Biomechanics of the Shoulder Joint

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I. Biomechanics related with stability

1. Static Stability Factors

1) Orientation of the Articular Surface

: articular geometry plays an important role in the motion and stability of the shoulder.

(1) Orientation of the humeral side: important for restoring the original geometry with prosthetic arthroplasty

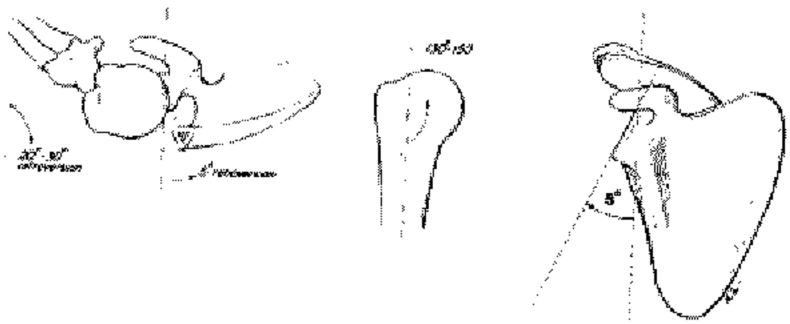
① humeral head center: offset 7 mm med. and 2 mm post. from the humeral axis

② humeral head retroversion: quite variable, average 19° (range, 9° to 31°) relative to transepicondylar axis of distal humerus.

③ humeral head inclination: average 41° (range, 34° to 47°)

④ neck-shaft angle 114°~147°

⑤ the superior aspect of the humeral head is 6 mm (range, 3 to 8 mm) higher than the superior aspect of the greater tuberosity.

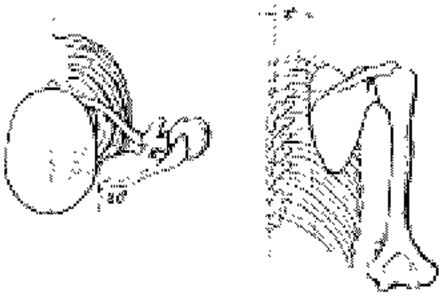


(2) Orientation of the glenoid side

① inverted comma-shape, pear-shape (lower half: upper half = 1 : 0.8).

- superoinferior dimension average 39 mm, anteroposterior dimension 29 mm.

- but. difficult to quantify. ∵ glenoid의 upper → lower 까지 version이 바뀐다.



② articuar surface
- superior tilt 5°, retroversion about 10° to the long axis of the scapula
- scapular: face 30°anteriorly on the chest wall, tilt 3° upward relative to transverse plane
- finally, the glenoid articular surface oriented about 20° anterior to the thoracic plane: the glenoid can stabilize the humeral head during activities with the arm in front of the body.
- concave, radius of curvature is 2.3 mm greater than that of the humeral head
- covered with hyaline cartilage: thinner in the center, thicker toward the periphery

2) Articular Conformity

① the GH joint is like a golf ball sitting on a tee

: the smaller area and larger radius of curvature of the glenoid compared with that of the humeral head.

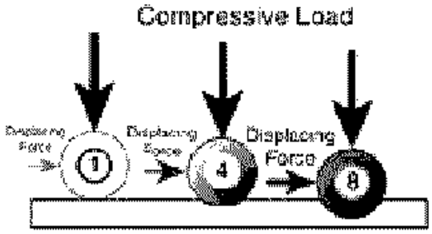
② the shallow glenoid fossa is deepened by the glenoid cartilage and by the labrum at its periphery.

: the articular cartilage is thicker at the periphery than in the center and the labrum deepen the fossa peripherally, thus the articular surfaces are almost perfectly conforming.

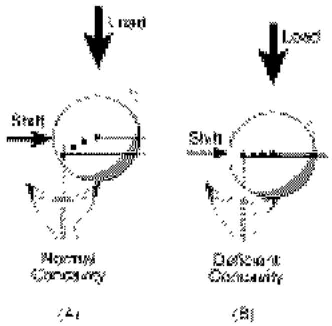
③ Biomechanics of the concavity

 # Load and shift concept

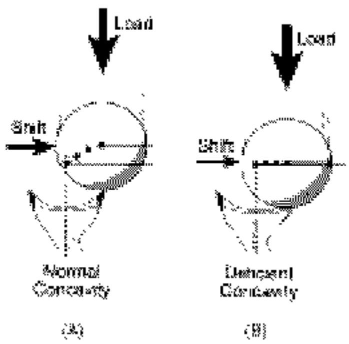
- In the absence of a concavity, only minimal translational force is require to displace the sphere. As the concavity becomes deeper, a greater force is required for a given compressive load.



- When the normally concave glenoid is loaded in compression, a substantial force is required to shift the head from the glenoid(A). When the glenoid concavity is deficient, less force is required to shift the head from the glenoid(B)



 # Balance stability angle concept



- the balance stability angle is the maximal angle that the net humeral joint reaction force can make with the genoid center line before dislocation (the angle between the glenoid center line and the line from humeral head center to the peripheral margin of glenoid).
- When the glenoid width is narrowed (ex,glenoid lip fracture) the balance stability angle is reduced resulting the unstable joint.
- the deeper the glenoid fossa, the bigger the balance stability angle.
- the articular conformity only is not enough to keep the shoulder stable.

3) Glenoid labrum

① wedge-shaped fibrous structure that consists of densely packed collagen bundles

② function

- acts as a structural support that the capsule-ligaments are anchored
- deepens the concavity of the glenoid socket. (50% of total depth)
- increase the contact surface area for the humeral head
- act as buttress for reducing translation
- facilitate the concavity-compression mechanism
- resection of labrum reduces the compression stability by 20%.

cf) glenoid와 labrum의 관계 개념의 변화(labrum의 역할)

: labrum이 편평한 glenoid의 peripheral에서“ chock block” 역할을 하여 humeral head가 밖으로 굴러 떨어지지 않게 한다고 생각했는데, 요즈음은 glenoid가 더 이상 편평하지만은 않고 이미 congruent surface를 가지고 있는데 여기에 labrum이 더해져서 increasing the depth of the articular surface and contact surface 한다는 것이다. glenoid bone radius는 humeral head 보다 크지만, peripheral에 thicker cartilage and labrum이 있어서 충분히 보상이 된다.

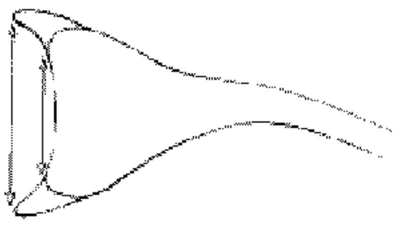


Fig. Labrum이 glenoid socket의 articular surface와 depth를 증가시킨다.

③ the superior portion of the labrum differs from the inferior portion

- superior portion: loosely attached to the glenoid, inserts into the biceps tendon at the supraglenoid tubercle, less vascular.
- inferior portion: firmly attached to the glenoid rim.

4) Capsuloligamentous Structure

- In the middle range of rotation, these structures are relatively lax, and joint stability is provided by the dynamic action of the rotator cuff muscles through compression of the humeral head in the glenoid socket. The ligamentous structures function passively at the extreme positions of rotation, preventing excessive translation of the humeral head on the glenoid.

(1) Glenohumeral ligament

: localized thickening of the joint capsule

① superior glenohumeral lig.(SGHL)

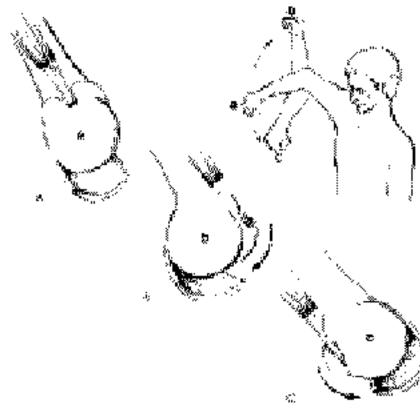
: the primary inferior stabilizer. The strain on the SGHL and the CHL is maximal with the arm in adduction and ext. rotation.

② middle glenohumeral lig. (MGHL)

: the primary anterior stabilizer with the arm in adduction and neutral rotation.

③ inferior glenohumeral lig. (IGHL)

: most important



<u> function like hammock in abduction.</u>*

: ant. stabilizer in E/R
post. Stabilizer in I/R
inf. Stabilizer in neutral

(2) Joint capsule

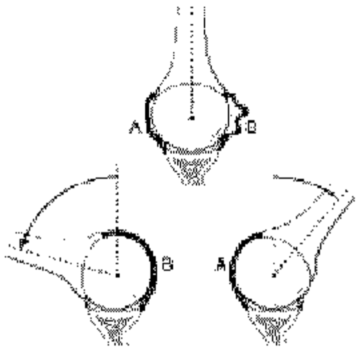
<u># Urayama and coworkers measured the strain of the anterior and posterior band of the IGHL (JSES, 2001)</u>

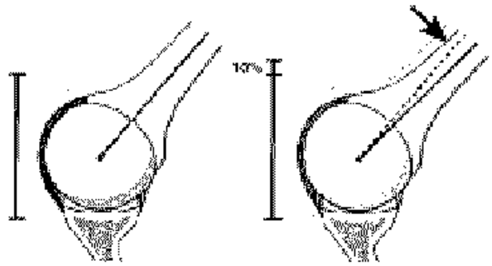
- ant. band: the highest strain with the arm in abduction and ext. rotation
- post. band: the highest strain with the arm in flexion and int. rotation.

<u># Biomechanical properties of the capsule</u>

- capsular tensile load was less than 20 kg.
- the mean tensile strength of the IGHL was 5.5 MPa.
- force necessary to rupture the whole ligament complex is less than 50kg.
- correlation of the biomechanical data and the anterior shear force from muscles contraction(42 kg) may help explain the spontaneous dislocation seen after some seizure episodes.

(3) Biomechanics of the glenohumeral ligaments and capsule
- the glenohumeral ligaments and capsule serve as checkrein, limiting the rotation and translation of the humeral head.
- they are not effective in centering the head in the glenoid; that is the task of the concavity compression mechanism.
- the laxity of a joint is determined primarily by the amount of slack (not the amount of stretch) in the ligaments, limiting that direction of movement, because the ligaments are relatively noncompliant, stretching to only 110% of their resting length
- ligaments are normally lax during most shoulder functions, allowing shoulder motion.

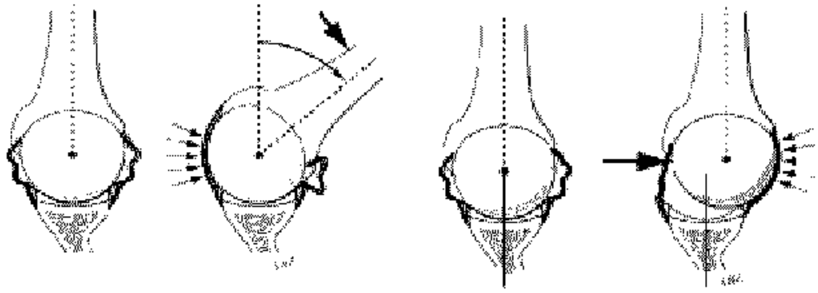




 # Physiologic laxities of the glenohumeral joint

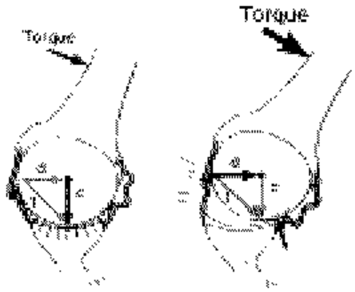
① Rotational laxity
- the angle that the humeral head can be rotated in a specified direction from a specified starting position while remaining centered in the glenoid (A).
- determined by (1) the length of the capsule and ligaments and (2) the position and orientation of the humeral head at the start of the rotation, and (3) the radius of curvature of the humeral head.

② Transitional laxity
- the distance that the humeral head can be moved in a specified direction from an initial position centered in the glenoid socket (B).
- determined by (1) the length of the capsule and ligaments and (2) the position and orientation of the humeral head at the start of the translation.
- this translation is both normal and essential to the mobility of the glenohumeral joint.



A B

③ Exerting a large torque, tight ligaments(frozen shoulder, diabetes, or after capsulorrhaphy) result in a major compressive force at the glenohumeral joint (A) and a siginificant amount of obligate translation of the humeral head on the glenoid, potentially damaging the glenoid rim(B).
→ capsulorrhaphy arthropathy.



5) Negative intra-articular pressure

- the stabilizing effect of intra-articular pressure is the result of the vacuum effect within the a sealed joint compartment.
- shoulder joint: closed compartment surrounded by joint capsule
- any force that tends to displace the articular surface develops the negative pressure (suction effect)
- this negative pressure is especially important in restriction inferior translation of the humeral head
  : in a 1985 study, when the joint capsule was vented with small puncture and eliminate the negative pressure in the joint, inferior subluxation of the glenohumeral joint readily occurs.
- the intra-articular negative pressure stabilizes the shoulder not only in the inferior direction but also in all the other directions
  : the pressure is minimal with the arm in slight elevation and maximal

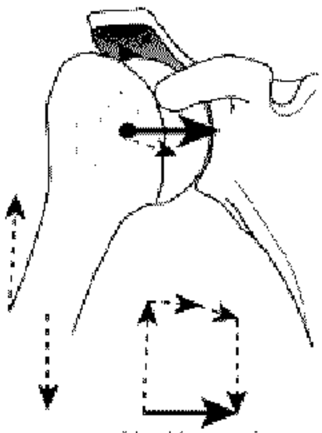
with the arm in full elevation.

6) Adhesion-Cohesion
- the glenohumeral joint contains a small amount of synovial fluid
  : viscous and intermolecular forces between the fluid and the joint surfaces create an this effect.

2. Dynamic Stability Factors

1) Passive muscle tension
- Ovesen and Nielsen s study (Acta Orthop Scand, 1986)
  : increased translation of the humeral head on the glenoid, both anteriorly and posteriorly with shoulder muscle release in cadaver specimens
- Howell and Kraft s study (Clin Orthop, 1991)
  : when the supraspinatus and infraspinatus were paralyzed by a suprascapular nerve block, normal kinematics were retained in 45 of 47 shoulders.
- But, this bulk effect of the muscles on the stability is minimal.

2) Compression of the articular surface
- Contraction of muscles around the shoulder joint causes compression and centering the humeral head on the glenoid articular surface.
- the net humeral joint reaction force is the vector sum of all the forces acting on the humeral head
- the following forces are represented as dotted lines: the suprespinatus, the subscapularis, the deltoid, and the weight of the humerus
- these sum of all the force vectors is compressive force on the glenoid



3) Dynamic factors causing secondary tightening of static constraints
- the cuff musculature rotates the shoulder to a configuration rendered stable by tightening of the ligaments in the direction opposite the rotation.
- "dynamization" of GH lig. in midrange of motion
  : rotator cuff mm. insert jt. capsule

→ jt. capsule (stretch receptors, Ruffini end organ & Pacinian corpuscles)
→ complex reflex arcs
⇒ Asymmetric tensioning of lig. to tense or relax(lig. dynamization.)

4) Barrier effect of the contracted muscle

- the torques generated by the rotator cuff muscles are balanced and represent a force couple that resists both anterior and posterior humeral head translation.

5) Scapulothoracic motion

: not a true joint, rather a space between the concave surface of the anterior scapula and the convex surface of the posterior chest wall.

① scapular rotator: trapezius, serratus anterior, levator scapulae and rhomboids.

② maintains the normal rhythm of shoulder motion

- glenohumeral rotation: scapulothoracic rotation= 2:1 overall in scapular plane, generally, 4:1 ratio during the first 30° of arm elevation, after the first 30° of elevation the ratio becomes 5:4.
- the arm against resistance elicits scapulothoracic motion earlier than with passive motion alone.
- at high speed, glenohumeral motion is more dominant at the beginning of motion.
- the glenohumeral rhythm remains the same, although the total range of motion is reduced with age.

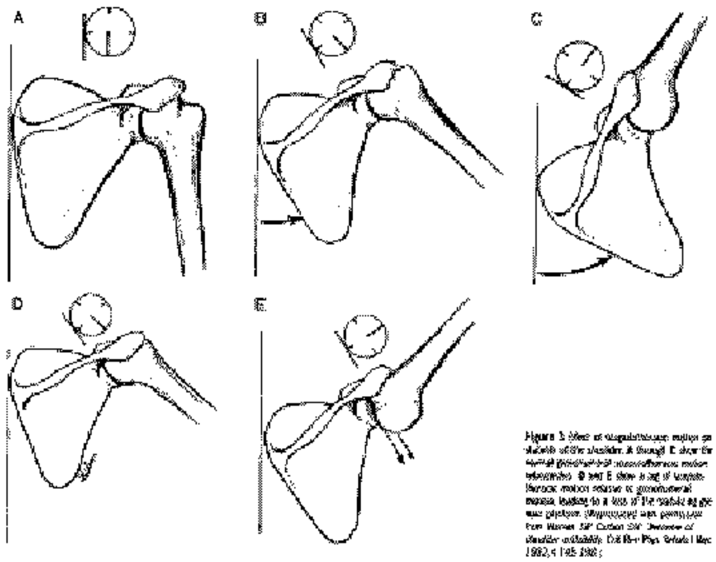


Figure [illegible] Effect of scapulothoracic motion on stability of the shoulder. A through C show the [illegible] scapulothoracic motion relationship. D and E show a lag of scapulothoracic motion relative to glenohumeral motion, leading to a loss of the [illegible] platform. [illegible] from Warner JJP, Caborn DN: Overview of shoulder instability. Crit Rev Phys Rehabil Med 1992;4:145-198.

- rotator cuff strengthening program in rehabilitation of treating shoulder instability.
- Effect of scapulothoracic motion on stability of the shoulder (figure below)
  : normal glenohumeral scapulothoracic motion relationship provide the stabilizing glenoid platform (A->B->C). But lag of scapulothoracic motion, leading to a loss of the glenoid platform (D->E).

3. Interactionship between Static and Dynamic Stabilizers

- Static and dynamic stabilizers do not function separately.

1) The dynamic stabilizers were more important when displacement of the humeral head was small, whereas the static stabilizers played a more important role in large displacement (Blasier RB, J Shoulder Elbow Surg 1994)
2) proprioception (kinesthesia)
   - the capsular-ligamentous structures detect position, motion, and stretching.
   - all these sensory modalities are transmitted from static stabilizers to dynamic stabilizers through a reflex arc.
   - joint capsule, ligament and surrounding tendons contain the highly specialized nerve ending (proprioceptive mechanoreceptors)
   - capsular stretch produces an afferent signal, which results in an efferent signal, causing a protective muscle contraction that enhances the stability of the joint.
   - also, protect the capsuloligamentous structures from failure caused by repetitive trauma.
   - the shoulder with anterior instability showed deteriorated proprioception, but that after surgical repair they showed no difference from the normal shoulders.

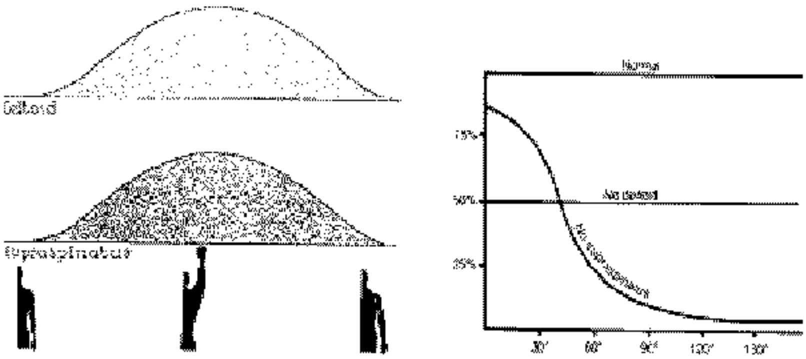
II. Biomechanics related with strength

1. The Rotator Cuff and the Deltoid Muscles

1) coordinated function of the rotator cuff muscles is required to counteract the shearing force of the deltoid.
   - the supraspinatus is an important elevator early in the motion, with its moment arm decreasing with increasing elevation
   - In an cadaver study: simulated supraspinatus paralysis required the greatest middle deltoid activity to elevate the humerus, especially early in

the motion from 15°~45°.

- EMG study demonstrated that the simultaneous electromyographic activity of the deltoid and supraspinatus muscles during arm elevation and descent.



- Absence of the deltoid causes an uniform decrease in abduction strength that is independent of joint position. On the other hand, absence of the rotator cuff allows almost normal initial abduction strength but a rapid drop-off at elevations greater than 30°.

2) Integrated activity

*"**force couple**"

: one muscle (primary agonist)에 의해 발생한 force는 antagonist muscle의 activation을 유발하여 joint의 stability를 유지한다. antagonist m은"eccentric contraction"하거나 agonist와 같은 magnitude로 neutralization force를 반대 방향으로 producing 한다.

ex) 1. coronal plane: deltoid ~ inf. portion of rotator cuff

2. transverse plane: subscapularis ~ post of R.C. (infraspinatus & teres min.)

① Forward elevation

- subscapularis & infraspinatus, teres minor(55°)
  : inf.로 45° → G.H jt를 depression & compression
- supraspinatus: 거의 horizontal → G.H jt compression
- prime mover: ant/middle deltoid m.

② Pure abduction

- m. activity는 same with above
- subscapularis increase activation via eccentric contraction

③ External rotation

- prime mover: infraspinatus m (특히 Abd 되었을 시)
- 나머지: post. head of deltoid, teres min

- antagonist: post & middle head of deltoid eccentric activity

④ Extension
- prime mover: post & middle head of deltoid
- autagouist : subscapularis, supraspinatus

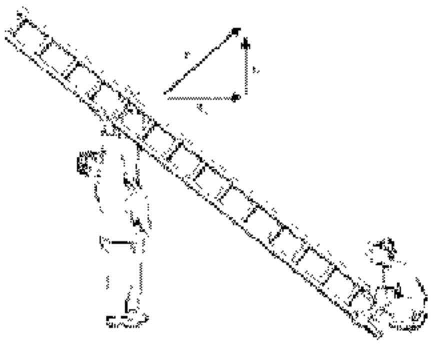
⑤ Scapulo thoracic motion
- full abduction or flexion 시 scapular가 rotation을 하게 되는데, 이때 upper trapezium, upper serratus ant, levata scapulae와 lower trapezium, lower serratus ant 사이에" rotational force couple"이 생긴다.

3) Function of rotator cuff

① fulcrum during active arm motion

② dynamic stabilizer
: direct joint compression &" steering" of humeral head into glenoid

③" dynamization" of GH lig. in midrange of motion
- rotator cuff muscle pre-tension the glenohumeral ligaments and capsule.
- capsule and ligaments may be dynamized (placed under tension) by contraction of cuff during active shoulder motion.

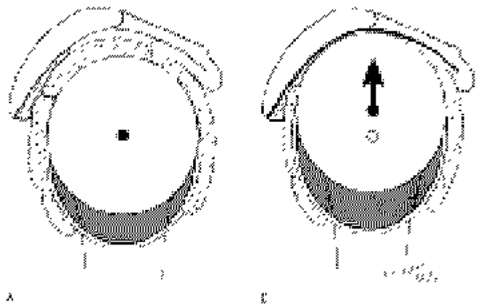


 # The relationship of the rotator cuff to the acromion during scapular elevation

- Acromion undersurface: subacromial contact start at the lateral edge of the acromion at 0° of elevation and shift medially when the arm is elevated.
- Rotator cuff tendon: contact shift from proximal to distal with elevation.
- closest between 60° and 120° of elevation
- some degree of contact between the rotator cuff and coracoacromial arch is normal. but markedly increased or focused contact may be harmful to the tendon.
- if the coracoacromial arch remains intact, the humeral head may be

stabilized by the arch against the upward pull of the deltoid.

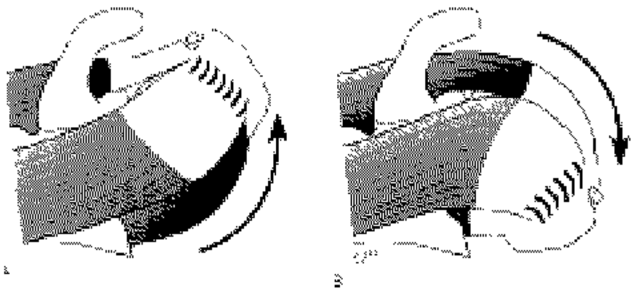
: the coracoacromial ligament functions as a superior stabilizer when the rotator cuff is impaired.



- factors causing superior translation of the humeral head in a rotator cuff -deficient shoulder
  ① the superiorly directed resultant vector that occurs with initiation of abduction by the intact deltoid.
  ② the lack of soft tissue interposition of the rotator cuff tendon.

 # The forces acting on the rotator cuff tendon

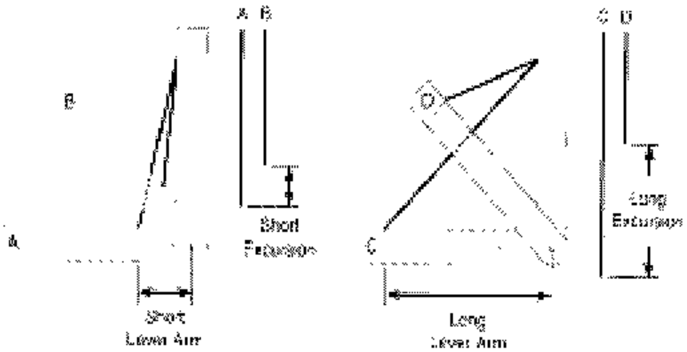
① traction force as a stabilizer
② compression force under the coracoacromial arch
③ bending force with internal/external rotation (figure)
→ the tendon insertion would be degenerated and become increasingly vulnerable to failure



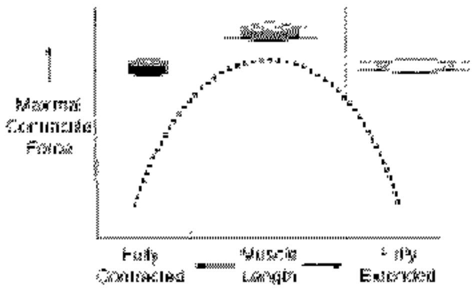
 # Muscle excursion

- excursion: the change in length over which the muscles can provide force
- muscles acting through longer lever arm (right) generate more torque per unit force (torque=force x lever arm), but require greater excursion than muscles acting through shorter lever arms, which require less excursion but

which result in less torque (left)



- A typical relationship between a muscle's length and the maximal force. The maximal force is less at the extremes of the range of motion (maximal extension or maximal contraction).
- Muscles that have been chronically detached, as in chronic cuff tear, tend to lose their excursion. Even if they are reattached, the length over which they can exert an effective force is often diminished.
- Effect of scapulothoracic motion on excursion of the scapuohumeral muscles.
  : Along the shoulder motion, the scapular position approximately 40° of adduction/abduction and 40° of protraction/retraction. This scapulothoracic motion enables the deltoid and the rotator cuff muscles to carry out most shoulder functions in the middle-range of their excursion, where they are the strongest.



2. Long head of the Biceps

: somewhat controversy

1) No function on the shoulder joint

① EMG analysis demonstrated that no significant activity was noted during any shoulder motion with fixed elbow brace in 100° flexion in both cuff-deficient and intact shoulders. (Yamguchi K. Clin Orthop 1997)

② Levy et al reported that they did not observe any EMG activity in the biceps during activities of daily living (Levy AS, J Shoulder Elbow Surg 2001)

2) Function on the shoulder joint

① Another EMG study with the elbow brace at either 0° or 90° of flexion
: the biceps is active, more active in E/R than I/R, but not significantly different in elbow flexion.

② Another EMG study compared 40 patients with full RCT with 40 normal individuals.
: Normal individuals did not recruit the biceps with arm elevation, but 14 of the 40 patients with cuff tears did, which demonstrated that the biceps plays a supplemental role in shoulder with rotator cuff tears. (Kido T. Acta Orthop Scand 1998)

③ Kim et al reported that the EMG activity of the biceps increased in shoulder with recurrent anterior dislocation whereas it did not in those without such dislocation. They concluded that LHB functions as an anterior stabilizer not in normal shoulders, but in shoulder with anterior instability (Kim S,H., Arthroscopy 2001).

④ stability mechanism
- in shoulder internal rotation, biceps stabilizes the humeral head anteriorly
- in shoulder external rotation, the biceps act to restrain posterior translation.
- contraction of the biceps reduces the superoinferior translation and enhance the stability by increasing the torsional rigidity of the joint and by reducing strain in the inferior glenohumeral ligament during throwing motion.

3. Loads at the glenohumeral joint

1) held at 90° of abduction
- deltoid muscle force (D)는 1/2 B.W
- joint - reaction force (J)도 1/2 B.W

2) force necessary for arm elevation
- D = 8.2 × arm weigh

- J = 10.2 × arm weigh

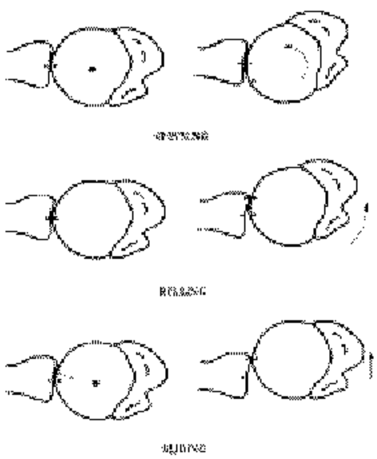
3) Joint contact pressure
   - maximal pressure with arm in 90° elevation
     : Max J = 89% BW (5.1 MPa)

III. Biomechanics related with motion

1. Glenohumeral joint motion

1) Early study: rolling, sliding, and spinning movement of the humeral head suggest that normal shoulder motion requires translations at the glenohumeral joint.
   - description of joint motion

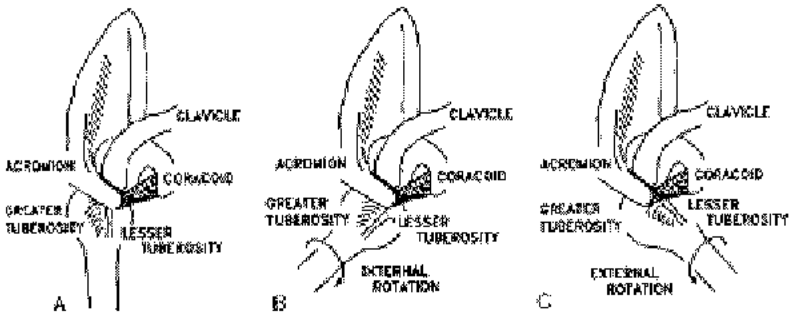
   ① spinning motion: the moving segment rotates and the contact point in the fixed surface does not change.
   ②② rolling motion: the motion between moving and fixed segments in which the contact points on each surface are constantly changing.
   ③ sliding motion: pure translation of a moving segment against the surface of a fixed segment.



2) Recent Electromagnetic tracking technology and radiographic study: humeral head remains centered on the glenoid for movements within the midrange when the ligaments are not under tension. In extreme position, the humeral head begins to translate in a direction away from the tight tissue (Capsular constraint).

3) External rotation of the humeral head for elevation
   -" obligatory" external rotation of the humerus is necessary for maximal elevation.
   - impingement of the tuberosity on the coracoacromial arch is assumed to be the mechanical constrain (A, B). External rotation (about 35°) clears the tuberosity posteriorly, thereby allowing full arm elevation (C).

- external rotation of the humerus also loosens the inferior ligaments of the glenohumeral joint, which releases the inferior checkrein effect and allows full elevation.
- In frozen shoulder, the limitation of external rotation induces an even more severe restriction of arm elevation.



4) Center of rotation
- a small amount (about 3 mm) of upward translation has been reported in the intact shoulder during the first 30° of elevation; only about 1mm of additional excursion occurs with elevation at greater than 30°.
- an increase in translation occurs with certain pathologic processes such as rotator cuff deficiency and tendon rupture of the LHB.

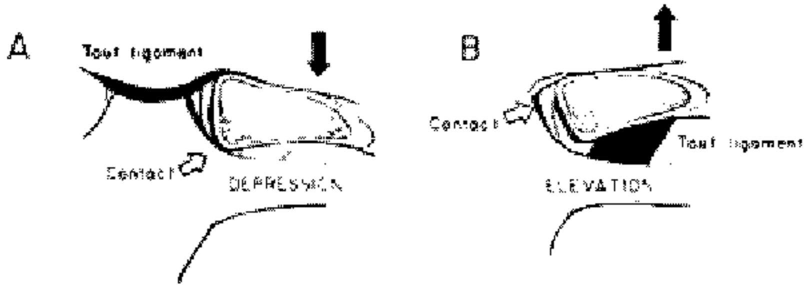
2. Stenoclavicular joint

1) true synovial jt. with fibrocartilaginous articular disc or meniscus

2) ligament
(1) ant- & post- sternoclavicular lig
(2) costoclavicular lig (major constraint): clavicle의 undersurface 15c rib
(3) interclavicular lig: connect the superomedial aspect of clavicles
(4) disc: prevent med. & inf. displacement of clavicle.

3) motion
(1) ant. & post. translation (35°)
- 주로 sternum과 disc 사이에서 movement.
- longitudinal axis through the costoclavicular lig
- stabilized with ant-post sternoclavicular lig
- only a limited amount of articular contact resists such displacement.
(2) elevation & depression (35°)

- 주로 clavicle와 meniscus(disc) 사이에서 motion
- sagittal axis through the costoclavicular lig
- depression : resisted by articular contact at the inferior aspect of the joint and by tautness developed in the interclavicular lig.
- elevation : resisted by tension developed in the entire costoclavicular complex.



(3) rotation (50°)
- longitudinal axis of the clavicle.
- downward 10° and upkward 45° rotation before capsular ligaments taut and limit further motion.
- costoclavicular ligament : the most important single constraint

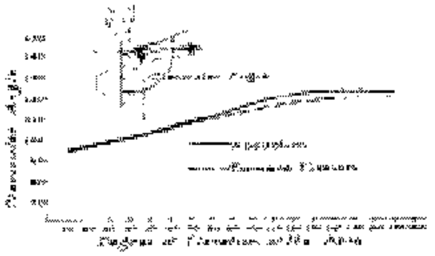
3. Acromioclavicular joint

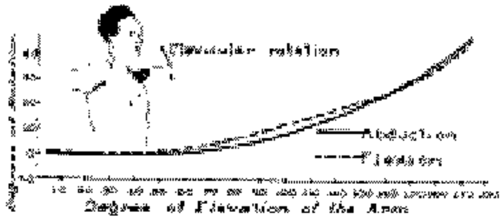
1) slight displacement is limited by the acromioclavicular ligament, but large displacements are resisted by the coracoclavicular ligaments
- ant. load increase tension in the conoid ligament,
- post. load increase tension in the trapezoid ligament.

2) arm elevation시, 생각보다 little motion at acromio-clavicular jt
→ thus rigid fixation or fusion 하더라도 little lose of overall shoulder function but sterno-clavicular jt는 fixation 시 motion loss of shoulder 초래한다.

4. Clavicle motion

- clavicle elevation of about 30° during abduction and forward flexion.
- axial rotation of about 40°-50° during arm elevation.
- these motion occur usually at the sternoclavicular joint.
- therefore, loss of motion at the acromioclavicular joint appears to be better tolerated than loss of motion at the sternoclavicular joint.





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