Biomechanics of the Shoulder

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Man's shoulder is moderately specialized from the primitive mammalian model. It is inherited from a tree-swinging quadripedal ancestor and modified by man's bipedal upright posture. The pectoral girdle is more mobile, less stable and weaker than the pelvic girdle. A review of the evolutionary comparative anatomy permits a better understanding of the orthopedic problems of the human scapula and shoulder.

The pectoral girdle follows Williston's law of evolution: "in the course of evolution the number of structural parts becomes reduced and the remaining parts become more specialized." The basic pattern for the mammalian shoulder girdle was established in the more primitive bony fishes. The cleithrum, a dermal bone forming the posterior edge of the gill opening, attaches to the skull. The paired dermal scapulae form a symphysis. The endochondral bone elements of modest dimensions lie on the inner and posterior surface of this shoulder girdle. The first increase in mobility of the pectoral girdle occurs in amphibians. The attachment of the cleithrum to the skull is lost, and the endoskeletal girdle is reduced. The cleithrum disappears entirely at an early reptilian stage, but the pectoral girdle remains reptilian until the early mammalian stage.[8]

The basic mammalian pattern began with the marsupials. This pattern consists of a well developed clavicle articulating with the sternum, a flat, fairly wide scapula with a moderate-sized coracoid. This design has diverged in 4 main directions (Fig. 1). One, those shoulder girdles modified for running have lost their clavicle to further mobilize the distal end of the scapula and the scapula is narrowed. Two, the shoulder girdles modified for swimming have also lost their clavicle but have become wide. Three, the shoulder girdles modified for flying have developed a large, long clavicle and a wide scapula with the lower portion particularly elongated. Four, the shoulder girdles modified for brachiating (swinging through the trees) have developed a strong clavicle, a large coracoid and a wide, strong scapula. Man's pectoral girdle is inherited from tree-swinging (brachiating) ancestors.[2] It has a strong clavicle and a broad, well developed wide-shaped scapula. The coracoid is well developed. Man's shoulder girdle is less mobile than that of active brachiators such as the Gibbon chimpanzee. In this sense, man's scapula has regressed.

The greatest alteration however, has come from man's upright posture, which has flattened the thorax in the anterior, posterior diameter. The scapular plane is approximately at 45° to the midline at rest. The plane of the forearm is habitually at 45° of internal rotation in most human activities.

MOTIONS OF THE SHOULDER GIRDLE

Motions of the shoulder are complex, as showed by Codman's 1934 analysis.[1] He

1300 N. Vermont Avenue, Los Angeles, CA 90027.
Received: April 11, 1979.

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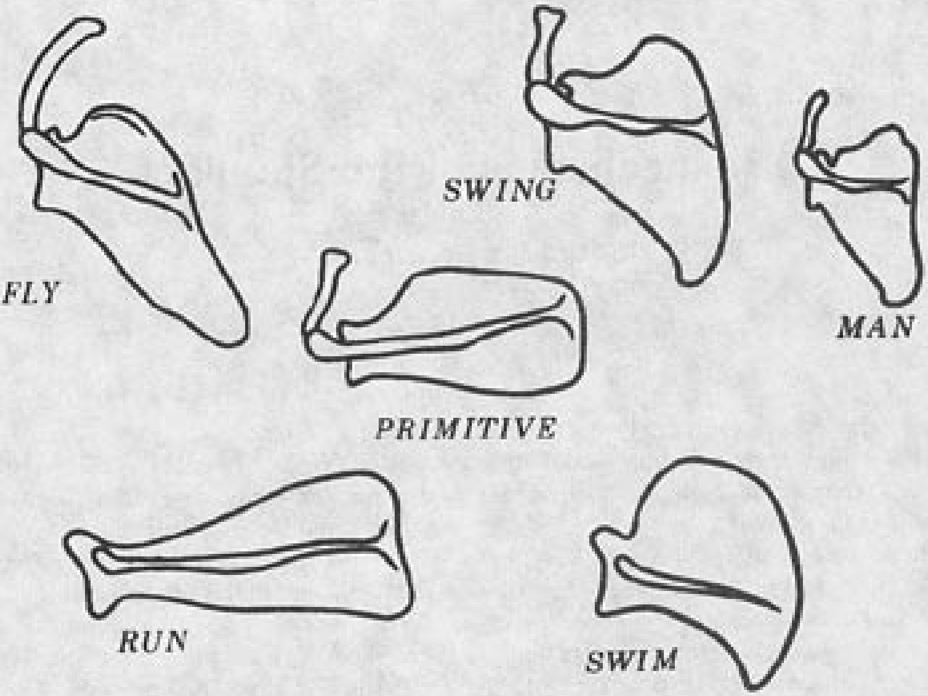

FIG. 1. Although the true primitive scapula is unknown, a composite of such primitive mammals as the opossum and shrew can be used as an adequate model. A clavicle is present; the coracoid is moderately developed; the spine of the scapula is well developed; and the blade of the scapula is flat. The 4 main modifications are shown, the greatest modification occurs in the running animal where the scapula has been freed by removing the clavicle and the motion of the four limb increased by hinging the limb on the vertebral border of the scapula. The modifications in the swimming mammals are similar except that a very wide scapula has developed. The most specialized development in the scapula retaining the clavicle is that in the bats where a long and powerful clavicle is present along with a very large coracoid and a markedly widened and elongated scapula. A similar but less striking modification has occurred in those animals which brachiate; the example shown in the drawing is that of a gorilla in which the scapula has achieved considerable width. Man's scapula is similar to the gorilla's in shape; however, it is reduced in size and can be considered to be a regression in evolution since its mobility is significantly less than any of the other primates.

recorded the following headings: (1) rotation of the long axis of the humerus; (2) the relative parts played by three different joints in the motion of elevation; (3) lateral elevation in coronal plane; (4) anterior, posterior motion in the sagital plane; (5) circumduction; (6) the motion at the acromoclavicular joint; (7) the scapulo-humeral rhythm which all structures cooperate. The sum of the motions of the shoulder girdle is such that more than 180° of motion of the humerus is possible in the plane of the scapula. The humerus can be passed behind the head in full abduction and behind the back in full adduction.

Rotation of the humerus is progressively diminished with abduction. One hundred and eighty degrees of rotation is possible with the arm adducted. Rotation is reduced to 90° at 90° of elevation, and a trace of rotation at full abduction, a result of tightening of the capsule and the threading of the rotator cuff muscles onto the coracoid and the spine of the scapula. Codman's "pivotal paradox" is explained by the humeral rotation men-

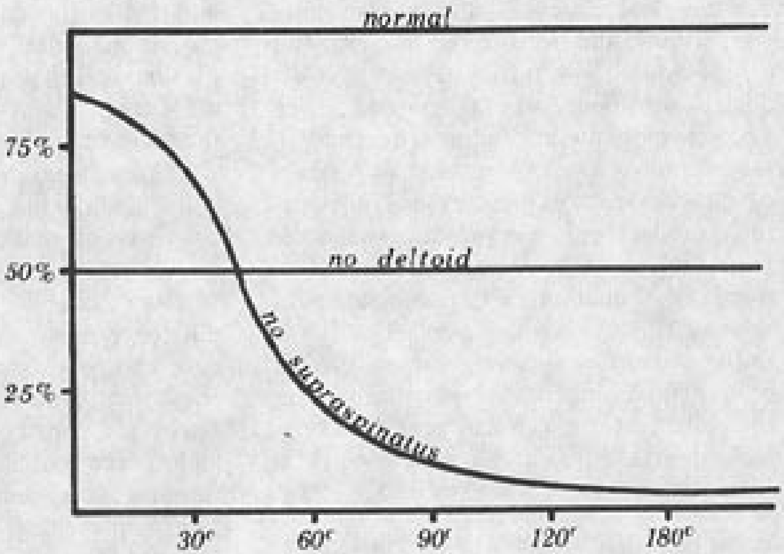

FIG. 2. Approximate strength in abduction of a normal shoulder. The torque which can be produced by the joint is approximately the same throughout the range of abduction. If the deltoid muscle is absent and the remaining rotator cuff is normal, about 50% of the abduction power is present throughout the range of motion. In contrast, if the supraspinatus function is absent and the shoulder is free of pain, abduction can be initiated with about 80% of normal strength. This however, rapidly falls off and above 90° the arm can barely be lifted against gravity.

tioned above. Starting with the arm fully abducted and fully internally rotated with the elbow maintained at 90° of flexion, the arm is fully abducted. This brings the humerus to neutral rotation in the fully abducted position. The arm is then brought to the side fully externally rotated. Thus, the forearm is now "pivoted" 180° from its starting position. This completes the "pivotal paradox." The position of greatest strength in abduction of the arm is approximately in the plane of the scapula (at 90° to the plane of the glenoid). This position places most of the muscles near their optimum fiber length.

The Force Couple of the Glenohumeral Joint

Elevation of the humerus normally requires a combined action of the deltoid and the rotator cuff.[4]

The deltoid hinge. The deltoid is not only a fan-shaped muscle which can contact any portion of its fibers, but is also hinged at its origin. Because of the hinge effect, the deltoid forces the humerus upward on the glenoid at 0° of abduction. As abduction at the glenohumeral joint progresses, the pull of the deltoid forces the humerus more directly into the glenoid. Further abduction passes the deltoid over center and, in higher abduction, the pull of the deltoid forces the head of the humerus downward out of the glenoid.

The fan-shaped rotator cuff. The pull of the hinged deltoid, which tends to displace the humeral head from the glenoid, is counteracted by the fan-shaped rotator cuff, which will fix the humeral head in the glenoid. This, in engineering terms, is called a *force couple*. A force couple is the basic application of forces to produce any rotation. This force couple applies the force necessary to abduct the humerus.

Function of the rotator cuff alone Fig. 2. Complete loss of the deltoid function due to isolated paralysis of the axillary nerve illustrates the function of the rotator cuff. The rotator cuff alone is able to produce full abduction of the glenohumeral joint.[7] The muscles, particularly the supraspinatus, wrap around the head of the humerus like a rope around a windlass. The arm is abducted with about 50% of the normal power. The scapulohumeral rhythm is normal.

Function of the supraspinatus. Absence of the supraspinatus muscle alone (provided the shoulder is pain-free) produces a marked loss of the power in the higher ranges of abduction. Abduction can be initiated with about 80% of normal power. The power in the abduction is rapidly lost and, by 90° of combined humeral and scapular motion, the weight of the arm can bearly be lifted against gravity. Full range of abduction, however, can be accomplished.

The Role of Pain in Shoulder Function

A significant degree of pain will markedly inhibit the muscle action of the shoulder. In a fresh rupture of the supraspinatus tendon, the pain inhibits the initiation of abduction. Temporary obliteration of the pain with a local anesthetic reveals a good initiation of abduction but marked weakness at 90° of abduction.[5]

Most of the chronic ills of the shoulder are due to man's upright posture with a modification of the plane of the scapula and the plane of the forearm as well as the chronically abducted position of the humerus. Typists, for example, have a much higher incidence of calcium in the supraspinatus tendon than file clerks who move their arms more freely. The subacromial bursa in man is poorly lined as compared with the subacromial bursa of the gorilla. The gorilla has a layer of fibrocartilage overlying the supraspinatus tendon and the tuberosities so that a smooth surface is formed. Man lacks a smooth surface, and the edge of the supraspinatus tendons and the tuberosities can be easily defined. The biceps tendon wears against the medial side of the groove due to the internal rotation of the humerus. In addition to this, man's groove is not consistent and many very shallow grooves are present as well as the supratubercular ridge of Meyer. All of these cause attrition of the biceps tendon.[3]

The shoulder is an easy joint to immobilize and still allow the patient to carry out most activities of daily living, including even limited hair-combing. This leads to the ease of establishing a "frozen shoulder," if abduction exercises are not carried out. The ease of dislocation of the shoulder is not surprising, considering the shallow glenoid. Successful repairs of recurrent dislocation all have the common factor limiting external rotation. The need for shoulder implants is rare. Replacement of a damaged or arthritic humeral head offers relief of pain. An intact rotator cuff and a normal glenoid are necessary for this type of replacement. Such a replacement is rarely successful in a severe fracture after the first 4 weeks, because of the extensive development of scar tissue and limitation of motion. A total shoulder implant seems to be slightly more successful than replacement of the humeral head alone with a metal prosthesis. If the rotator cuff is deficient, a restrained (ball and socket) type of shoulder will offer stability and relief of pain. As with all joint implants, only light activities should be permitted after any type of shoulder implant. The shoulder can be truly described as a most improbable joint.

SUMMARY

Man's shoulder girdle is of the general pattern of his tree-swinging ancestors. With assumption of the upright posture, man's thorax has flattened from anterior-posterior. This results in a rotation of the scapula to a position of 45° with the sagittal plane. In addition to this, man's forearm is habitually used in a position of approximately 45° of internal rotation. This places the biceps

tendon "off its trolley" and leads to biceps tinosynovitis. Motions of the glenohumeral joints result from the force couple of the deltoid muscle plus the rotator cuff muscles. the rotator cuff alone can abduct the arm with 50% force throughout the full range of its motion. In the absence of the supraspinatus muscle, however, the force couple is disrupted. Although initiation of abduction is with full force, the force rapidly falls off to 90°. Above 90° the arm can barely support its own weight. Although the shoulder undergoes progressive degenerative changes with age, the necessity for a joint implant, either partial or total—although successful—is rare.

REFERENCES

1. Codman, E. A.: Motions and Pivotal paradox *In*: The Shoulder, Boston, T. Todd, 1934, p. 32, p. 44.
2. Gregory, W. K.: Evolution Emerging, Vol. 2, New York, MacMillan, 1951, ch. xix-xxiv.
3. Hitchcock, H. H., and Bechtol, C. O.: Painful shoulder—observations on role of the tendon of the long head of the biceps brachii and its causation, J. Bone Joint Surg. 30A:263, 1948.
4. Inman, V., Abbott, L., and Saunders, J. B.: Observations on the functions of the shoulder, J. Bone Joint Surg. 26:1, 1944.
5. Mosley, H. F.: Ruptures of the Rotator Cuff, Springfield, Charles C Thomas, 1952.
6. Romer, A. S.: The Vertebrate Body, Philadelphia, W. B. Saunders, 1949, p. 178.
7. Staples, O. S., and Watkins.: Full active abduction in traumatic paralysis of the deltoid, J. Bone Joint Surg. 25:85, 1934.