Factors Affecting the Design of Shoulder Prosthetics

Joseph P. Iannotti, Gerald R. Williams, and Andrew R. Karduna

The goals of prosthetic reconstruction of the shoulder are to re-establish the normal articular anatomy and to restore the normal soft-tissue balance of the static and dynamic stabilizer of the glenohumeral joint. Prosthetic design alone cannot achieve these goals. However, several anatomic and biomechanical factors have been identified that are important to consider during prosthetic design. Anatomic factors include humeral head radius, humeral neck length, glenoid radius, and lateral humeral offset. Biomechanical factors include normal and pathologic translational patterns of the humeral head, articular component conformity, glenoid component rim loading, and glenoid component strain patterns.

There are several categories of factors that influence the outcome of prosthetic reconstruction of the shoulder (Table 1), among which are the nature and degree of shoulder disease, the surgical technique, the postoperative rehabilitation program, and the design of the prosthetic components. The goals of prosthetic reconstruction of the shoulder are to re-establish the normal articular anatomy and to restore the normal soft-tissue balance of the static and dynamic stabilizer of the glenohumeral joint. When these surgical goals are achieved, the normal kinematics and function of the joint should be restored. In all shoulders undergoing prosthetic reconstruction, each of the aforementioned categories plays a significant role in achieving these goals. In some cases of severe joint destruction, the surgical techniques, rehabilitation program, and prosthetic systems available are insufficient to reconstruct or compensate for all of the disease present. Within the limitations offered by the disease, the outcome can be optimized by the surgical techniques, rehabilitation program, and the prosthetic design. Shortcomings in surgical technique and postoperative rehabilitation cannot and will not be corrected or minimized by prosthetic design. This article will present some of the more important anatomic and biomechanical factors that are important in the design of shoulder prosthetics and the surgical reconstruction of the glenohumeral joint.

Normal Glenohumeral Articular Anatomy

The articular surface of the humeral head is defined by its size and shape. For practical purposes, the size of the articular surface can be defined by its radius of curvature and its thickness (Figs 1A, 1C, B-C). The size and shape of the glenoid articular surface can be defined by its radius of curvature and its linear superior-inferior (SI) and anterior-posterior (AP) dimensions (Fig 1B). The glenoid is pear-shaped, with its superior AP dimension being smaller than its inferior AP dimension. The size of the humeral head and the location of the joint line (surface of the glenoid) with relation to the base of the corocoid defines the lateral humeral offset (Fig 1A, F-H). The lateral humeral offset plays a critical role influencing the capsular soft-tissue tension and the moment arm of the deltoid and rotator cuff musculature. The lateral humeral offset is decreased, in most cases of severe arthritis, by both cartilage loss and bone loss on both the humeral and glenoid surfaces. A longstanding decrease in the lateral humeral offset is often associated with asymmetric capsular contracture and, in some cases, rotator cuff deficiency.

Surgical techniques are independent of prosthetic design and are critically important in achieving a balance of soft tissue. Prosthetic design will influence the availability of sizes and shape to either reconstruct or compensate for the bony disease. With optimal soft-tissue balanc-

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From the Shoulder and Elbow Service, University of Pennsylvania, Philadelphia, PA and the Physical Therapy Biomechanics Laboratory, Medical College of Pennsylvania, Allegheny University, Philadelphia, PA.

Address reprint requests to Joseph P. Iannotti MD, PhD, Hospital of the University of Pennsylvania, 3400 Spruce St, Philadelphia, PA 19104.

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Table 1. Factor Affecting Outcome After Shoulder Joint Replacement

- Disease Process
  - Rotator cuff disease
  - Glenoid erosion bone loss
  - Humeral bone loss
  - Bone density
- Surgical technique
  - Prosthetic placement
  - Prosthetic-cement-bone interface
  - Soft-tissue balancing
    - Releases and repair
- Prosthetic design
  - Size selection
    - Glenoid
    - Humeral head
    - Humeral stem
  - Offsets
  - Material properties
- Rehabilitation Program
  - Range of motion
  - Strength
  - Stability

ing and reconstruction, the prosthetic system available will affect the anatomic reconstruction of the lateral humeral offset and influence outcome. Overlengthening of the lateral humeral offset or lengthening the offset beyond the soft-tissue envelope available after all soft-tissue releases, will result in overtightening of the soft tissue and thereby the loss of motion or postoperative rupture of the subscapularis. Excessive shortening of the lateral humeral offset will result in a decreased moment arm for the deltoid and rotator cuff which may result in weakness and soft-tissue laxity that may contribute to instability.

The lateral humeral offset is defined by the size of the humeral head and the location of the joint line. The lateral humeral offset has a wide range of 43 mm to 68 mm[1] (Fig 2). The humeral head radius of curvature also has a wide range between 19 mm and 28 mm[1] (Fig 3). The differences are closely correlated with the height of the individual. In contrast, regardless of the size of the individual, the surface of the glenoid (joint line) is within 5 mm of the base of the corocoid.[1] It is obvious that the lateral humeral offset is dependent on the size of the humeral head (Fig 4). If reconstruction of the lateral humeral offset is necessary among different size individuals, a wide range of humeral head sizes is needed. In addition, the anatomic data require the glenoid component to be thin.

The size of the humeral head is defined by the radius of curvature and the thickness of the articular segment. Correlation of the radius of curvature and thickness shows specific anatomic combinations of radius and thickness[1] (Table 2).

The AP location of the humeral articular surface, in relation to the anatomic axis of the

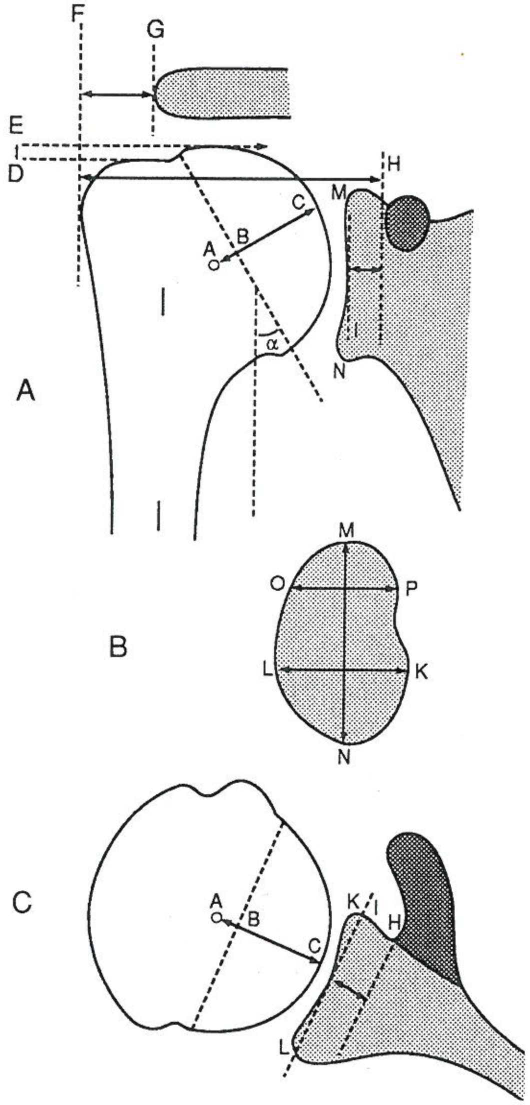

Figure 1. (A-C) Line drawing of the normal glenohumeral relationships. Radius of curvature of the humeral head. (A, C) Thickness of the humeral head, B-C. (B) AP and SI of the genoid. (A) Lateral humeral offset, F-H. (Reprinted with permission, Iannotti JP, Gabriel JP, Schneck SL, et al: The normal glenohumeral relationships: An anatomical study of 140 shoulders. J Bone Joint Surg Am 74:491–500, 1991[1])

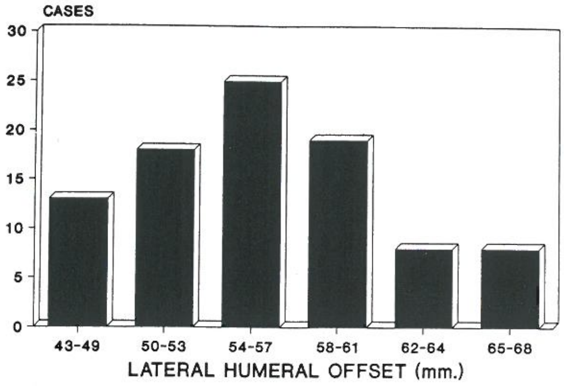

Figure 2. Range and distribution of the lateral humeral offset. (Reprinted with permission, Iannoti JP, Gabriel JP, Schneck SL, et al: The normal glenohumeral relationships: An anatomical study of 140 shoulders. J Bone Joint Surg Am 74:491–500, 1991[1])

humeral shaft, defines the AP humeral offset (Fig 5). In anatomic studies, the humeral head is generally set 3 to 5 mm posterior to the axis of the humeral shaft.[2] Press fit humeral stems that are located in line with the axis of the humeral shaft will place the humeral head articular surface 3 to 5 mm anterior to the anatomic head location. The clinical and biomechanical consequence of nonanatomic placement in the AP plane of 3 to 5 mm is not well defined at this time.

The neck shaft angle varies between 30° and 50° and is also correlated with humeral head size, with the greater angle associated with a larger head size[1] (Fig 6). Most current prosthetic designs have a fixed neck shaft angle. When the neck shaft angle is abnormally increased (more varus), the humeral prosthetic articular surface is more distal than the anatomic position. A more inferior articular position will result in prominence of the greater tuberosity. Compensating for this nonanatomic positioning with a larger humeral head will result in an oversized head, increased soft-tissue tension, loss of shoulder motion, or rupture of the subscapularis repair site.

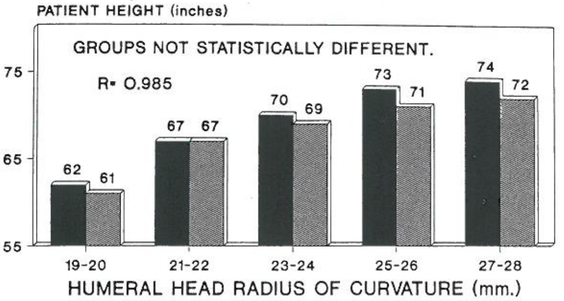

Figure 3. Range and distribution of the humeral radius of curvature. (Reprinted with permission, Iannoti JP, Gabriel JP, Schneck SL, et al: The normal glenohumeral relationships: An anatomical study of 140 shoulders. J Bone Joint Surg Am 74:491–500, 1991[1])

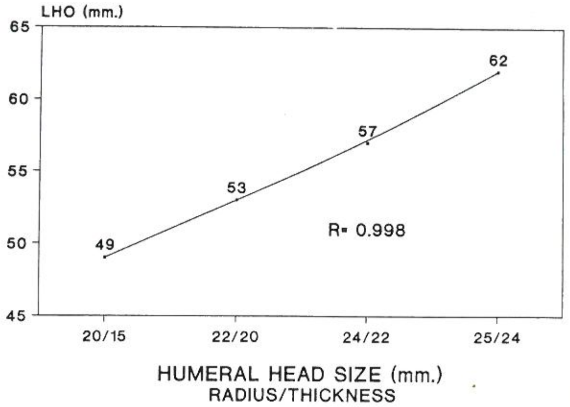

Figure 4. Correlation of the lateral humeral offset and the humeral head size. (Reprinted with permission, Iannoti JP, Gabriel JP, Schneck SL, et al: The normal glenohumeral relationships: An anatomical study of 140 shoulders. J Bone Joint Surg Am 74:491–500, 1991[1])

The glenoid component is pear shaped, with the superior AP length being smaller than the inferior AP length. The size of the glenoid component is also closely correlated with the size of the humeral head[1] (Fig 7). The size and shape of the glenoid and its correlated size of the humeral head influence the contact between the nonarticular portions of the proximal humerus (rotator cuff) and the glenoid rim (labrum) when the arm is at the extremes of motion. In

Table 2. Frequencies of Fixed Combinations of the Radius of Curvature and the Thickness of the Humeral Head*

Radius of Curvature (mm)	*Thickness* (mm)		
	15-17	*18-20*	*21-24*
19-20	10	3	2
21-22	7	18	3
23-24	0	9	18
25-26	0	8	14
27-28	0	0	4

*Eighty-five percent of all sizes of the humeral head are defined by eight combinations of head sizes, shown in the boxes.

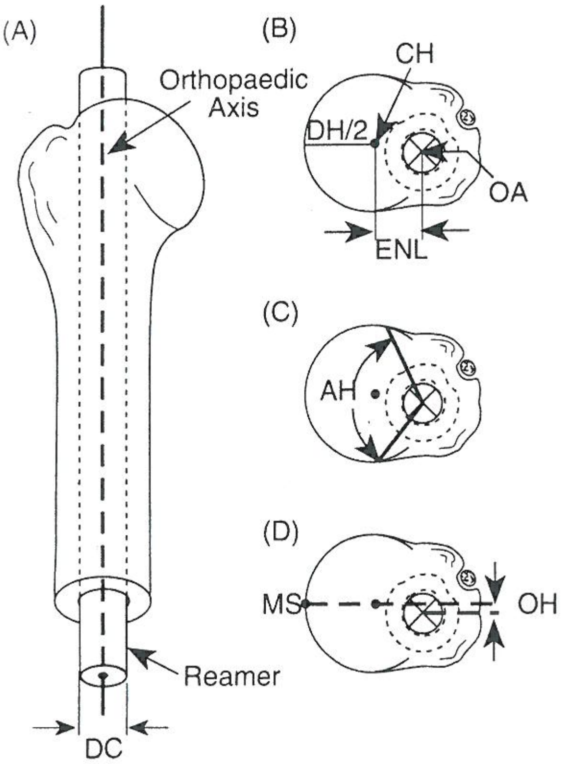

Figure 5. The axis of the center of the humeral intramedullary canal defines the orthopedic axis (OA) of the humerus. DC, diameter of the canal; ENL, effective neck length; Ah, angle subtended by the head; OH, anterior-posterior humeral offset, MS, midpoint of the articular surface. (Reprinted with permission, Matsen FA, Lippitt SB, Sidles JA, et al: Smoothness in Practical Evaluation and management of the Shoulder. Philadelphia, PA, Saunders, 1994, pp 151-219)

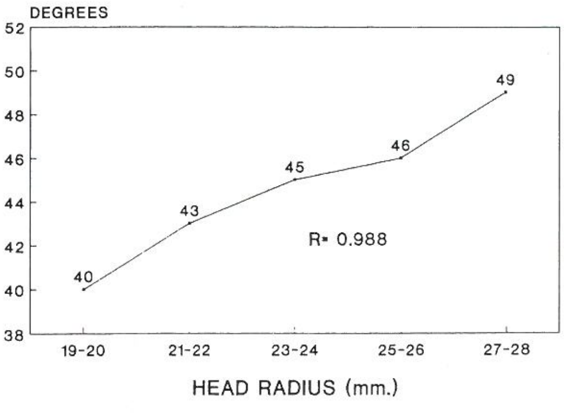

Figure 6. Correlation of the neck shaft angle to the humeral head size. (Reprinted with permission, Iannotti JP, Gabriel JP, Schneck SL, et al: The normal glenohumeral relationships: An anatomical study of 140 shoulders. J Bone Joint Surg Am 74:491–500, 1991[1])

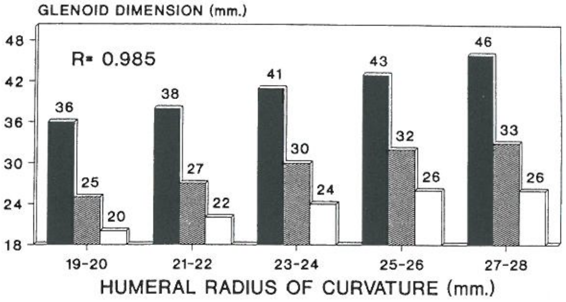

Figure 7. Correlation of glenoid size to humeral head size. (Reprinted with permission, Iannotti JP, Gabriel JP, Schneck SL, et al: The normal glenohumeral relationships: An anatomical study of 140 shoulders. J Bone Joint Surg Am 74:491–500, 1991[1])

the normal shoulder this phenomenon has been termed internal glenoid impingement.[3,4] Deviation in the normal anatomic sizes or shape of the humeral or glenoid articular surfaces in prosthetic components may result in component impingement,[5] which could lead to premature glenoid component loosening. Deviations from the anatomic shape and size that will increase the chance for internal glenoid impingement include decreased humeral head articular surface area (Figs 8a, 8b); increased glenoid AP dimension; nonanatomic anterior humeral head placement; and an oval rather than a pear-shaped glenoid. Abnormalities in humeral kinematics will also affect the likelihood of internal glenoid impingement.

Normal and Prosthetic Kinematics

The motion of the humeral head within the glenoid fossa can be described in clinical terms as components of rotation and translation. Factors that affect the kinematic of the glenohumeral joint include the conformity of the articular surfaces, the glenohumeral ligaments, the rotator cuff, the negative intra-articular pressure, and proprioception. The normal kinematic motion of the glenohumeral joint varies and is dependent upon the conditions under which motion is achieved.

When the glenohumeral joint moves in the midranges of motion and with an intact and well-functioning rotator cuff, the humeral head has a relatively fixed center of rotation within the glenoid fossa that is located at the anatomic center of the spherical humeral articular surface.[6-10] Under this circumstance the glenohu-

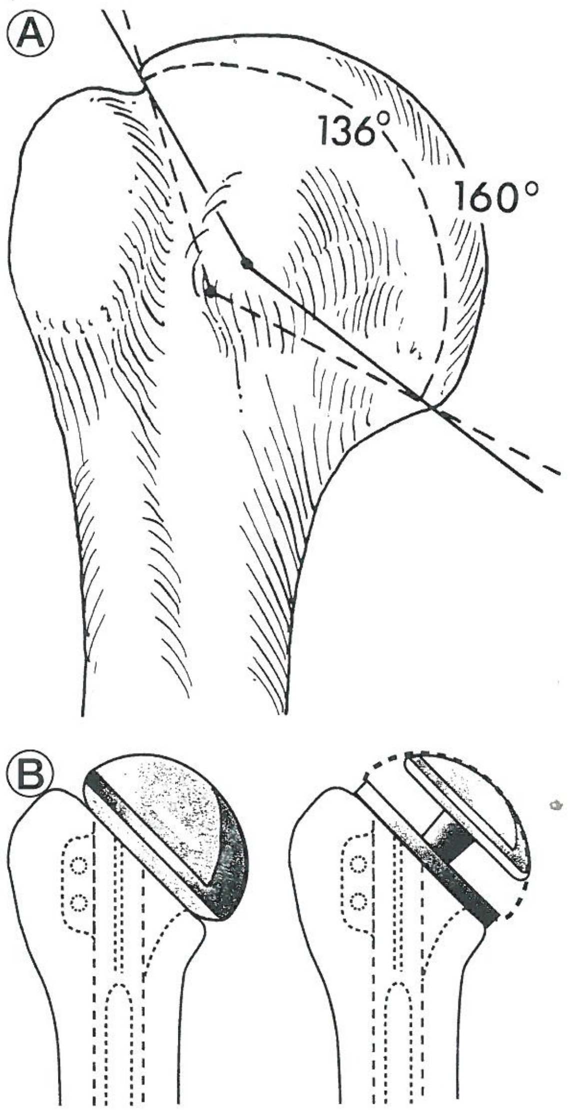

Figure 8. (A) Relationship of humeral head size and the arc of rotation allowed before glenoid impingement. (Reprinted with permission[5]) (B) Use of a modular system with a large gap between the humeral head component and the osteotomy site will result in a decrease in the available articular surface for a given lateral humeral offset. A decrease in the available articular surface can result in internal glenoid impingement. (Reprinted with permission, Matsen FA, Lippitt SB, Sidles JA, et al: Smoothness in Practical Evaluation and management of the Shoulder. Philadelphia, PA, Saunders, 1994, pp 151-219)

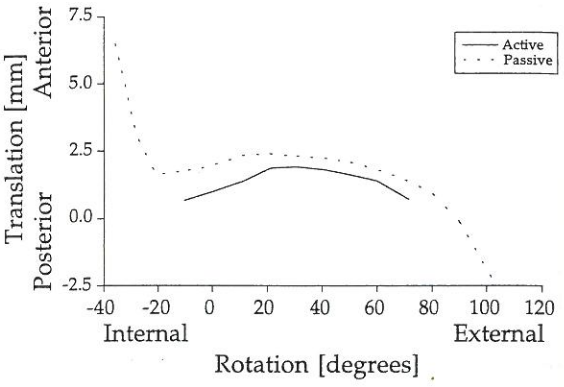

Figure 9. Typical polhemus kinematic tracing of a cadaveric shoulder tested in passive and active motion. Anterior to posterior translation of the humeral head in a cadaveric shoulder placed through both an active (dashed line) and passive (solid line) range of internal to external rotation. The arm is tested in the plane of the scapula and 90° of total arm elevation. In the midrange of motion, both with passive and active range of motion, the humeral head translation is within 1 to 2 mm. During passive range of motion that is available, humeral head translation can increase to several millimeters. (Reprinted with permission[6])

meral joint approximates a "ball-in-socket articulation" (Figs 9, 10), with small translations that are between 0 and 2 mm. The variability in this normal transitional motion is dependent on the congruency between the glenoid and humeral articular surfaces.[6,10] In shoulders with a mismatch between the glenoid and humeral radii of curvature there is a greater degree of transitional motion. When the rotator cuff is deficient or when there is capsular contracture, humeral head translation can be markedly increased. With rotator cuff deficiency, excessive translation is usually in the superior direction.[11-14] With asymmetric capsular contracture, there is excessive translation in a direction opposite to the side of capsular contracture.

The normal glenohumeral articulation has a near perfect spherical humeral articular sur-

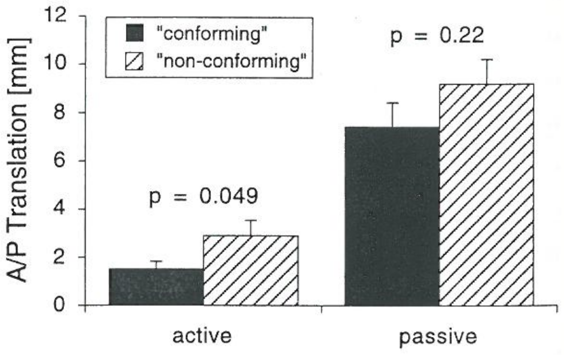

Figure 10. Effects of conformity on translation. Mean ± SEM on net AP translation for conforming and nonconforming joints, in both active and passive range of motion of the normal glenohumeral joint.

face.[15-17] The glenoid subchondral bone is nearly flat, with a radius of curvature significantly greater than that of the humeral head. The glenoid articular surface is composed of articular cartilage and the peripheral labrum. The labrum and the thicker peripheral articular glenoid cartilage result in a radius of curvature that is on average equal to the humeral head radius of curvature. However, significant individual variation in articular conformity is noted, and in some cases there is a significant mismatch in the radii of curvature between the humeral and glenoid surfaces. The radial mismatch can account for variation in the amount of humeral head translation during active range of motion[6,10] (Fig 11).

When the glenohumeral joint moves passively at the extremes of motion, there is significant humeral head translation[6,18-21] (Figs 10, 11). The direction and magnitude of humeral translation are dependent upon the capsular ligaments. With the extremes of external rotation in the 90° abducted position, and posterior to the plane of the scapula, there is posterior humeral head translation that in some cases can reach 10 to 12 mm (Fig 11).[18] With the extremes of internal rotation in the forward flexed and adducted arm position, there is anterior and superior humeral head translation of 10 to 12 mm. Humeral head translation noted during passive positioning of the arm is in a direction opposite to the portion of the capsule that is tightened and is obligate in nature.

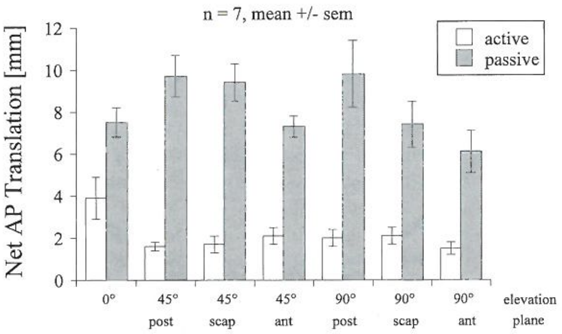

Figure 11. Average humeral head translation of seven cadaver shoulders tested in active and passive range of motion in 45° and 90° of total arm elevation posterior (post), anterior (ant), and within the plane of the scapula (scap). With active range of motion the average humeral head translation is on average 1 to 2 mm (open bars). With passive motion, humeral head translation is significantly greater and can average several millimeters (shaded bars).

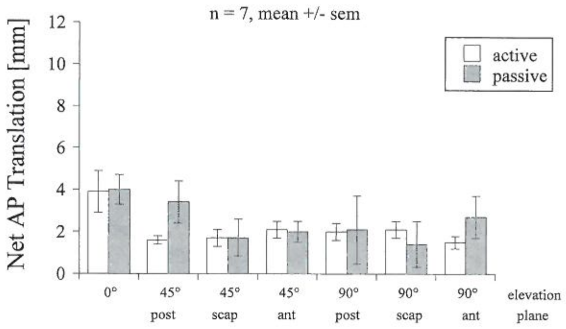

Figure 12. When comparing active (open bars) and passive (shaded bars) for the same arc of motion, the degree of anterior-posterior translation of the humeral head is the same.

Interestingly, we have found that when translations are compared during passive range of motion within the same limited arc of motion achieved with active range of motion, humeral head translation is the same (Figs 11, 12). This, therefore, explains that the rotator cuff functions to minimize humeral head translation and the extremes of motion that can be achieved with passive positioning.[6] It is at the extremes of motion, which are normally achieved passively, when humeral head translation occurs. Abnormal asymmetric capsular tightening of the capsule, as a result of surgery or disease, may result in greater degrees of humeral head translation during a shorter arc of motion that can occur either with passive or active joint positioning. Under pathologic conditions of anterior capsular tightness there is dynamic or static posterior humeral head translation. Abnormal asymmetric posterior capsular tightness will result in abnormal and excessive anterior and superior translation of the humeral head, particularly with forward flexion.

Active arm positioning of the prosthetic shoulder also results in humeral head translation. The amount of humeral head translation is dependent on the conformity between the glenoid and humeral components. With a perfectly conforming prosthetic articulation there is little translation motion with active arm positioning.[22] Humeral head translation doubles with greater radial mismatch up to 2 to 3 mm. There is a direct correlation between radial mismatch and humeral head translation, although with active arm positioning the rotator cuff functions to limit translation.[6] In the prosthetic shoulder normal humeral head translation with active

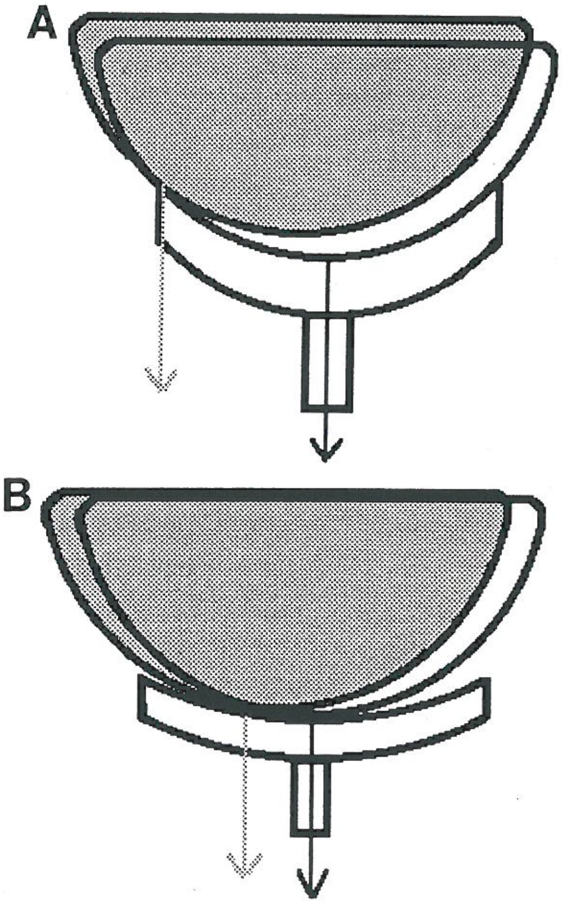

Figure 13. Effect on conformity with humeral translation. With conforming surfaces any degree of translation will result in rim loading.

arm positioning is recreated with a 3 to 4-mm radial mismatch.[22] In the patient with a prosthetic reconstructed shoulder there is translation and rim loading when the prosthetic components are perfectly conforming[23] (Fig 13). The degree of humeral translation allowed before rim loading will be dependent on conformity between the components.[24]

Although the normal osteochondral glenohumeral articulation is in most cases nearly perfectly conforming, a small amount of humeral head translation is allowed without pathologic consequences. Humeral head translation is allowed in the normally conforming glenohumeral joint because of the reversibly deformable articular cartilage and labrum. In the prosthetic shoulder the components are not deformable. Excessive restraint of normal humeral head translation will result in rim loading, which may result in glenoid loosening.

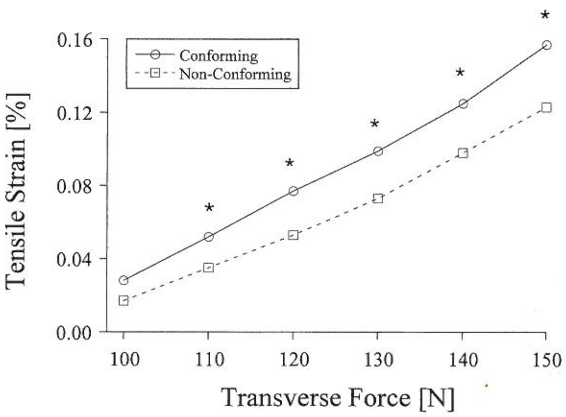

Figure 14. Effect of conformity on tensile strain at the glenoid keel. Conforming surfaces show increased tensile strain (statistically significant *) with humeral head translation.

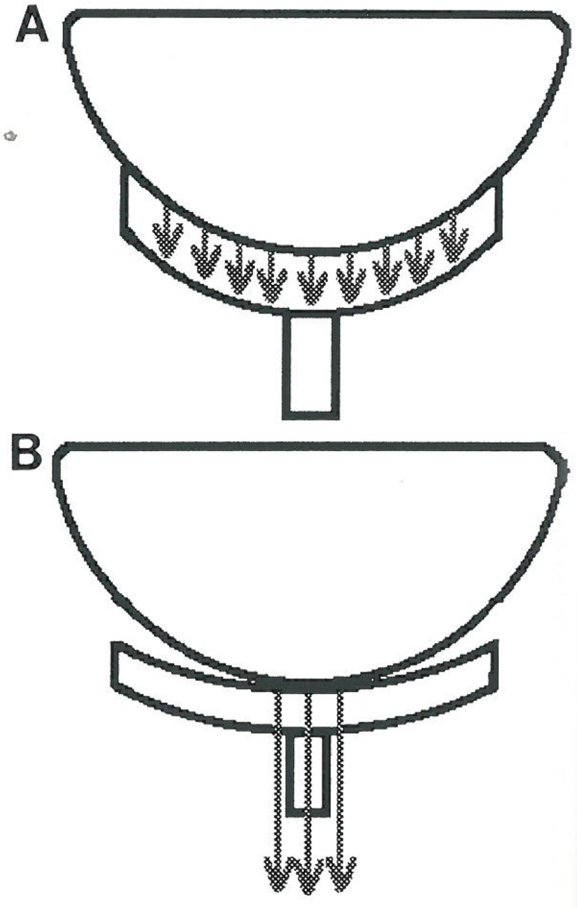

Figure 15. Effect of conformity on compressive stress. With less conformity there is a decreased unit area of contact with increased stress.

Although this correlation has not been shown in a clinical setting, strain-gauge measurement at the keel of a cemented glenoid component in vitro shows higher tensile strain with a perfectly conforming articulation and humeral head translation[25] (Fig 14). The theoretical advantages associated with decreased component strain of a nonconforming prosthetic articulation with humeral head translation may be offset by the theoretical disadvantages of increased contact stresses with less congruent joints (Fig 15). The balance between these two opposing factors may define the optimal degree of conformity between the prosthetic glenoid and humeral components.

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