6 Total Shoulder Arthroplasty: Principles and Biomechanics

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6.1 Introduction

Total shoulder arthroplasty (TSA) is a common treatment for patients with a deteriorated glenohumeral joint, often a result of rheumatoid arthritis or osteoarthritis. The main objective of this treatment is pain relief, which is achieved in most cases.

Shoulder arthroplasty remains the standard treatment to restore shoulder function and improve patient's quality of life in severe glenohumeral arthritis. The modern prosthetic system takes advantage from modularity and the availability of additional sizes of the prosthetic components.

Total shoulder arthroplasty requires release of contracted tissues, repair of rotator cuff defects, and reconstruction of normal skeletal anatomy with proper sizing and positioning of components.

Arthroplasty of the shoulder is different from hinge joint arthroplasty where collateral ligaments provide a high degree of stability with a large bony conformity and less range of motion. Normal shoulder kinematics can only be achieved when normal articular anatomy is reestablished and the passive and active stabilizers are balanced.

6.2 Shoulder Biomechanics

The complex biomechanics of the shoulder girdle encompasses the motion of 3 bones, 4 joints, and 16 muscles. The glenohumeral joint has the greatest range of motion of any diarthrodial joint in the body.

Understanding shoulder biomechanics in both the native shoulder and the prosthetic shoulder is essential for achieving a well-functioning, mobile, and stable anatomic shoulder arthroplasty.

When viewed from a biomechanical perspective, the anatomic elements of importance in shoulder arthroplasty are the proximal humerus, the glenoid, the capsuloligamentous structures, and the rotator cuff. The surgeon must evaluate the rotator cuff, as well as other structures, to perform a biomechanically good shoulder arthroplasty.

Meticulous analysis of the humeral and glenoid anatomy has been made with the purpose of producing components that will achieve normal shoulder kinematics. The humeral head is defined by its size and shape. Articular surface size can be defined by its radius of curvature and its thickness [1].

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These parameters are also compared with the center of rotation and to adjacent bony structures, having special implications in the final outcome of arthroplasty. The typical angle of the humeral axis to the center of the humeral head is 135°.

The humeral head offset refers to the position of the center of rotation of the humeral head from the axis of the humeral shaft in both the transverse and coronal planes. Several studies have shown that the humeral head center of rotation is offset from the humeral shaft axis, in both the transverse and coronal planes. In the transverse plane, the center of rotation is offset an average of 3 mm (range 2–4 mm) posteriorly. In the coronal plane, the center of rotation is offset an average of 7.5 mm (range 6–9 mm) medially. Therefore, these offsets both combine creating a center of rotation that is posteromedially offset [2].

The humeral head center line usually makes a retroversion angle of about 10–30° from the axis of elbow flexion.

The glenoid is pear shaped, with the superior anterior-posterior dimension being smaller than the inferior anterior-posterior radius. The glenoid center line, a line perpendicular to the planar surface of the glenoid, is usually neutral plus or minus a few degrees from the plane of the scapula. This relationship is altered in glenohumeral arthritis in which posterior wear of the glenoid results in glenoid retroversion, making arthroplasty more technically difficult [3] (Fig. 6.1).

The distance from the base of the coracoid to the greater tuberosity is called "lateral humeral offset" and generally measures about 57 mm. This reflects the size of the humeral head and the location of the joint line (the surface of the glenoid). The lateral humeral offset usually decreases in glenohumeral arthritis due to cartilage and bone loss on both sides of the joint. Shortening of the lateral humeral offset causes a decreased deltoid lever arm and a shortening of the resting length of the rotator cuff [4].

The physiological plane of elevation of the upper limb is situated on the plane of the scapula (anterior elevation) and not in the frontal plane (abduction) or in sagittal plane (flexion).

The biomechanics of the shoulder involves a complex variety of synchronous movements of the sternoclavicular, scapula-thoracic, and glenohumeral joints.

Anterior elevation of the glenohumeral joint is about 120°, combined with humerus lateral rotation.

In order to allow the arm to achieve full elevation (180°), a supplementary curve of 60° is needed and is possible because of scapula rotation.

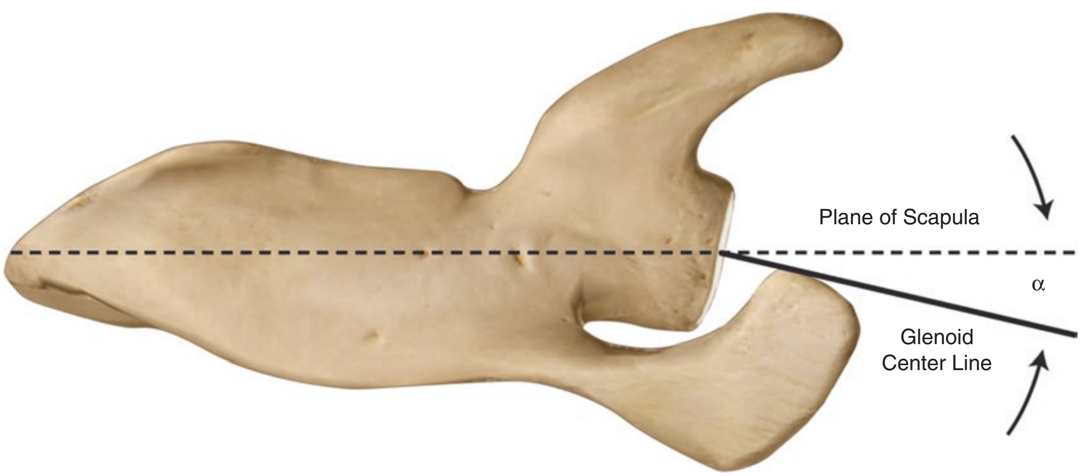


Fig. 6.1 The glenoid center line

6.3 Shoulder Stabilizers

The primary muscles and dynamic stabilizers of the shoulder can be divided into three primary groups. The scapulohumeral group includes the deltoid and rotator cuff muscles (supraspinatus, infraspinatus, teres minor, and subscapularis). The axioscapular group comprises muscles that act on the scapula and includes the rhomboids, trapezius, serratus anterior, and levator scapulae. The axiohumeral group includes the muscles that originate on the thorax and insert on the humerus and includes the latissimus dorsi and pectoralis major muscles.

Trapezius, rhomboids, serratus anterior, and levator scapulae are scapular rotators muscles. Scapula-thoracic joint is constituted by a sliding surface between anterior face of the scapula and thoracic cage. The coordinated movement between the scapula-thoracic joint and the glenohumeral joint has been defined by Codman as *scapula-thoracic rhythm*. The term scapula-humeral rhythm refers to the 2:1 ratio of glenohumeral to scapulothoracic motion. Full 180° elevation of the humerus cannot be achieved without 60° of upward rotation by the scapula on the thoracic spine [5].

The scapula-thoracic muscles transfer the potential energy of the trunk to kinetic energy in the shoulder. The kinetic train is a concept describing the transfer of energy from the trunk to the shoulder and arm. The scapula is a key link in the kinetic chain between the trunk and the shoulder. Any alteration in scapula-thoracic rhythm could predispose to shoulder joint modification. During an abduction movement of the arm, in the shoulder the glenoid (concave) is stable while the humerus (convex) abducts resulting in a sliding down or glide of the convex humerus on the concave glenoid surface.

The deltoid muscle is the primary abductor of the arm with supraspinatus contributing in the initiation of movement.

Biomechanically, during abduction of the arm at the shoulder, the supraspinatus muscle raises the arm during the first 15° of shoulder abduction. Then, from 15° to 90° of shoulder abduction, the medial deltoid assists to raise the arm biomechanically.

The rotator cuff muscles are important stabilizers of the glenohumeral joint during shoulder motion. They work in concert to elevate and rotate the arm, to compress and center the humeral head within the glenoid fossa, and to counteract antagonist moments from the three prime shoulder movers (deltoid, pectoralis major, and latissimus dorsi) at multiple shoulder angles.

Multiple muscles are activated synchronously to move the clavicle, scapula, and humerus to generate smooth movement of the arm.

The supraspinatus compresses, abducts, and generates a small external rotation torque peaking between 30° and 60° of elevation. In the absence of this check, the humeral head translates superiorly during humeral elevation resulting in subacromial impingement.

The infraspinatus and teres minor muscles provide glenohumeral compression, external rotation, and abduction. They also resist superior and anterior humeral head translation by exerting a posteroinferior force to the humeral head.

The subscapularis acts to produce glenohumeral compression, internal rotation, and abduction. Similar to infraspinatus, its muscle bellies generate their peak torque with the arm at 0° of abduction.

With rotator cuff pathology, altered kinematics and muscle activity are present, and superior humeral head translation increases and subacromial space decreases. In conditions such as osteoarthritis, cartilage degeneration and a collapsed head further alter the joint kinematics.

Retraction of the scapula is accomplished by the joint action of the trapezius and rhomboids. Upward rotation of the scapula is achieved by a force coupling of the upper trapezius, lower trapezius, and serratus anterior muscles. Scapular elevation is achieved through a force coupled action of the upper trapezius, elevator scapulae, and rhomboids. These force couples work together to rotate the scapula upward and contribute to the elevation of the arm.

The goal of conventional TSA is to restore stability, motion, strength, and smoothness—critical characteristics of a healthy shoulder joint. This is accomplished by replacing the humeral head and glenoid with prosthetic implants that are designed

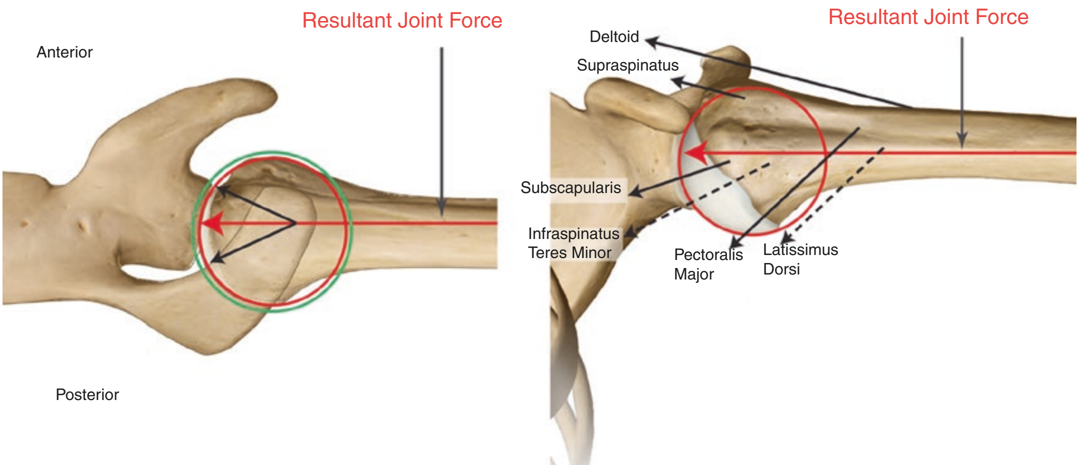


Fig. 6.2 Anatomic resultant joint force

to recreate the original anatomy. In the presence of intact rotator cuff and extrinsic shoulder muscles, a TSA is successful in restoring motion and improving function (Fig. 6.2).

6.4 Prostheses Biomechanics

Conformity is the interrelationship of the articular surface of the glenoid to the humeral head (Fig. 6.3). Glenohumeral conformity has been reported to be one of the most critical implant-related features that may affect the occurrence of glenoid loosening.

Perfect conformity would mean identical radii of curvature between the glenoid articulating surface and the humeral head. Studies that report conspicuous different radii of curvature, even in normal shoulders, may be defected because they fail due to the increased articular thickness at the level of the glenoid. Glenohumeral conformity in TSA influences humeral head translations to the glenoid component, contact stresses on the glenoid component and accompanying component wear, which may finally lead to glenoid-component radiolucency.

With perfectly conforming components, humeral head translations in any direction will result in edge loading. On the other hand, when there is a higher degree of component radial mismatch, contact stress rises due to the decreased contact area. There is therefore a balance between radial mismatch, which permits translation and conformity, and a minimized contact stress.

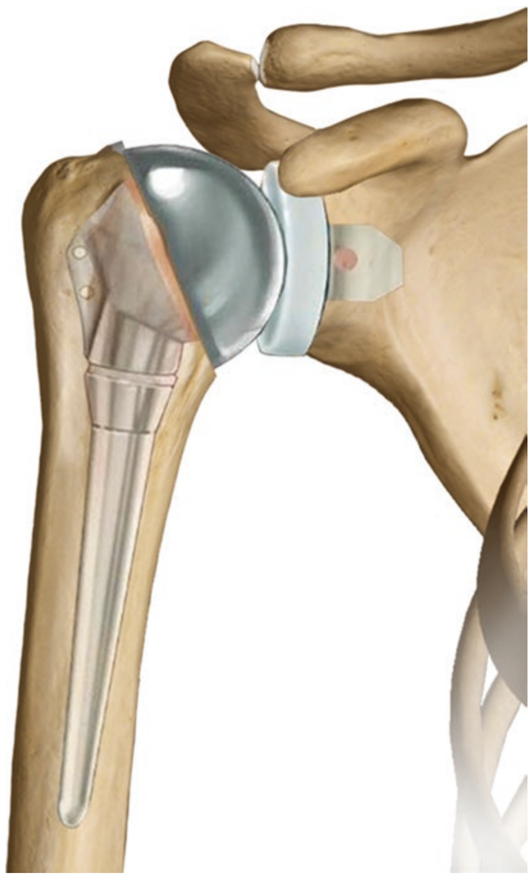


Fig. 6.3 Anatomic shoulder arthroplasty

In the normal shoulder, sufficient capsular laxity allows a large range of motion [6].

Tension of the capsuloligamentous structures varies depending on arm position, and the preservation of the length-tension relationship is critical for stability.

Deltoid is the most important muscle in shoulder arthroplasty. Surgeon's goal must be the preservation of its origin, insertion, and nerve supply. In addition, cuff tendons are at risk when humeral head osteotomy is performed. If the humeral cut is too low, the supraspinatus insertion may be detached, whereas an excessively retroverted cut could damage the cuff posteriorly. It is well accepted that the rotator cuff must be undamaged for successful total shoulder arthroplasty and the normal tension of the cuff must be preserved to restore the glenohumeral joint forces. Overstuffing shoulder joint disposes to excessive tension on soft tissues, limits tendon excursion, decreases range of motion, and predisposes to cuff tendons rupture [7].

The goal of arthroplasty surgery is to restore or alter shoulder biomechanics and joint kinematics in the affected shoulder in an effort to decrease pain and improve function.

Satisfactory results of replacement depend on

1. Prosthetic reproduction of a physiological bone conformity (shape of the humeral epiphysis and the glenoid silhouette corresponding to the normal structures in size, orientation, centers of rotation, and lever arm of the cuff tendons and deltoid muscle).
2. Optimum restoration of capsular tension to remove the asymmetric restraint caused by changes in capsule volume.
3. Restoration of the motor function and muscle balance.

The most important geometric parameters of a total shoulder arthroplasty include essentially humeral head diameter and thickness, neck inclination, humeral head height, humeral head retroversion, acromion-humeral distance, and medial and posterior head offsets. The cervico-diaphyseal angle is most often 135° + 5°. Prostheses are usually designed with a fixed angle of 130–135°, and the instrumentations perform head osteotomy at that angle.

Humeral head is extremely variable in shape and size: it is retroverted on average 19° (range 9–31°) and is proportional to the angle of retroversion of the scapula which instead is widely variable (0–60°). The humeral head is also inclined on average 41° (range 34–47°); head radius measures 23 mm (range 17–28 mm), and medial and posterior head center offset are on average 7 mm (range 4–12 mm) and 2 mm (range 1–8 mm), respectively [8].

Whereas degenerative diseases alter the spherical shape, the prosthetic head diameter often cannot be determined. The component's diameter is therefore chosen at the time in base of a trial reduction established on other parameters with special attention to the height of the hemisphere that seems to have a clear relationship with the head diameter.

Inaccurate anatomic recreation of the size of the humeral head may cause biomechanical consequences through malpositioning of the joint line or displacing the center of rotation [9].

Fischer has shown that displacing the center of rotation by 20% of its radius (5 mm for an average radius of curvature of 25 mm) changes the lever arm of the rotator cuff by 20% [10].

In all humerus the superior edge of the head protrudes 2–5 mm up to the superior edge of the greater tuberosity. If the head component is positioned under the edge of the greater tuberosity, joint's center of rotations drops causing a lowering of the humeral head and an increased tension in adduction, with a premature painful subacromial impingement.

On the other hand, a head protruding excessively above the greater tuberosity induces an increased tension on the cuff ("overstuffing") that leads to an increased risk of secondary rotator cuff tears.

It is important to note that alterations in neck-shaft angle may alter the tension on the rotator cuff and deltoid tendons potentially leading to rotator cuff and/or deltoid dysfunction. This variability can be approached in one of these two ways: using an adaptable implant with a variable neck-shaft angle or if using an implant with a fixed neck-shaft angle, plan the osteotomy and insertion depth to achieve an appropriate articular surface arc for the humerus. These two options can be summarized as adapting the prosthesis to the patient's anatomy or adapting the patient's anatomy to the prosthesis (Figs. 6.4 and 6.5).

Small errors in head retroversion do not strongly influence capsulo-ligamentous system tension nor the instantaneous center of rotation; an

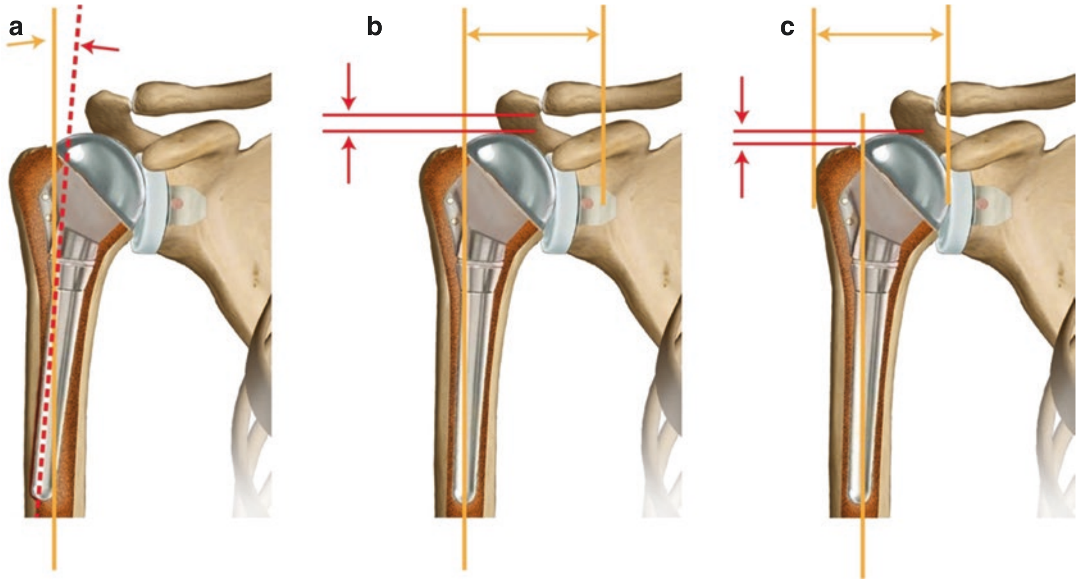


Fig. 6.4 Prosthetic components orientation

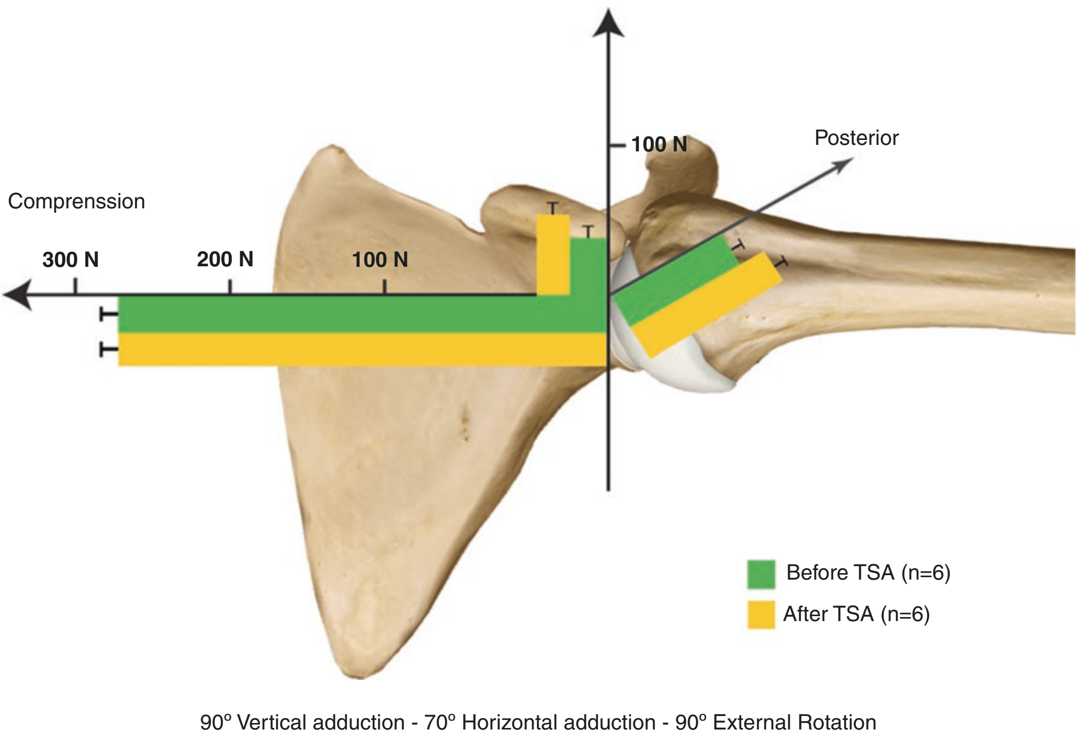
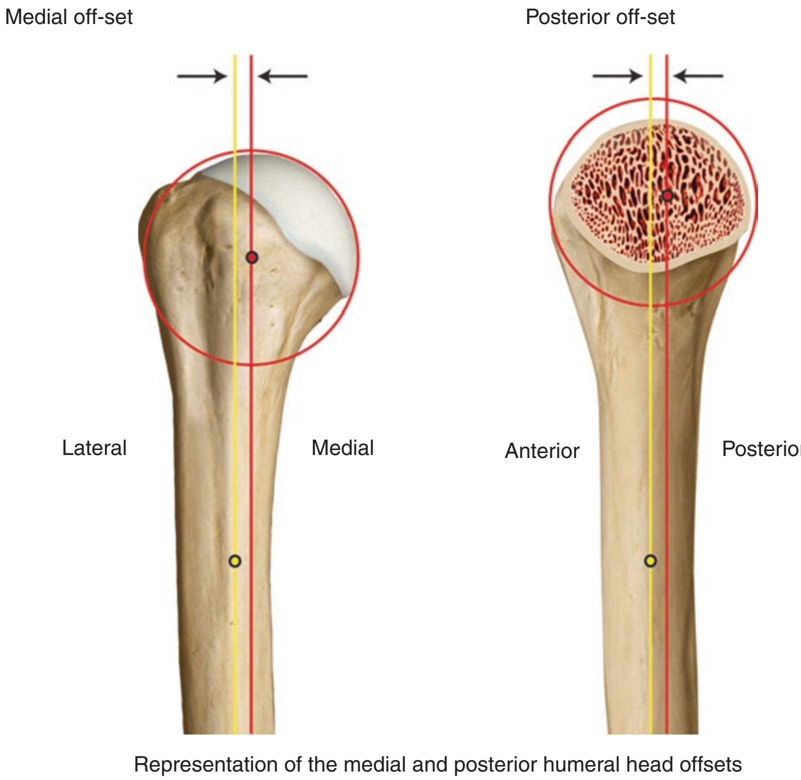


Fig. 6.5 Glenohumeral joint forces before (green) and after (yellow) shoulder arthroplasty

Fig. 6.6 Medial and posterior offset



excessive retroversion, on the other hand, may induce posterior head subluxation in case of a posterior cuff tear, whereas an insufficient retroversion may cause subscapularis impingement [6].

The center of the head is not in line with the diaphyseal humeral axis but is displaced both in the coronal and the sagittal planes. In the coronal axis, the medial and lateral translation of the humeral component is measured as the distance between a line through the center of the humeral stem and a tangent to the lateral margin of the acromion that is parallel to the first line. It is called medial or lateral offset and ranges from 2 to 12 mm (median 7 mm).

An excessive amount of lateral or medial intramedullary bone may result in an excessively lateralized or medialized humeral component, altering load distribution and eventually cortical bone reabsorption. Also the change of the fulcrum of rotation may lead to rotator cuff and deltoid insufficiency [2].

The center of the head lies 0–10 mm (median 5 mm) posteriorly to the diaphyseal axis (posterior humeral head offset); if this point, and therefore the new center of rotation moves anteriorly, can induce an abnormal contact with the glenoid and abnormal pressure on the subscapularis (anterior offset). The acromion-humeral distance indicates the free space of the rotator cuff between the head component and the inferior face of the acromion and measures about 2 cm. A wider space reduces muscle tension and produces a loss of strength in elevation while a narrower spacer results in a stiffer joint and a possible subacromial impingement (Fig. 6.6).

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