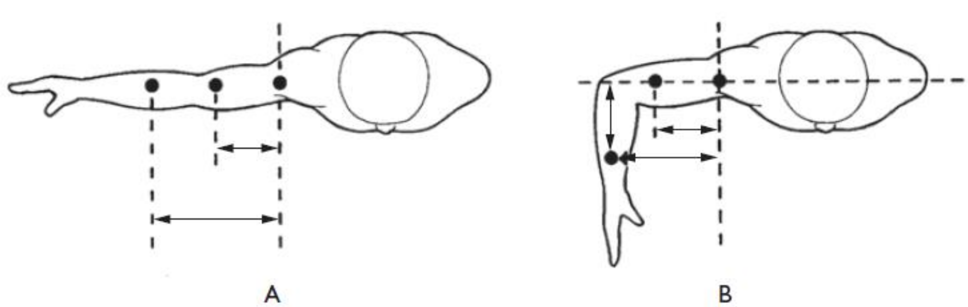


Fig. 7 shows that these torques act in both **frontal and sagittal planes**, meaning the shoulder muscles must stabilize the joint in multiple directions during arm movement. Even though the arm's weight is small (about 5% of body weight), its length magnifies the **rotational effect**, producing joint forces that may reach **up to 50% of body weight**.

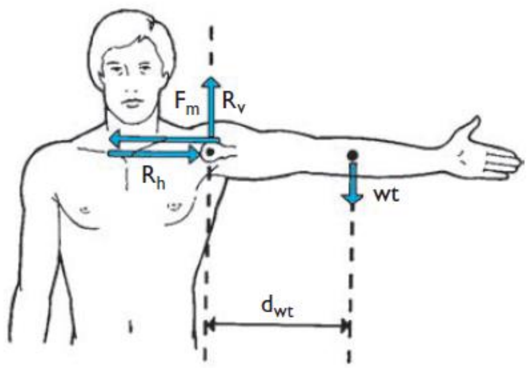


SAMPLE PROBLEM. I

Using the simplifying assumptions of Poppen and Walker (38), a free body diagram of the arm and shoulder can be constructed as shown below. If the weight of the arm is 33 N, the moment arm for the total arm segment is 30 cm, and the moment arm for the deltoid muscle (F_m) is 3 cm, how much force must be supplied by the deltoid to maintain the arm in this position? What is the magnitude of the horizontal component of the joint reaction force (R_h)?

Known

$$wt = 33\ N$$
$$d_{wt} = 30\ cm$$
$$d_m = 3\ cm$$



Solution

The torque at the shoulder created by the muscle force must equal the torque at the shoulder created by arm weight, yielding a net shoulder torque of zero.

$$\sum T_s = 0$$
$$\sum T_s = (F_m)(d_m) - (wt)(d_{wt})$$
$$0 = (F_m)(3\ cm) - (33\ N)(30\ cm)$$
$$0 = (F_m)(3\ cm) - (33\ N)(30\ cm)$$
$$F_m = \frac{(33\ N)(30\ cm)}{3\ cm}$$
$$F_m = 330\ N$$

Since the horizontal component of joint reaction force (R_h) and F_m are the only two horizontal forces present, and since the arm is stationary, these forces must be equal and opposite. The magnitude of R_h is therefore the same as the magnitude of F_m.

$$R_h = 330\ N$$

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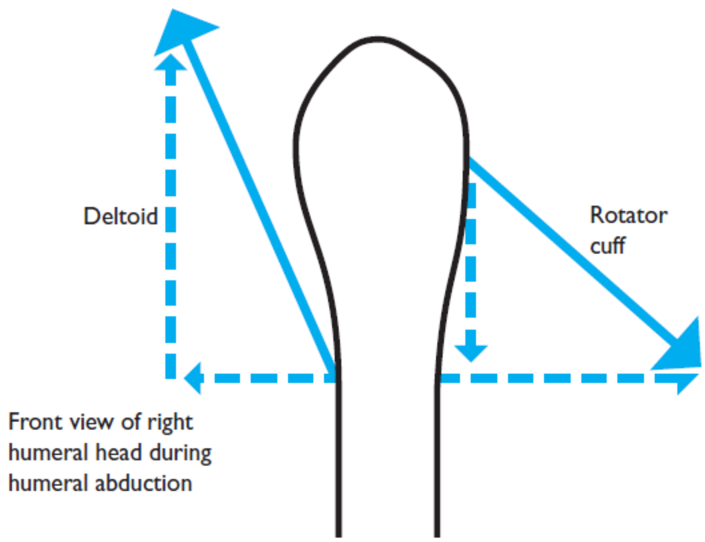
Finally, **Fig .8** illustrates the **cooperative action** between the **deltoid** and **rotator cuff** muscles.

The **deltoid** tends to pull the humeral head upward, while the **rotator cuff** exerts a downward and stabilizing force, keeping the humeral head centered in the **glenoid fossa**. This balance between shear and compressive forces ensures **joint stability during abduction** and prevents dislocation.



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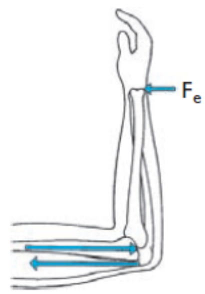
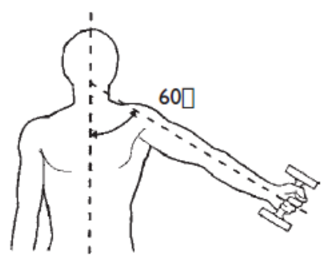
1. How much tension (F_m) must be supplied by the triceps to stabilize the arm against an external force (F_e) of 200 N, given d_m = 2 cm and d_e = 25 cm? What is the magnitude of the joint reaction force (R)? (Since the forearm is vertical, its weight does not produce torque at the elbow.) (Answer: F_m = 2500 N, R = 2700 N)



2. What is the length of the moment arm between the dumbbell and the shoulder when the extended 50 cm arm is positioned at a 60° angle? (Answer: 43.3 cm)



3. The medial deltoid attaches to the humerus at an angle of 15°. What are the sizes of the rotary and stabilizing components of muscle force when the total muscle force is 500 N? (Answer: rotary component = 129 N, stabilizing component = 483 N)