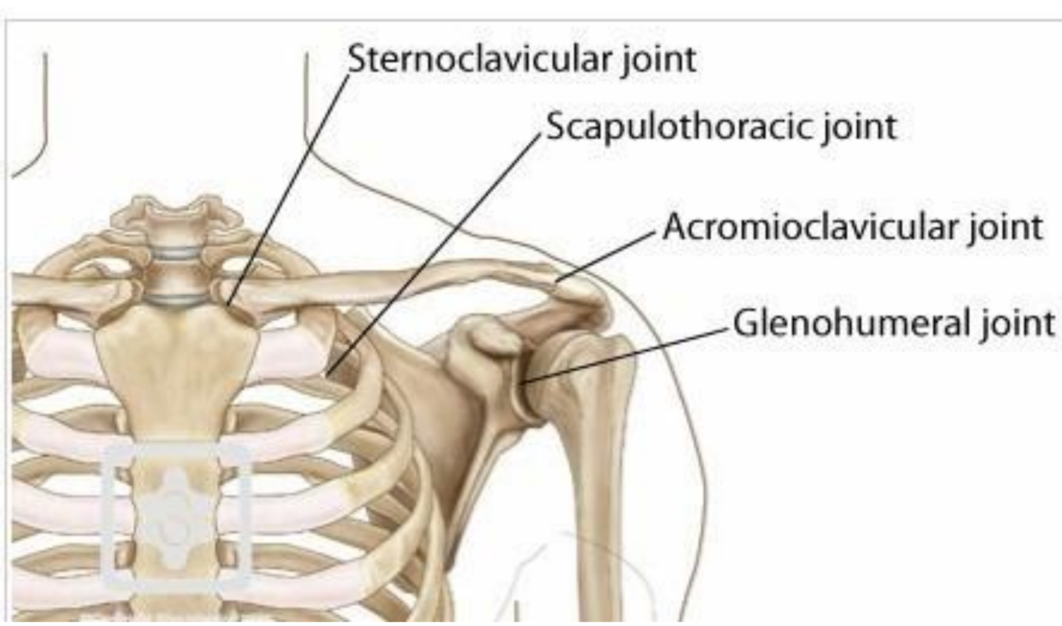
Lecture No.: 5

The Biomechanics of the Human Upper Extremity

STRUCTURE OF THE SHOULDER

The shoulder is the most complex joint in the human body, largely because it includes five separate articulations: the glenohumeral joint, the sternoclavicular joint, the acromioclavicular joint, the coracoclavicular joint, and the scapulothoracic joint. The glenohumeral joint is the articulation between the head of the humerus and the glenoid fossa of the scapula, which is the ball-and-socket joint typically considered to be the major shoulder joint. The sternoclavicular and acromioclavicular joints provide mobility for the clavicle and the scapula—the bones of the shoulder girdle.



Joints of the Shoulder Complex

Sternoclavicular Joint

Modified ball-and-socket joint between the proximal clavicle and the manubrium of the sternum.

- The clavicles and the scapulae make up the shoulder girdle.
- Most of the motion of the shoulder girdle takes place at the sternoclavicular joints.

Acromioclavicular Joint

The articulation of the acromion process of the scapula with the distal end of the clavicle is known as the acromioclavicular joint. It is classified as an irregular diarthrodial joint, although the joint's structure allows limited motion in all three planes.

Coracoclavicular Joint

The coracoclavicular formed where the coracoid process of the scapula and the inferior surface of the clavicle are bound together by the coracoclavicular ligament. This joint permits little movement.

Glenohumeral Joint

The glenohumeral joint is the most freely moving joint in the human body, enabling flexion, extension, hyperextension, abduction, adduction, horizontal abduction and adduction, and medial and lateral rotation of the humerus (Figure 1). The almost hemispherical head of the humerus has three to four times the amount of surface area as the shallow glenoid fossa of the scapula with which it articulates. The glenoid fossa is also less curved than the surface of the humeral head, enabling the humerus to move linearly across the surface of the glenoid fossa in addition to its extensive rotational capability.

The tendons of four muscles also join the joint capsule. These are known as the rotator cuff muscles because they contribute to rotation of the humerus and because their tendons form a collagenous cuff around the glenohumeral joint. These include supraspinatus, infraspinatus, teres minor, and subscapularis. The muscles of the lateral rotator group exchange muscle bundles with one another, which increases their ability to quickly develop tension and functional power. The rotator cuff surrounds the shoulder on the posterior, superior, and anterior sides. Tension in the rotator cuff muscles pulls the head of the humerus toward the glenoid fossa, contributing significantly to the joint's minimal stability. It has been shown that the rotator cuff muscles and the biceps are activated to provide shoulder stability prior to motion of the humerus.

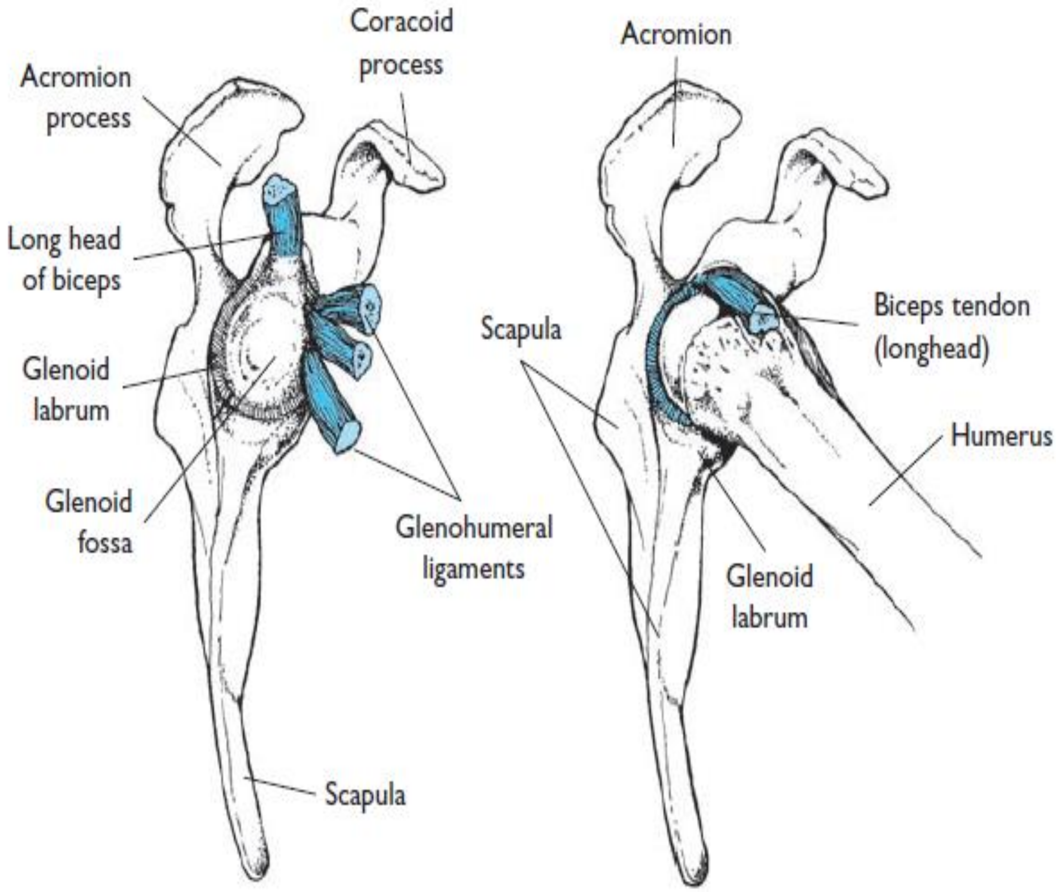


Figure 1: The glenohumeral joint

Scapulothoracic Joint

Because the scapula can move in both sagittal and frontal planes with respect to the trunk, the region between the anterior scapula and the thoracic wall is sometimes referred to as the scapulothoracic joint. The muscles attaching to the scapula perform two functions. First, they can contract to stabilize the shoulder region. Second, the scapular muscles can facilitate movements of the upper extremity through appropriate positioning of the glenohumeral joint.

Bursae

Several small, fibrous sacs that secrete synovial fluid internally in a fashion similar to that of a joint capsule are located in the shoulder region. These sacs, known as bursae, cushion and reduce friction between layers of collagenous tissues. The shoulder is surrounded by several bursae, including the subscapularis, subcoracoid, and subacromial.

MOVEMENTS OF THE SHOULDER COMPLEX

Although some amount of glenohumeral motion may occur while the other shoulder articulations remain stabilized, movement of the humerus more commonly involves some movement at all three shoulder joints (figure 2).

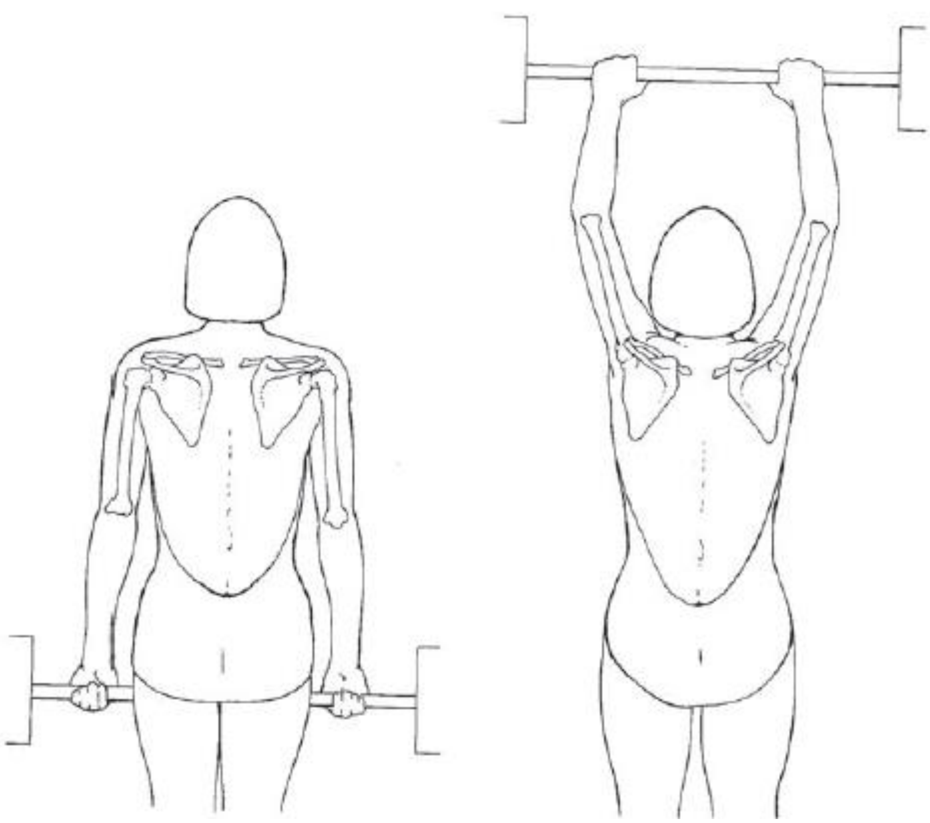


Figure 2: Elevation of the arm is accompanied by rotation of the clavicle and scapula

Elevation of the humerus in all planes is accompanied by approximately 55° of lateral rotation. As the arm is elevated in both abduction and flexion, rotation of the scapula accounts for part of the total humeral range of motion. Although the absolute positions of the humerus and scapula vary due to anatomical variations among individuals, a general pattern persists. During about the first 30° of humeral elevation, the contribution of the scapula is only about one-fifth that of the glenohumeral joint. As elevation proceeds beyond 30°, the scapula rotates approximately 1° for every 2° of movement of the humerus. This important coordination of scapular and humeral movements, known as scapulohumeral rhythm, enables a much greater range of motion at the shoulder than if the scapula were fixed. During the first 90° of arm elevation (in sagittal, frontal, or diagonal planes), the clavicle is also elevated through approximately 35–45° of motion at the sternoclavicular joint. Rotation at the acromioclavicular joint occurs during the first 30° of humeral elevation and again as the arm is moved from 135° to maximum elevation. Positioning of the humerus is further facilitated by motions of the spine. When the hands support an external load, the orientation of the scapula and the scapulohumeral rhythm are altered, with muscular stabilization of the scapula reducing scapulothoracic motion as dynamic scapular stabilization provides a platform for upper extremity movements. Generally, scapulohumeral relationships are more fixed when the arm is loaded and engaged in purposeful movement as compared to when the arm is moving in an unloaded condition.

Muscles of the Scapula

The muscles that attach to the scapula are the levator scapula, rhomboids, serratus anterior, pectoralis minor, and subclavius, and the four parts of the trapezius. Figures 3 and 4 show the directions in which these muscles exert force on the scapula when contracting. Scapular muscles have two general functions. First, they stabilize the scapula so that it forms a rigid base for muscles of the shoulder during the development of tension. Second, scapular muscles facilitate movements of the upper extremity by positioning the glenohumeral joint appropriately.

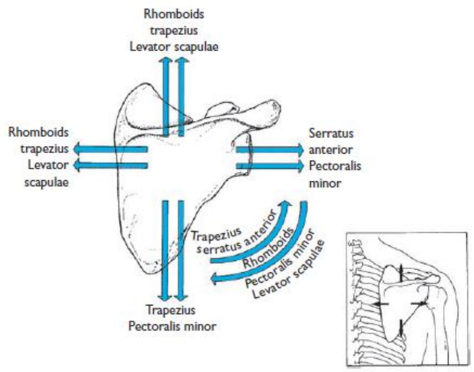


Figure 3: Actions of the scapular muscles

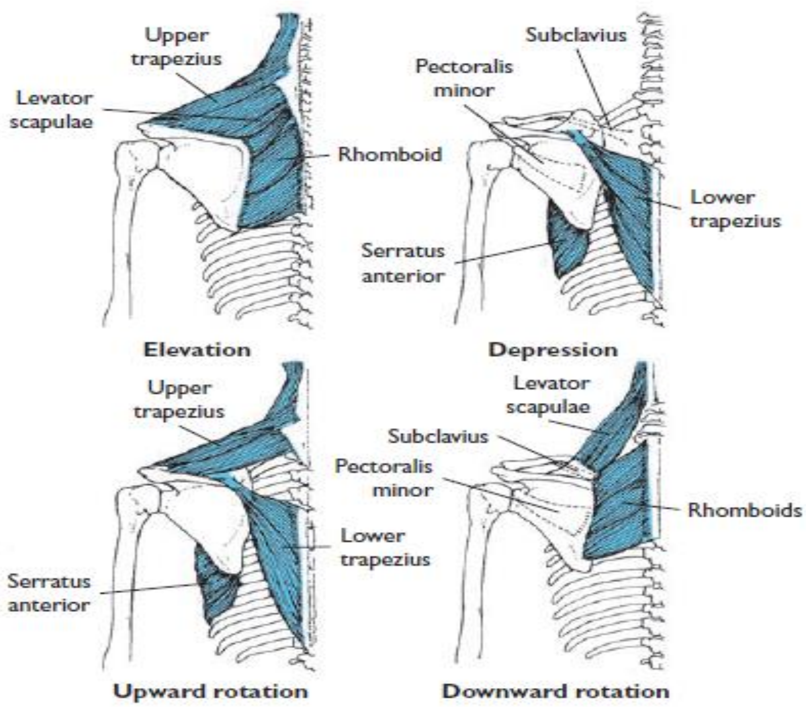


Figure 4: The muscles of the scapula.

Muscles of the Glenohumeral Joint

Many muscles cross the glenohumeral joint. Because of their attachment sites and lines of pull, some muscles contribute to more than one action of the humerus. A further complication is that the action produced by the development of tension in a muscle may change with the orientation of the humerus because of the shoulder's large range of motion. With the basic instability of the structure of the glenohumeral joint, a significant portion of the joint's stability is derived from tension in the muscles and tendons crossing the joint. However, when one of these muscles develops tension, tension development in an antagonist may be required to prevent dislocation of the joint.

LOADS ON THE SHOULDER

Because the articulations of the shoulder girdle are interconnected, they function to some extent as a unit in bearing loads and absorbing shock. However, because the glenohumeral joint provides direct mechanical support for the arm, it sustains much greater loads than the other shoulder joints.

We assume that the weight of each body segment acts at the segmental center of mass. The moment arm for the entire arm segment with respect to the shoulder is therefore the perpendicular distance between the weight vector (acting at the arm's center of gravity) and the shoulder (Figure 5). When the elbow is in flexion, the effects of the upper arm and the forearm/hand segments must be analyzed separately (figure 6).

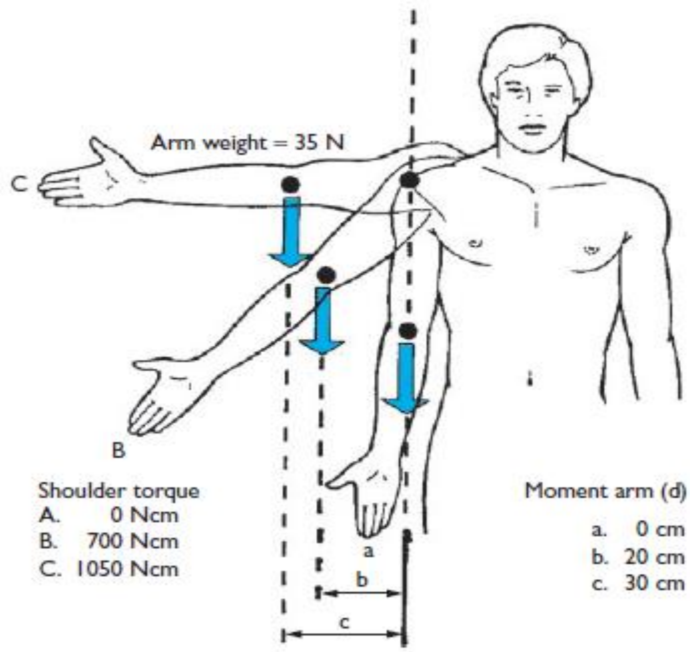


Figure 5: The torque created at the shoulder by the weight of the arm is the product of arm weight and the perpendicular distance between the arm's center of gravity and the shoulder

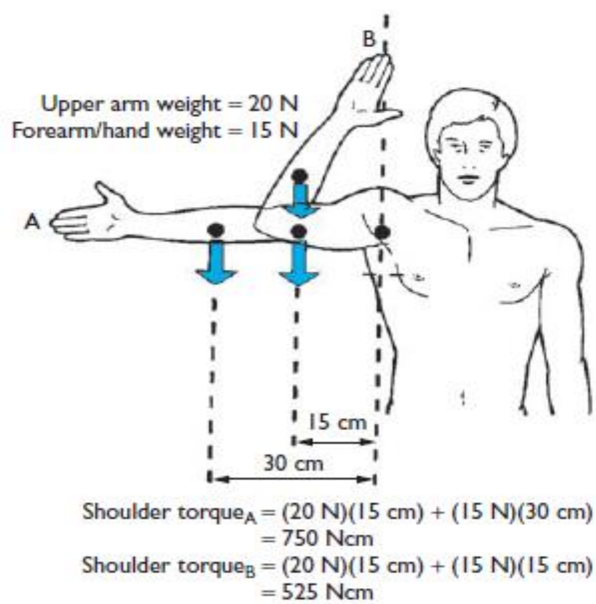


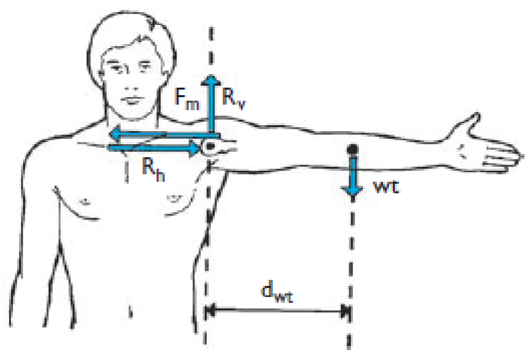
Figure 6: The torque created at the shoulder by each arm segment is the product of the segment's weight and the segment's moment arm.

Sample Problem

Using the simplifying assumptions of Poppen and Walker, 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.

$$R_h = 330\ N$$

Note: Both components of the joint reaction force are directed through the joint center, and so have a moment arm of zero with respect to the center of rotation.

STRUCTURE OF THE ELBOW

Although the elbow is generally considered a simple hinge joint, it is actually categorized as a trochoginglymus joint that encompasses three articulations: the humeroulnar, humeroradial, and proximal radioulnar joints.

MOVEMENTS AT THE ELBOW

Flexion and Extension

The muscles crossing the anterior side of the elbow are the elbow flexors. The strongest of the elbow flexors is the brachialis. Another elbow flexor is the biceps brachii, with both long and short heads attached to the radial tuberosity by a single common tendon. The brachioradialis is a third contributor to flexion at the elbow. The major extensor of the elbow is the triceps, which crosses the posterior aspect of the joint.

Pronation and Supination

Pronation and supination of the forearm involve rotation of the radius around the ulna. There are three radioulnar articulations: the proximal, middle, and distal radioulnar joints. Both the proximal and the distal joints are pivot joints, and the middle radioulnar joint is a syndesmosis at which an elastic, interconnecting membrane permits supination and pronation but prevents longitudinal displacement of the bones.

LOADS ON THE ELBOW

Although the elbow is not considered to be a weight-bearing joint, it regularly sustains large loads during daily activities. Since the attachment of the triceps tendon to the ulna is closer to the elbow joint center than the attachments of the brachialis on the ulna and the biceps on the radius, the extensor moment arm is shorter than the flexor moment arm. This means that the elbow extensors must generate more force than the elbow flexors to produce the same amount of joint torque. Because of the shape of the olecranon process, the triceps moment arm also varies with the position of the elbow. As shown in Figure 7, the triceps moment arm is larger when the arm is fully extended than when it is flexed past 90°.

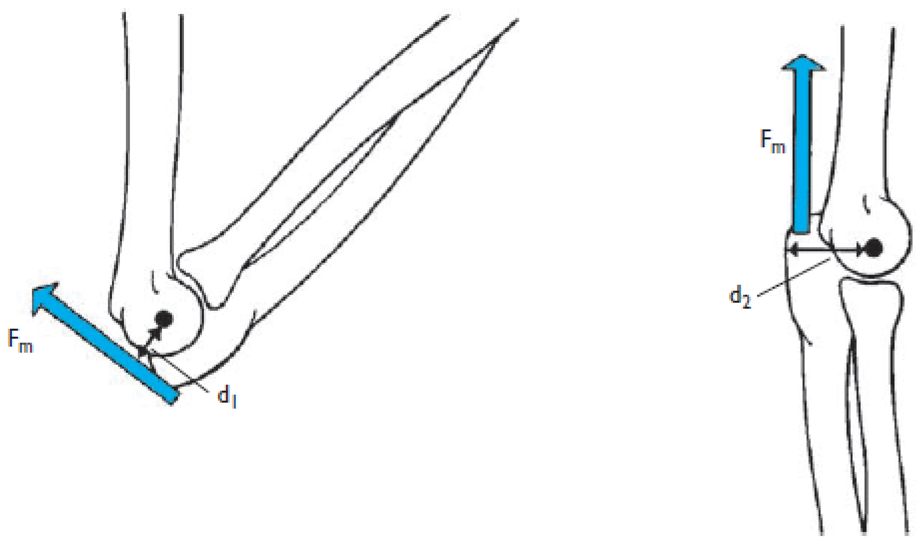


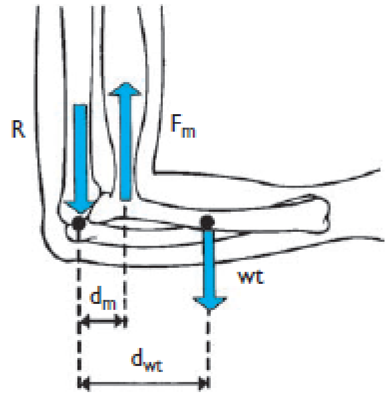
Figure 7: Because of the shape of the olecranon process of the ulna, the moment arm for the triceps tendon is shorter when the elbow is in flexion.

Sample Problem

How much force must be produced by the brachioradialis and biceps (F_m) to maintain the 15 N forearm and hand in the position shown below, given moment arms of 5 cm for the muscles and 15 cm for the forearm/hand weight? What is the magnitude of the joint reaction force?

Known

$$wt = 15\ N$$
$$d_{wt} = 15\ cm$$
$$d_m = 5\ cm$$



Solution

The torque at the elbow created by the muscle force must equal the torque at the elbow created by forearm/hand weight, yielding a net elbow torque of zero.

$$\sum T_e = 0$$
$$\sum T_e = (F_m)(d_m) - (wt)(d_{wt})$$
$$0 = (F_m)(5\ cm) - (15\ N)(15\ cm)$$
$$F_m = \frac{(15\ N)(15\ cm)}{5\ cm}$$
$$F_m = 45\ N$$

Since the arm is stationary, the sum of all of the acting vertical forces must be equal to zero. In writing the force equation, it is convenient to regard upward as the positive direction.

$$\sum F_v = 0$$
$$\sum F_v = F_m - wt - R$$
$$\sum F_v = 45\ N - 15\ N - R$$
$$R = 30\ N$$

STRUCTURE OF THE WRIST

The wrist is composed of radiocarpal and intercarpal articulations (Figure 8). Most wrist motion occurs at the radiocarpal joint, a condyloid joint where the radius articulates with the scaphoid, the lunate, and the triquetrum. The joint allows sagittal plane motions (flexion, extension, and hyperextension) and frontal plane motions (radial deviation and ulnar deviation), as well as circumduction. Its close-packed position is in extension with radial deviation.

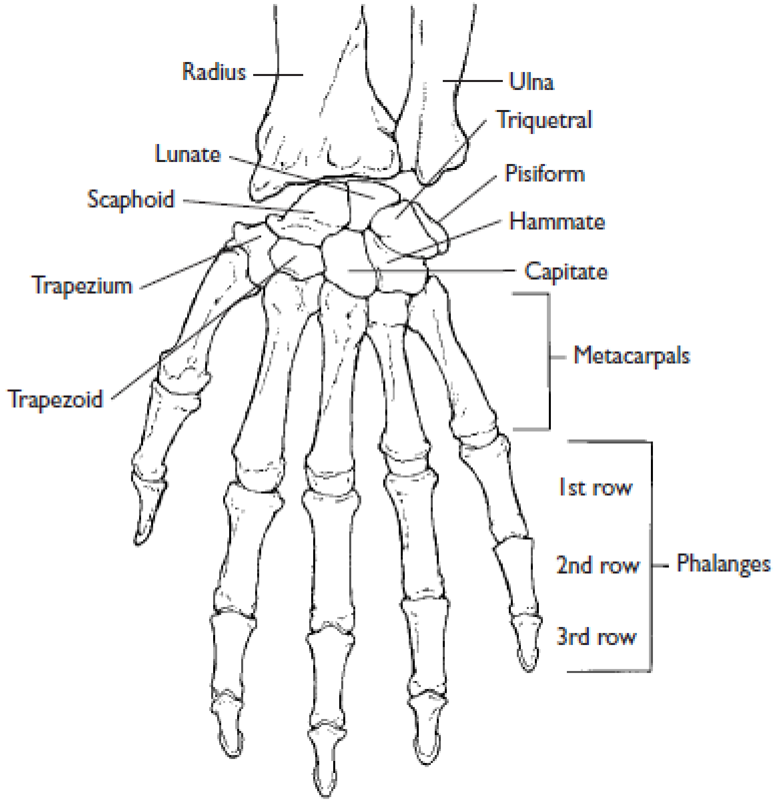


Figure 8: The bones of the wrist.

MOVEMENTS OF THE WRIST

The wrist is capable of sagittal and frontal plane movements, as well as rotary motion (Figure 9). Flexion is motion of the palmar surface of the hand toward the anterior forearm. Extension is the return of the hand to anatomical position, and in hyperextension, the dorsal surface of the hand approaches the posterior forearm. Movement of the hand toward the thumb side of the arm is radial deviation, with movement in the opposite direction designated as ulnar deviation. Movement of the hand through all four directions produces circumduction. Because of the complex structure of the wrist, rotational movements at the wrist are also complex, with different axes of rotation and different mechanisms through which wrist motions occur.

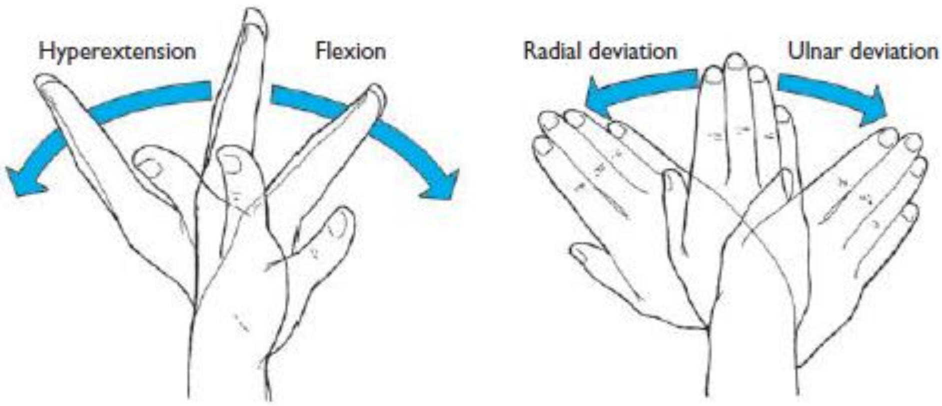


Figure 9: Movements occurring at the wrist.

STRUCTURE OF THE JOINTS OF THE HAND

A large number of joints are required to provide the extensive motion capabilities of the hand. Included are the carpometacarpal (CM), intermetacarpal, metacarpophalangeal (MP), and interphalangeal (IP) joints. The fingers are referred to as digits one through five, with the first digit being the thumb.

MOVEMENTS OF THE HAND

The carpometacarpal (CM) joint of the thumb allows a large range of movement similar to that of a ball-and-socket joint (Figure 10). Motion at CM joints two through four is slight due to constraining ligaments, with somewhat more motion permitted at the fifth CM joint.

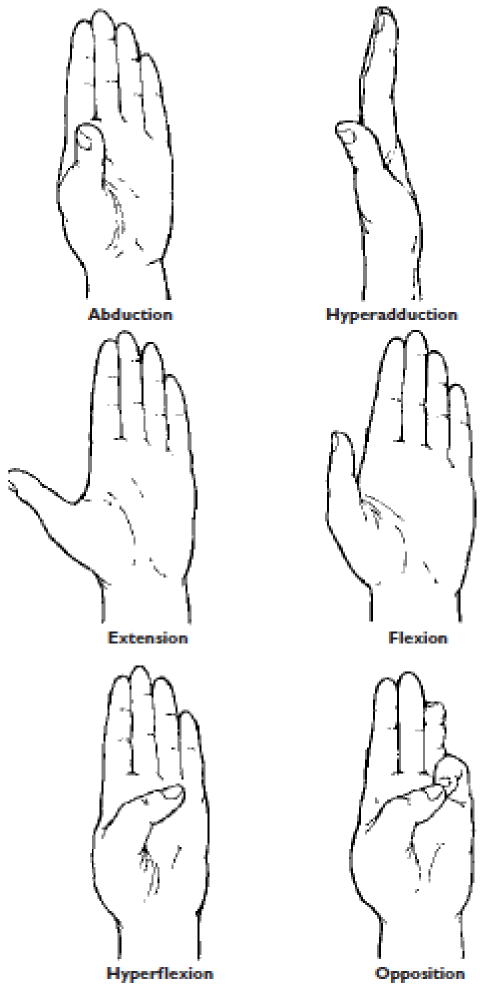


Figure 10: Movements of the thumb

The metacarpophalangeal (MP) joints of the fingers allow flexion, extension, abduction, adduction, and circumduction for digits two through five, with abduction defined as movement away from the middle finger and adduction being movement toward the middle finger (Figure 11). Because the articulating bone surfaces at the metacarpophalangeal joint of the thumb are relatively flat, the joint functions more as a hinge joint, allowing only flexion and extension. The interphalangeal (IP) joints permit flexion and extension, and in some individuals, slight hyperextension. These are classic hinge joints.

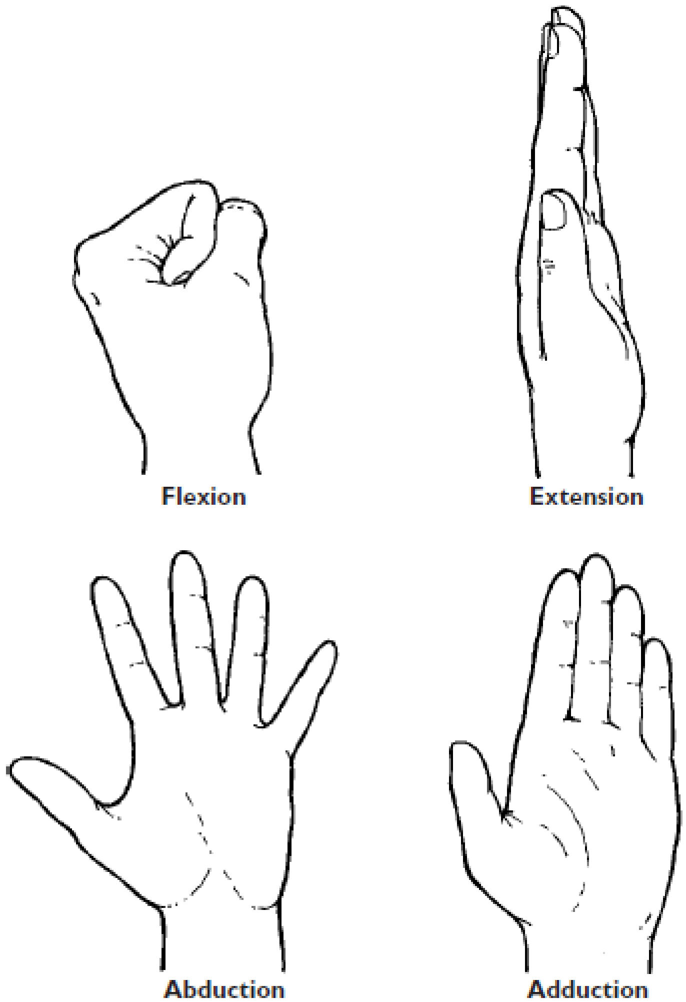


Figure 11: Movements of the fingers.