회전근 개의 생역학
(Biomechanics of the Rotator Cuff)

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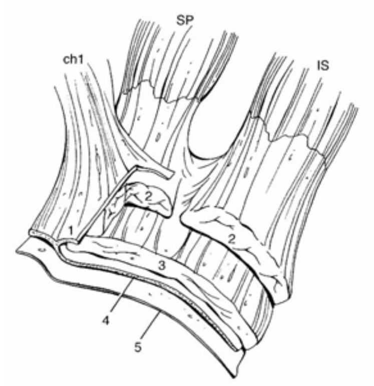
조 남 수

1. Rotator Cuff and related Functional Anatomy

- The rotator cuff : a complex of four muscles that arise from the scapular and blend in with the subjacent capsule as they attach to the tuberosities of the humerus
- The rotator cuff fuse into one continuous band at or near their insertions around the humeral head, which permits the cuff muscles to provide an infinite variety of moments to rotate the humerus.

- Microscopic layers of the cuff and capsule complex near the insertion
  1) Uppermost layer : superficial fibers of the coracohumeral ligament (CHL)
  2) 2nd layer : main portion of the cuff tendons
  3) 3rd layer : deep layer of rotator cuff, thick tendinous structure with small and less uniform fascicles
  4) 4th layer (rotator cable, transverse band, pericapsular band)
     : deep extension of the coracohumeral ligament (CHL), loose connective tissues with thick bands of collagen fibers
  5) 5th layer : true capsule



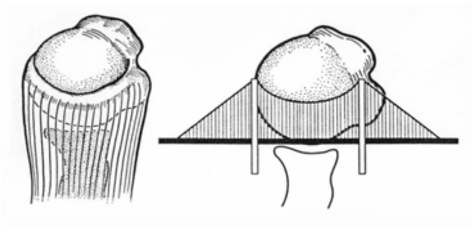
- This structural architecture
  1) enhances cuff resistance's failure with repeated load
  2) distributes tension of one tendon over expanded area
  3) if cuff fails, afford retention of structures

* Due to the various fiber orientations & distinct layers, significant shear stress
→ intrasubstance cuff tear & various tear pattern

* Complex woven pattern
: better purchase for suture materials during repair

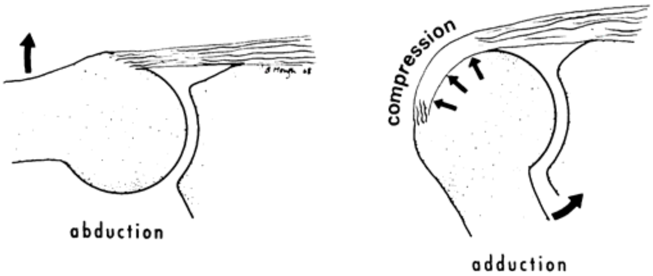
• Rotator cable (=transverse band, pericapsular band)
1) Although the function of rotator cable is unclear, it appears to support the cuff in a way to load-bearing suspension bridge.
2) Stress is transferred along the cable as a distributed load, thereby stress-shielding the thinner, avascular crescent tissue
3) functional rotator cuff tear

* Rotator Cable-Crescent Complex
■ Tear occur in stress-shielded crescent
■ Progressive thinning of the crescent may be an inevitable consequence of aging



• Critical zone of the rotator cuff
1) hypovascular zone in the tendinous portion of the supraspinatus tendon just proximal to its insertion, which is prone to rupture and calcium deposits
2) less frequently infraspinatus (37%), subscapularis (7%)
3) significant decrease in vascularity with aging, degeneration, advanced impingement and position of the arm (less vascular filling in adduction)

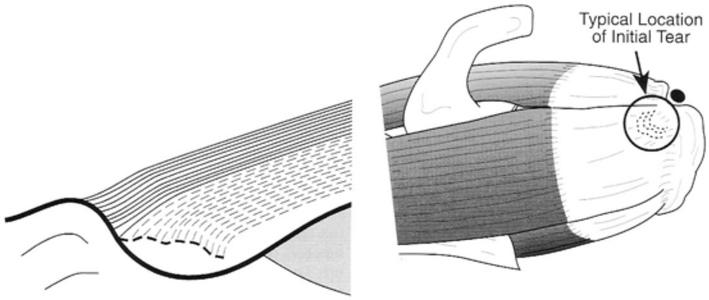
* Rathbun and Macnab (J Bone Joint Surg Br, 1970)
: Although this region has a rich capillary network (anastomoses between the osseous and tendinous vessels), normal bending, tensile and compressive forces within the tendon compromised its blood flow.



• Cross-sectional area
: The cross sectional area of the anterior belly of the supraspinatus muscle is larger than its posterior belly. However, in the supraspinatus tendon, the anterior belly is found to have a smaller

cross-sectional area than that of its posterior belly.

➡This increase in muscle strength-to-tendon area ratio explain why rotator cuff tears often begin in the anterior portion of the supraspinatus.



- Bursal side vs. articular side tendon
  - ■ The bursal side tendon showed a lower modulus of elasticity and higher ultimate strain and stress.
  - ■ relative hypovascularity on articular side than bursal side

  ➡Articular side of tendon is more susceptible to mechanical failure.

- The tendinous insertion into bone (Histology)
  1) Tendon
  2) uncalcified fibrocartilage
  3) caicified fibrocartilage
  4) bone

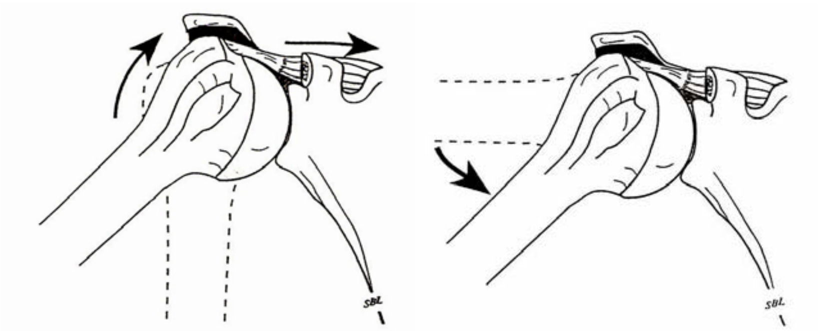
  - ■ The fibrocartilage provide a transitional zone between hard and soft tissues, which protects the fibers from sharp angulation at the interface between bone and tendon.
  - ■ The intervening zones of fibrocartilage serve to absorb impact loading and to protect the insertion against excessive shear, compression, and tension for positions of acute repetitive bending.

2. Function of the Rotator Cuff

- Functions of the rotator cuff
  1) rotate the humerus with respect to the scapula
  2) dynamic stabilizer

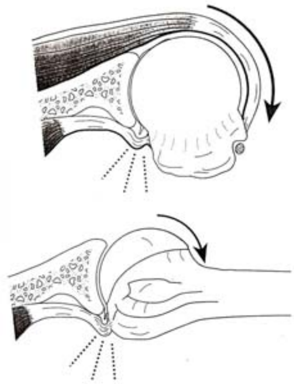
3) provide muscle balance
4) spacer effect

1) Loading environment (rotate the humerus)
   - ✓ concentric tension load when the humerus is moved actively in the direction of action of the cuff muscle
   - ✓ eccentric tension load as they resist humeral motion or displacement in directions opposite the direction of action of the cuff muscles



Concentric action of the cuff muscle — Eccentric action of the cuff muscle

   - ✓ The tendon fibers are subjected to bending loads when the humeral head rotates.
   - ✓ When the arm positioned at the limits of motion, the glenoid rim can apply a sheering load to the deep surface of the tendon insertion. This abutment of the labrum against the cuff insertion may be explanation of internal impingement.



2) The rotator cuff provide dynamic stability to the glenohumeral joint through four different mechanisms.
   A) passive muscle tension from the bulk effect of the muscles
      : passive arc of motion increases when the muscle is removed (up to 10mm of additional superior or inferior translation)
   B) contraction causing compression of the articular surfaces (head depressor)
      : stimulation of the rotator cuff muscles causes a centering of the humeral head without balanced muscle activity (by secondary obligatory tightening of ligaments of glenohumeral joint)

C) dynamic elements causing secondary tightening of static constraint

: the rotator cuff muscle rotated the shoulder into more stable configuration by tightening the ligaments in the direction opposite the rotation

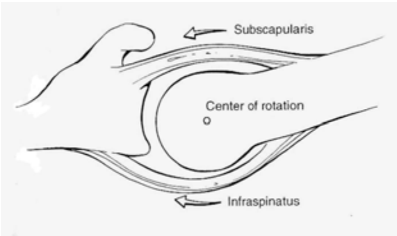
D) barrier effect of the contracted muscles

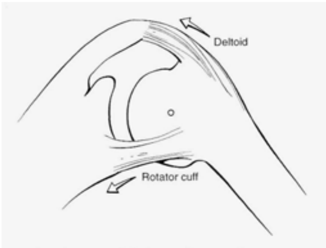
: dynamic and well-balanced stabilizers of the humeral head

3) Force couples of the shoulder (muscle balance)

: action of two opposing muscle groups required to achieve a given moment

- ✓ integral to maintain normal function
- ✓ deltoid vs. subscapularis, infraspinatus, teres minor
- ✓ subscapularis vs. infraspinatus (large or massive rotator cuff tear)
- ✓ The tears of the rotator cuff muscles typically produce abnormal and unstable mechanical action at the glenohumeral joint, because of the disruption of the force couples either in the coronal plane, transverse plane, or both.
- ✓





4) Spacer effect of the cuff tendon

: When the cuff tendon was excised, the humeral head moved cephalad 6mm until the superior humeral load was applied directly to the acromion

The rotator cuff muscles and description of function

Rotator cuff muscle	Description	Action
Supraspinatus	Circumpennate muscle. Average width at midportion of tendinous insertion is 14.7 mm. Mean area of insertion is 1.55 cm^2	Initializes humeral abduction to 90°
		Deficiency can be compensated for by the remaining rotator cuff muscles
Infraspinatus	Circumpennate muscle. Mean area of infraspinatus insertion is 1.76 cm^2	Resists posterior and superior translation Generates 60% of external rotation force
Teres minor	Circumpennate muscle	Resists posterior and superior translation Generates 45% of the external rotation force
Subscapularis	Multicircumpennate muscle	Contributes to the floor of the bicipital sheath Resists anterior and inferior translation Strong internal rotator

- The rotator cuff acts as a functional unit maintaining the humeral center within the glenoid during active arm motion.

1) Supraspinatus
- ✓ active in all patterns of arm elevation, primarily initiate arm abduction to approximately 30° of elevation by compressing the humeral head
- ✓ the short lever arm and small size of the supraspinatus limit the torque which can further elevation beyond 30° without assistance from the deltoid muscle

2) Infraspinatus
: prime function is external rotation of the humeral head, while providing a counterforce to prevent excessive external rotation and hyperextension from posterior deltoid action

3) Subscapularis
- ✓ internal rotator of the humerus, acting in concert with the pectoralis major, teres major, and latissimus dorsi
- ✓ its activity serves to decelerate external rotation, thereby contributes to overall stability by providing anterior restraint

4) Teres minor
- ✓ external rotator of the humerus, acting in concert with the infraspinatus
- ✓ oppositional inferior stability is provided by opposing the superior forces of the middle deltoid

- Rotator cuff function during shoulder motion

1) Abduction
- ✓ supraspinatus and deltoid muscles
- ✓ both are active throughout abduction, as demonstrated by EMG, reaching maximal activity between 90° and 180°
- ✓ trapezius and serratus anterior muscles : synergistic in scapular rotation

* suprascapular nerve block : reduction in the force of elevation in the scapular plane by 35% at 0° elevation, 60% at 60°, and 30% at 150°
* axillary nerve block : reduction in the force of elevation in the scapular plane by 35% at 0° elevation, and 60%~80% at 150°
* axillary nerve stimulation : 40° abduction

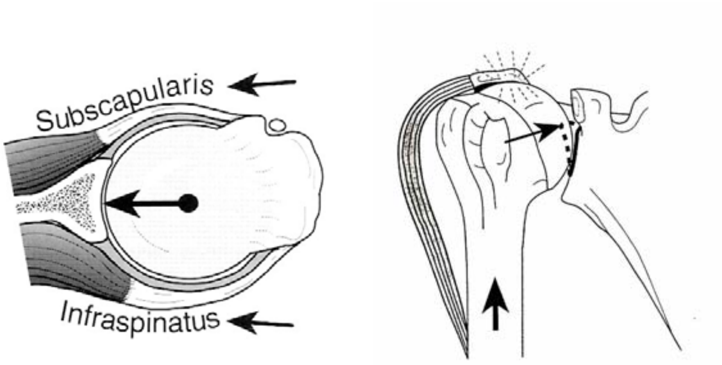
* suprascapular nerve stimulation : 90° abduction and 45° external rotation

■ short rotators (subscapularis, infraspinatus, and teres minor)

: during abduction, the directional force of the short rotators is directed downward and inward, serving to depress the humeral head into the glenoid fossa and thereby opposing the upward and outwardly directed force of the deltoid and supraspinatus from superiorly subluxating the humeral head against the acromion process.

✓ The action of short rotators provides a fixed fulcrum and allows elevation of the humerus to occur through the resultant force couple.

✓ The deltoid acting alone when rotator cuff tear elicits only an upward subluxation of the humeral head because the fulcrum is lost.



2) Adduction and Extension

✓ latissimus dorsi, teres major, lower portion of the pectoralis major, posterior deltoid, and the long head of triceps

✓ rotator cuff plays little part

3) Flexion

✓ anterior head of the deltoid and the clavicular portion of the pectoralis major

✓ coracobrachialis and biceps brachii act mainly through the first 90° of flexion

✓ the short rotators depress the humerus, which along with the upward force of action of the deltoid creates a force couple that elevates the humerus

4) Internal rotation

✓ subscapularis, teres major, lartissimus dorsi, pectoralis major, anterior deltoid

✓ pure internal rotator : subscapularis

✓ If the subscapular nerve is stimulated, the arm will internally rotate 25° and flex 20° from the action of the subscapularis alone.

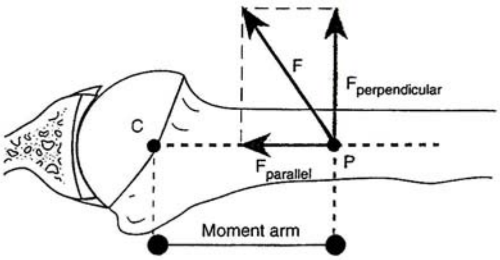
5) External rotation
✓ infraspinatus, teres minor
✓ infraspinatus being active throughout the entire 70° of motion and the teres minor assuming an active role after 30° of external rotation
✓ the deltoid also externally rotates, primarily at initiation until 30° external rotation
✓ scapular stabilizers during external rotation include the supraspinatus, upper trapezius, serratus anterior, biceps, and the deltoid after 30° of external rotation

• Rotator cuff mechanics during throwing

1) The rotator cuff
: plays a crucial role in the actions of throwing a ball, because a wide range of dynamic stabilization is necessary to prevent subluxation of the humeral head secondary to increased stresses put on the glenohumeral joint complex
2) Supraspinatus
- plays a role in humeral abduction, with its EMG action at peak activity in the late cocking phase in which the arm is already abducted and most vulnerable to subluxation
- also serves to draw the humeral head closer to the glenoid
3) Infraspinatus and teres minor muscles
- responsible for external rotation and stability of the shoulder by the depressing the head of the humerus towards the glenoid fossa
- Peak activity showed during late cocking and follow-through, though both muscles lag behind the supraspinatus in timing.
4) Subscapularis
- has its peak activity in late cocking when it contracts eccentrically to protect the anterior joint, which at this point is under extreme tension
- then functions as an internal rotator to help carry the arm across the chest during acceleration and follow-through

3. Biomechanics of the Rotator Cuff

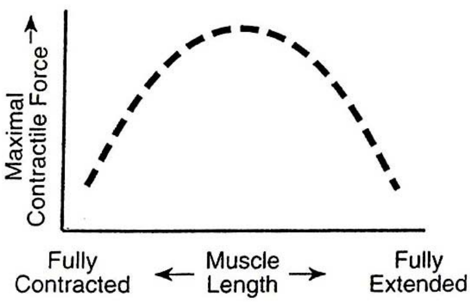
• The humeral torque resulting from contraction of rotator cuff
: determined by the moment arm (the distance between the point of application of a force and the center of movement)



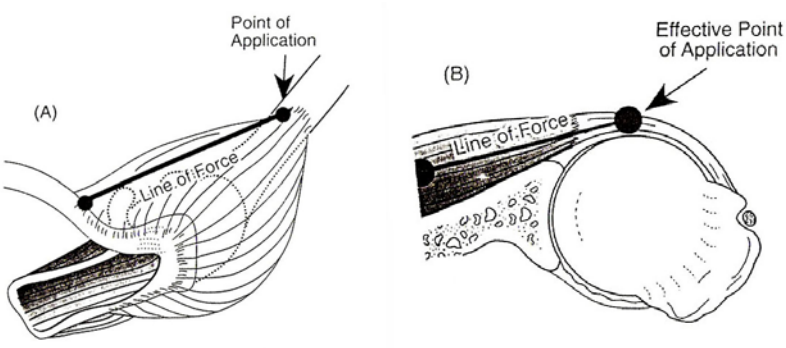
- The magnitude of force delivered by the rotator cuff
  : determined by its size, health, and condition, as well as the position of joint
- Glenohumeral motion
  - The instant centers of rotation of the glenohumeral joint have been shown to lie close to each other and to the center of the humeral head itself in normal subjects.
  - In contrast, patients with rotator cuff pathology demonstrated instant centers that deviated considerably from the center of the humeral head.

- Factors of the contribution of a given muscle to shoulder strength

1) Force and torque from muscle vary with the position of the joint
   : muscles are usually stronger near the middle of their excursion and weaker at the extremes



2) Direction of a muscle force is determined by the position of the joint
   : The supraspinatus can contribute to abduction and/or external rotation, depending on the initial position of the arm.
3) Effective humeral point of application for a cuff tendon wrapping around the humeral head is not its anatomic insertion, but rather the point at which the tendon first contracts the head, a point that usually lies on the articular surface.

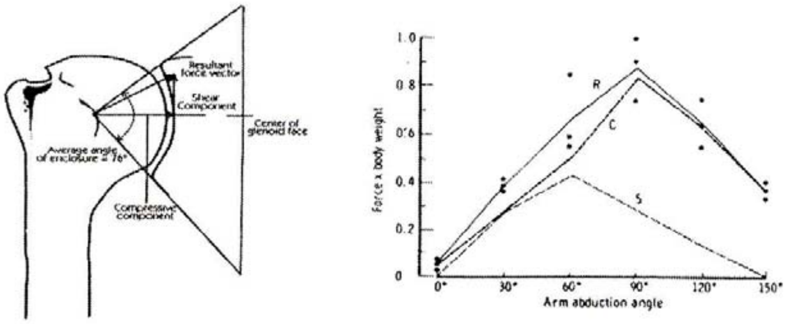


- Forces at the glenohumeral joint

  : deltoid muscle itself can generate a maximum force of 6 times limb weight, the supraspinatus 2.5 times, the rotators 5 times

- Resultant force = compressive force + shear force (allows the extremity to abduct efficiently and prevents the humeral head from simply sliding up the face of the glenoid)

  : when abduction of the arm is initiated, compressive forces are generated by the rotator cuff muscles to hold the humeral head against the glenoid fossa and counter the shear forces up the face the glenoid being created by the abducting muscle forces.



✓ <60° abduction : compressive = shear force, resultant force 증가

✓ 60°-90° abduction : compressive force 증가, shear force감소, resultant force 증가

✓ >90° abduction : compressive force 감소, shear force감소, resultant force 감소

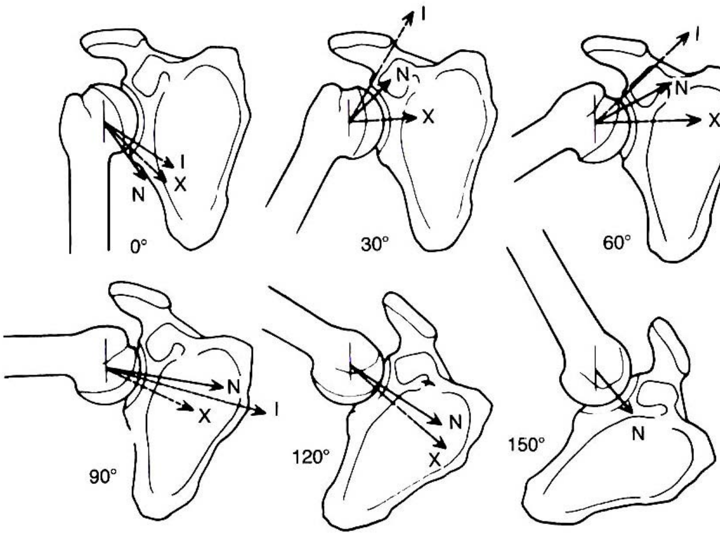
* The resultant force also peaks at 90° of abduction, and then it decreases at the same rate it increased as abduction increases.

- the resultant force : 0.4 times body weights at both 30° and 150° of abduction

- the resultant force : 0.8 times body weights at both 60° and 120° of abduction
- the resultant force : 1 times body weights at 90° of abduction

* The direction of resultant force vector

- For the humeral head to remain in the glenoid cavity with abduction, the resultant force vector must lie within the angle, or arc of safety of the glenoid.
- As the arm abducts to 30° and 60°, the force moves to the superior edge of the glenoid, consistent with the high shear forces generated, and move back towards the center of the glenoid as abduction continues to increase.



• The muscle efficiency and stability are superior in external rotation compared to the internal rotation.

1) The forces in external rotation are similar to those in neutral rotation, but the resultant force vector is directed more centrally into the glenoid cavity because of the deltoid muscle increasing its contributable to compressive forces and decreasing the shear component.
2) The force vector for internal rotation is larger than in neutral or external rotation and directed more superiorly, because of an increased shear force. The resultant forces in internal rotation are twice that in external rotation at 90° of abduction.
3) In neutral rotation with abduction to 60°, the resultant force vector of the humeral head is contained just within the arc of enclosure of the glenoid. The loss of a functioning rotator cuff mechanism, particularly the supraspinatus, causes a decrease in the compressive forces and an increase in the shear forces, shifting the resultant force vector superiorly out of the arc of enclosure of the glenoid. The

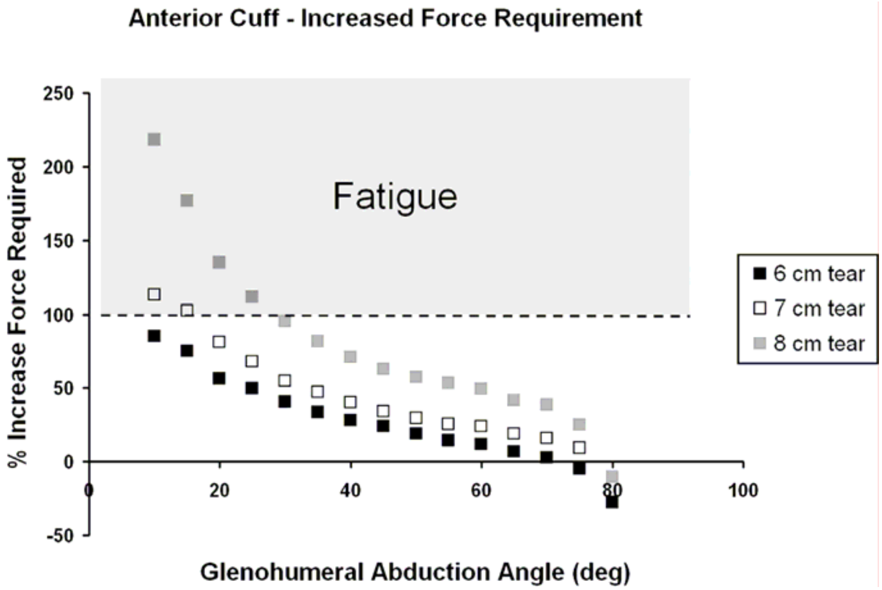
resulting instability is seen clinically with superior subluxation of the humeral head on the glenoid.

- Biomechanics of Massive Rotator Cuff Tears (Hansen et al, J Bone Joint Surg Am, 2008)

: Some individuals with massive rotator cuff tears maintain active shoulder abduction, and some maintain good postoperative active range of motion despite high rates of repeat tears after repair.

✓ In the presence of a massive rotator cuff tear

- Stable glenohumeral abduction without excessive superior humeral head translation requires significantly higher forces in the remaining intact portion of the rotator cuff.
- These force increases are within the physiologic range of rotator cuff muscles for 6-cm tears and most 7-cm tears.
- Increases in deltoid force requirements occur in early abduction; however, greater relative increases are required of the rotator cuff, especially in the presence of larger rotator cuff tears.



✓ important determinants of shoulder function in the presence of a massive rotator cuff tear → rotator cuff tear size, rotator cuff muscle force, and deltoid muscle force

➔ These findings can provide guidance for the rehabilitation of patients with rotator cuff tears and after rotator cuff repair and may provide justification for early surgical repair of rotator cuff tears.

4. The long head of the biceps tendon

* The role of the intra-articular biceps tendon in glenohumeral biomechanics
: a source of controversy

• Long head of the biceps tendon
- historically, both an active depressor and a static stabilizer of the glenohumeral joint
- functions as an effective humeral head depressor, maintaining proper ligament tension in some of the glenohumeral ligaments as predicted by the complementary tightening concept of shoulder stability

• Loss of the biceps
➔ induces increased forces in glenohumeral ligaments
➔ associated with a superior shift in the glenohumeral articular contact point

* In patients with rupture of the long head of biceps tendon
: the humeral head translates superiorly during abduction

• Increased EMG activity of the biceps in anteriorly unstable shoulders during throwing
➔ Although the biceps has been thought to be a depressor of the humeral head, the biceps can compensate for glenohumeral joint instability.

•With loading of the biceps
: there is significantly decreased anterior-posterior translation, particularly with external rotation

* When artificial Bankart lesions are created
➔ the biceps is more important than any rotator cuff muscle in stabilizing the glenohumeral joint against anterior displacement

* Long head of the biceps tendon origin instability and its association with the superior aspect of the glenoid labrum (known as the SLAP lesion)
➔ a loss of the effective depressor function from the tendon

* Pagnani et al (J Shoulder Elbow Surg, 1996)
: application of force to the biceps tendon
➔ reduced both anterior-posterior and superior-inferior translation
- when the arm was in internal rotation : it tended to stabilize the joint anteriorly
- when the humerus was in external rotation : served as a posterior stabilizer

* Rodosky et al (Am J Sports Med, 1994)
  : application of force through the long head of the biceps
    ➔ reduced stress on the IGHLC

- The importance of the biceps can also be seen with its hypertrophy in patients with chronic rotator cuff insufficiency.
  - ✓ With loss of dynamic stabilizers
    : the biceps tendon takes on larger stresses, and it reacts accordingly to compensate for the deficiency
  - ✓ In addition, the biceps tendon can often be found dislocated from the bicipital groove in association with subscapularis tendon tears

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