



Biomechanics of anatomic and reverse shoulder arthroplasty

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- The biomechanics of the shoulder relies on careful balancing between stability and mobility. A thorough understanding of normal and degenerative shoulder anatomy is necessary, as the goal of anatomic total shoulder arthroplasty is to reproduce premorbid shoulder kinematics.
- With reported joint reaction forces up to 2.4 times body-weight, failure to restore anatomy and therefore provide a stable fulcrum will result in early implant failure secondary to glenoid loosening.
- The high variability of proximal humeral anatomy can be addressed with modular stems or stemless humeral components. The development of three-dimensional planning has led to a better understanding of the complex nature of glenoid bone deformity in eccentric osteoarthritis.
- The treatment of cuff tear arthropathy patients was revolutionized by the arrival of Grammont's reverse shoulder arthroplasty. The initial design medialized the centre of rotation and distalized the humerus, allowing up to a 42% increase in the deltoid moment arm.
- More modern reverse designs have maintained the element of restored stability but sought a more anatomic postoperative position to minimize complications and maximize rotational range of motion.

Keywords: complication; distalization; eccentricity; glenohumeral arthritis; glenosphere size; humeral and glenoid morphology; inclination; inlay; mismatch; neck shaft angle; onlay; polyethylene; prosthesis design; replacement; shoulder pathology

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Introduction

The glenohumeral joint is a complex biomechanical entity. In the physiologic state, the shoulder relies on bony

anatomy, as well as on static (labrum and ligaments) and dynamic structures (rotator cuff) to adequately balance the force couples applied to the humeral head.¹ The goal of anatomic total shoulder arthroplasty (ATSA) is, therefore, to restore the premorbid state by recreating normal shoulder kinematics. This simple objective can, however, be challenging to achieve, as anatomy is subject to premorbid variations, in addition to distortion secondary to degenerative or traumatic changes.² On the contrary, reverse shoulder arthroplasty (RSA) is a non-anatomic procedure that achieves stability through a semi-constrained design and relies on the deltoid and other remaining muscles to move the humerus around a fixed glenosphere. While originally intended to treat patients with cuff tear arthropathy, its indications are continually expanding. Since the initial Grammont design, much innovation has been proposed to optimize active and impingement-free range of motion.

We provide an overview of the current biomechanical understanding of ATSA and RSA. These principles should help surgeons to plan and perform shoulder replacement surgeries in daily practice.

Anatomic total shoulder arthroplasty (ATSA)

As mentioned, anatomy is key to successfully reproduce patients' physiologic joint kinematics. By virtue of its mobility, the glenohumeral joint is predisposed to instability. One factor affecting stability is the radius of curvature mismatch between the humeral head and glenoid. Further, only 20 to 30% of the humeral head is in contact with the glenoid.³ The rotator cuff acts as an essential dynamic stabilizing force centring the humeral in the mid-portion of range of motion, and is crucial for an ATSA to be effective.⁴ The supraspinatus helps to centre the humeral head against the force of the deltoid in lower

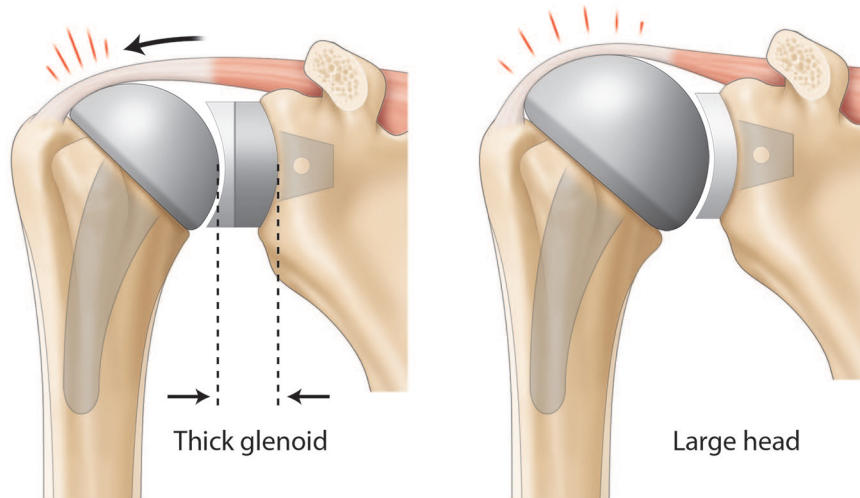


Fig. 1 The goal of anatomic total shoulder arthroplasty (ATSA) is to restore physiologic shoulder kinetics. Glenoid lateralization or increased humeral component sizing ('overstuffing') will stress the rotator cuff.

degrees of abduction, while the infraspinatus and teres minor help to clear the greater tuberosity under the coracoacromial arch when the arm is moved in abduction and external rotation.^{4,5} Lastly, even though the shoulder is not a weight-bearing joint, joint reaction forces as high as 2.4 times bodyweight have been reported during shoulder rehabilitation.⁶

Humeral head

Proximal humerus anatomy is subject to great variability, which is further significantly modified by arthritic changes.^{7,8} As ATSA can restore physiologic shoulder kinetics, a thorough knowledge of normal anatomy appears mandatory, as one cannot simply rely on perioperative measures (Fig. 1).⁹ The non-arthritic humeral head has a mean three-dimensional measured diameter of 46.2 ± 5.4 mm (range, 37.1 to 56.9 mm) and a humeral height of approximately 19 mm (Fig. 2).^{10–14}

The osteoarthritic head is flattened and widened with a mean diameter of 59 ± 9 mm.⁷ The humeral head has the particularity to be elliptic in the periphery and become spherical in its central part, meaning that the cut surface will be about 2 mm larger from medial to lateral than from anterior to posterior.¹⁴ While spherical humeral head implants are mainly used in shoulder arthroplasty, elliptic implants have been proposed to reproduce anatomy and theoretically improve the rotational range of motion. The ratio between humeral head size and height is relatively constant.¹⁵ The highest point of the humeral head lies 8 ± 3.2 mm above the greater tuberosity (Fig. 3).¹⁴ Lastly, relative to the humeral canal, the head has a posterior and medial offset of 0.35 to 2.6 mm and 5.6 to 9.7 mm, respectively (Fig. 2 and Fig. 4).^{2,16}

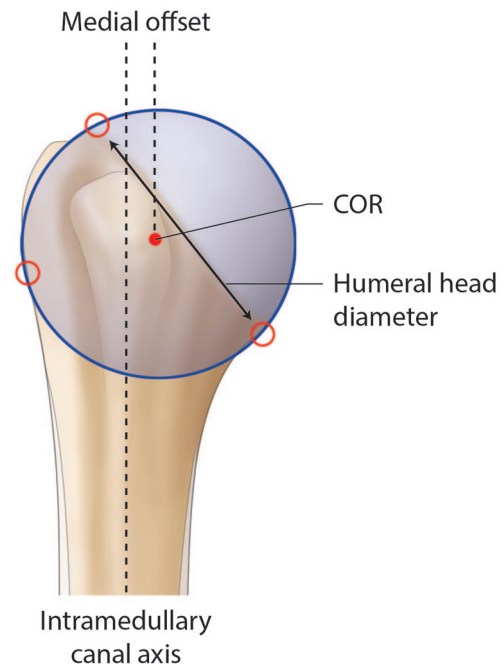


Fig. 2 Illustration of a right non-arthritic humeral head. The humeral head diameter, the centre of rotation (COR), the intramedullary canal axis and the medial offset (distance between the intramedullary canal axis and the COR) are represented.

These parameters are helpful to select the appropriate humeral head implant, as this crucial step will ultimately determine the joint centre of rotation (COR). However, current biomechanical data do not support significant superiority of the elliptic design over the spherical one regarding the range of motion in internal and external rotation.¹⁷

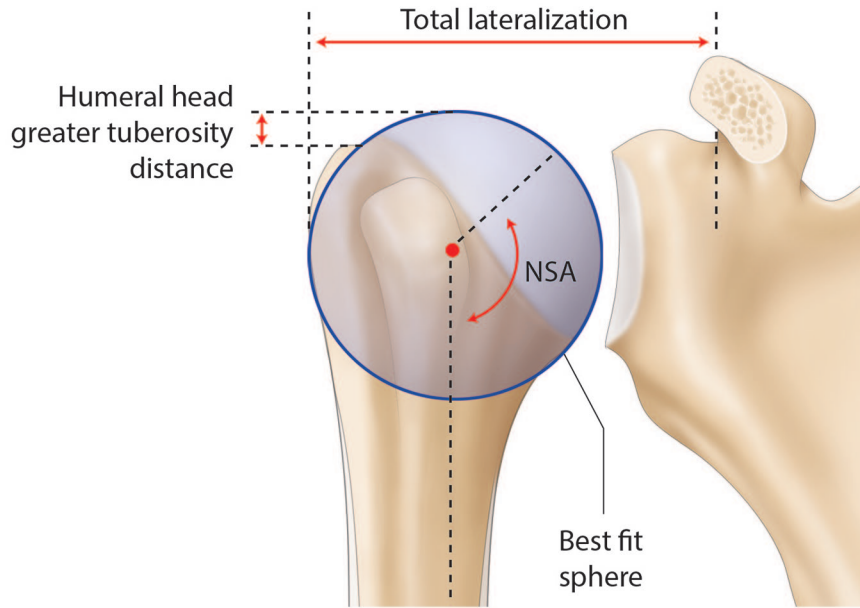


Fig. 3 Illustration of a right non-arthritic humeral head. The humeral head–greater tuberosity distance, the neck-shaft angle (NSA), the best fit centre and the total lateralization are represented. The total lateralization reflects the glenohumeral offset, taking into account potential glenoid bone loss.

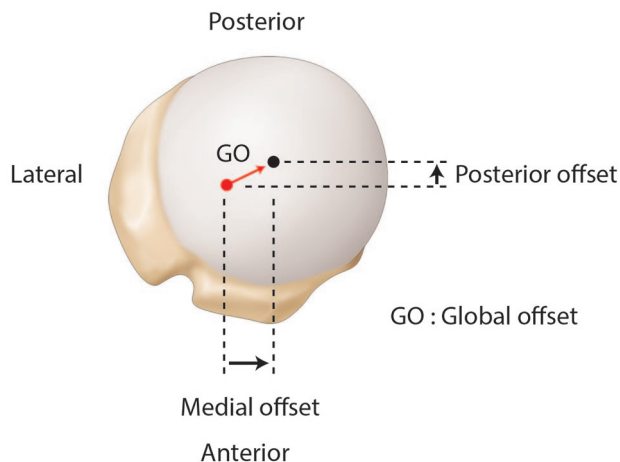


Fig. 4 Superior view of a right shoulder. Representation of the medial, posterior and global (GO) offsets.

Terrier et al illustrated in a numerical shoulder model that a 5 mm malposition of the humeral head implant resulted in impingement or subluxation for an inferior or superior shift, respectively. Both resulted in increased stress on the cement mantle.¹⁸ While joint COR can be determined three-dimensionally by a best-fit sphere using preserved non-articular landmarks, this technique has been translated to a two-dimensional process to allow intraoperative as well as postoperative radiographic evaluation (Fig. 2 and Fig. 3).^{8,19}

However, there is no consensus on cut-off values for joint COR modification, as values as low as 2.5 mm can have been reported to impact impingement-free range of motion.²⁰ Further, if the humeral head is implanted 5 mm too high in regard to the tuberosity, shoulder function will not solely be impaired by a 4 mm decrease in infraspinatus and subscapularis lever arms but also by the tight inferior capsule.²¹ Cadaveric studies have revealed that an increased humeral component sizing (commonly called ‘overstuffing’) would modify the COR and add stress to the rotator cuff (Fig. 1). Overstuffing not only decreases shoulder range of motion but also changes rotator cuff lever arm, exposing patients to the potential risk of secondary cuff failure.^{22,23} Restoring physiologic soft tissue tension will provide stability and prevent complications such as aseptic loosening and osteolysis induced by stress shielding.²⁴ Lastly, controversy exists regarding the superiority of resurfacing the humeral head over stemmed implants to reproduce physiological shoulder biomechanics.^{8,25}

Neck-shaft angle

The mean neck-shaft angle (NSA) or inclination of the proximal humerus is approximately 135 degrees but varies between 115 and 148 degrees (Fig. 3). A study of 2058 humeri by Jeong et al notes that 22% are either < 130 degrees or > 140 degrees.²⁶ Thus, fixed NSA humeral stems rely on surgeons to adapt their surgical techniques to accommodate patient anatomy. Modern modular systems

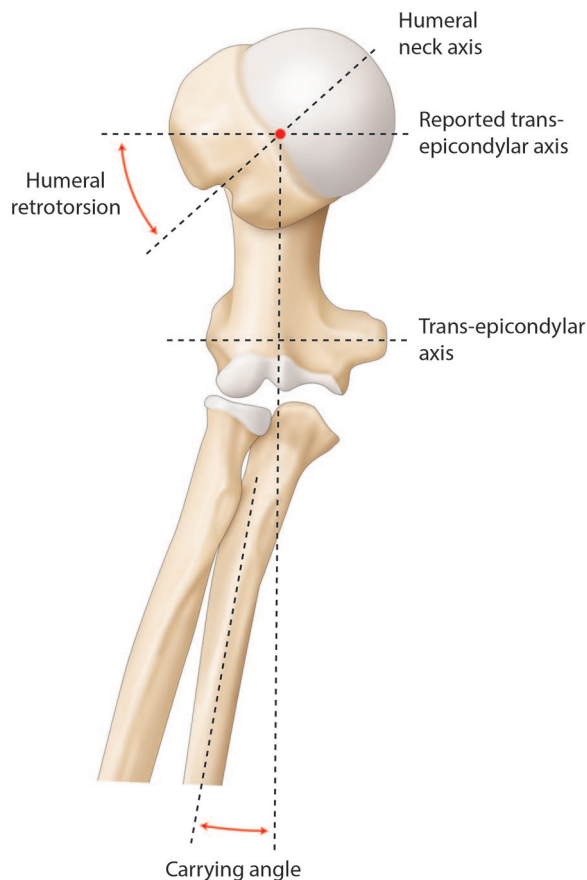


Fig. 5 Illustration of right humerus and proximal radius and cubitus. The axes used to characterize the humeral retrotorsion and the carrying angle are the humeral neck, the diaphyseal, the trans-epicondylar, and the forearm axis. The humeral retrotorsion is defined by the angle between the humeral neck axis and the trans-epicondylar axis. The carrying angle is determined by the angle between the diaphyseal axis and the forearm axis. A humeral osteotomy guide relative to the forearm has to take into account the carrying angle.

provide centred and eccentric humeral heads as well as multiple NSA options.

Humeral torsion

Humeral head torsion is important in ATSA as it directly affects joint COR and thereby influences mobility in external rotation and shoulder stability.^{27–29} A cadaveric study by Pearl and Volk reported a mean humeral retrotorsion of 29.8 degrees with a 95% confidence interval of 7 to 52 degrees (Fig. 5).³⁰ While they used the trochlear axis as reference, other reported values were based on the trans-epicondylar axis (which differs from 3 to 8 degrees). Furthermore, current systems use a jig aligned on the forearm as a reference, in this case, a 10 to 15 degree carrying angle must be added to the reported values (Fig. 5). When using a stem with lateral fins, another reliable landmark is to

place it 12 ± 4 mm behind the bicipital groove.³¹ It should, however, be emphasized that the groove rotates about 16 ± 7 degrees and appears therefore as an unsuitable landmark in fracture or posttraumatic cases.³² Lastly, Raniga et al reported that in Walch B type glenoids, humeral retrotorsion is significantly lower compared to non-arthritic shoulders (14 ± 9 degrees vs. 36 ± 12 degrees, $p < 0.001$), suggesting a potential correlation between humeral retrotorsion and glenoid retroversion.³³

Glenohumeral offset

Osteoarthritis results in loss of glenohumeral offset secondary to humeral and glenoid bone wear. While glenohumeral offset is subject to inter-person variability, a diminished glenohumeral offset implies altered deltoid and rotator cuff moment arms, as well as modified capsular tension (Fig. 2).^{10,14} This is thought to influence the postoperative range of motion by limiting active abduction as well as creating a tendency to inferiorly sublux the humeral head.^{28,34} Conversely, thick glenoid components create overstuffing (Fig. 1). Bodrogi et al recently described a reliable computerized tomography (CT)-based method to assess changes between pre- and post-arthroplasty glenohumeral offset measures.³⁵ In the absence of humeral head sphericity (particularly in the setting of osteoarthritis), their method relied on the centre of the humeral shaft (rather than the centre of the humeral head) as described by Jacobsen and Friedman's line to be independent of retroversion on the glenoid side.³⁶

Medullary canal

Finally, the intramedullary canal not only becomes tighter but also increasingly retroverted from proximal to distal.¹³ Fixation of the humeral component is widely varied. Diaphyseal press-fit stems induce proximal stress shielding. Cementation is reliable at time zero but difficult in revision. The goals of reduced stress shielding, easier stem revision, and preservation of vascularity have led to a progressive shift towards short metaphyseal stem or stemless fixation.²⁴ While a comparative cadaveric study revealed decreased micromotion and enhanced rotational stability in cemented stems,³⁷ optimal stem fixation, length, and filling ratio to avoid stress shielding,³⁸ subsidence,³⁹ and misalignment remains controversial.⁴⁰

Glenoid anatomy

Glenoid loosening remains the primary cause of ATSA failure.⁴¹ Similar to the humeral side, osteoarthritis appears to modify normal glenoid anatomy significantly. The glenoid seems relatively small and shallow compared to the humerus, with only 9 cm² of articular surface.⁴² The glenoid is pear-shaped with a superior to an inferior dimension of 39 mm an inferior glenoid width averaging

29 mm.¹⁴ There is a radii mismatch between the glenoid and humeral head, while the radius of curvature is greater in the anteroposterior than the superoinferior direction (41 vs. 32 mm).³ Biomechanically, perfect conformity leads to a more stable joint but increased stress on the glenoid. On the other hand, an increased mismatch in radii will lead to increased translation of the humerus onto the glenoid with rim loading of the glenoid component causing a 'rocking horse' effect.^{43,44} Based on current techniques, the best compromise appears to be a mismatch ranging between 4 and 8 mm.⁴⁵ However, it should be noted that these findings are based on a spherical humeral head. It has been proposed that conformed designs are better suited for elliptical heads.⁴⁶

Glenoid version and inclination

Reported three-dimensional CT-derived measures report mean normal glenoid retroversion of 6 ± 4 degrees and inclination of 7 ± 5 degrees. Retroversion has been correlated ($r = 0.7$, $P < 0.001$) to posterior humeral head subluxation ($59\% \pm 7\%$).⁴⁷ The contralateral shoulder may be a reliable model; like side to side differences are limited to 5 degrees in 95% of cases.⁴⁸ It is also important to assess the version in three dimensions, as in cases with > 10 degrees version, it is not solely direct posteriorly but also in superior, inferior, and anterior directions.⁴⁹ A further important indicator when performing ATSA is that the version of the inferior part of the glenoid shows substantially less variability compared to the upper part and should therefore be used as the preferred intraoperative landmark in order to achieve adequate implant positioning.⁵⁰

Concerning inclination, Moor et al proposed the critical shoulder angle (CSA) as a measure of scapular morphology with the benefit of combining measurements of glenoid inclination and lateral acromion coverage.⁵¹ They identified an angle inferior to 30 degrees as being associated with primary shoulder osteoarthritis. This finding is supported by subsequent biomechanical studies reporting increased joint reaction forces in case of a lower CSA.^{52,53} A CSA > 35 degrees is, on the other hand, related to an increased incidence of rotator cuff tears secondary to increased supraspinatus loading to compensate for increased joint instability as a consequence of increased glenohumeral joint shear forces.^{51,54,55} In the setting of ATSA, an increased CSA has been related to an increased incidence of glenoid radiolucencies.⁵⁵

Humeral head subluxation

The Walch classification, with subsequent modifications, is the most common means of assessing glenoid changes secondary to primary osteoarthritis.^{56,57} Walch classified glenoid deformity based on posterior glenoid retroversion and humeral head subluxation. In opposition to type A

glenoids (symmetrical bone loss), type B glenoids (asymmetrical bone loss) have been associated with progressive posterior glenoid bone loss over time.⁵⁸ This factor is important when evaluating posterior humeral head subluxation; in type B3 glenoids, the head might be centred in regard to the glenoid but be posteriorly translated in relation to the scapula. Iannotti et al, by using three-dimensional standardized measures, reported a continuum of measures among the different type B and C glenoids rather than defined categories (B1, B2, B3, and C) in regard to glenoid retroversion and humeral head subluxation.⁵⁹ Currently, it is still debated whether posterior humeral subluxation is the cause or consequence of increased retroversion.⁶⁰ Static posterior humeral head subluxation and posterior glenoid wear have both been associated with premature osteoarthritis in young men and related to higher complication rates after ATSA.^{61–64} Recently, Beeler et al identified a flat acromion roof as a potential risk factor for posterior humeral head subluxation and posterior glenoid wear.⁶⁵ This hypothesis was confirmed in a subsequent study by Meyer et al, reporting a median of 4 degrees more glenoid retroversion and a 5-degree less steep acromion in type B2 and C compared to type A and B1 glenoids ($P \leq 0.022$).⁶⁶

Instability

The rotator cuff and the horizontal force couple are critical to glenohumeral stability.¹ By respecting cuff insertion and restoring bony anatomy, force couples should be adequately restored. Soft tissue balancing, by the combination of the anterior subscapularis tendon and capsule release sometimes associated with a capsulorrhaphy of the redundant posterior capsule, is indicated to reach Matsen's criteria (40 degrees of external rotation, 60 degrees of internal rotation and a 50% posterior shift of the humeral head over the glenoid).⁶⁷ If bony correction is necessary, one should carefully re-evaluate adequate humeral implant size as COR has likely changed secondary to the additional bone removal. When facing a retroverted glenoid, posterior instability can be compensated for by anteriorly offsetting the humeral head component, leading to a significant anterior humeral displacement on muscle activation as well as an anterior shift of the centre of pressure ($p < 0.05$).^{68,69} A major downside of this technique, however, is increased tension on the subscapularis with potentially higher rates of subscapularis failures. Chronic irreparable subscapularis deficiency is a contraindication to ATSA as it tends to destabilize the joint secondary to an upward migration of the humeral head and eccentric contact pressure onto the glenoid.⁷⁰ While subscapularis preserving approaches have been described, most surgeons access the glenohumeral joint by subscapularis detachment with either a tenotomy, peel, or lesser tuberosity osteotomy. Effective subscapularis repair⁷¹ during surgery

is therefore mandatory; a review of biomechanical cadaveric studies suggests superior load to failure for the osteotomy at time zero but no difference at cyclic loading.^{72,73} While de Wilde suggested that a C-block lesser tuberosity osteotomy might prevent postoperative subscapularis fatty infiltration, a recent systematic review reported no statistical difference in clinical and radiological outcomes between tenotomy, peel and osteotomy.^{74–76} In case of postoperative rupture, a prompt secondary repair can be considered to prevent instability but has been associated with variable results.^{77,78} The addition of anterior latissimus dorsi transfer seems biomechanically superior to the pectoralis major transfer in ATSA due to an improved internal rotation moment arm and more similar line of pull relative to the subscapularis.⁷⁹

Glenoid bone loss

Correcting glenohumeral bone loss is an important step when implanting the glenoid component. Implanting the component in excessive retroversion will result in posterior translation of the humeral head and subsequent rim-loading known to cause early component loosening.^{80,81} According to a finite element model by Farron et al, 10 degrees of retroversion should be considered as the cut-off value.⁸² In their analysis, an implant with 20 degrees of retroversion resulted in a 326% increased stress within the cement mantle and a 706% increase of micromotion at the bone–cement interface. Recent work using statistical shape modelling allowed a computer reconstruction of the pre-morbid glenoid with a precision of about 1 mm and 2 degrees for version and inclination.^{83,84} Several techniques to correct retroversion were developed. If version is corrected alone by means of anterior glenoid reaming, it will lead to significant joint line medialization and central cortex perforation when correction exceeds 15 degrees.⁸⁵ Consequently, posterior augmented glenoid implants were developed to avoid the medialization of the joint line, with encouraging early results.⁸⁶ However, severe deformity has been associated with loosening of such components.⁸⁷

Proper implantation technique avoiding superior inclination or retroversion is thought to be crucial to avoid edge-loading causing micromotion and subsequent breakdown at the bone–implant interface, ultimately leading to aseptic loosening.^{82,88} For the same reason, an intact cuff is also mandatory to conserve physiologic joint kinematics and therefore limit polyethylene wear.⁸⁹ While most current ATSA heads are metallic, experimental studies suggest that a change to ceramic heads could reduce the polyethylene wear rate by up to 26.7%.⁹⁰ A wide range of onlay all-polyethylene glenoid shapes (pear-shaped versus elliptic) and sizes are currently available on the market, with no current consensus on optimal designs regarding back surface (flat versus curved), anchorage

(keel versus peg) or level of conformity.⁹¹ Further, a recent cadaveric study comparing inlay (implanted into the bone socket and therefore allowing for circumferential bone support) with onlay components revealed superior outcome regarding joint reaction forces and fatigue failure in favour of the inlay design.⁹² There is also renewed interest towards metal-back glenoids in response to the reported encouraging survival rates of modern designs.⁹³ While the theoretical benefit of more stable fixation and easy conversion to RSA seems appealing, long-term outcomes are awaited based on the long list of retrieved pre-existing metal-back designs.⁹⁴

Reverse shoulder arthroplasty

Historically, RSA was developed to address arthritis in cuff deficient shoulders as the loss of dynamic compression provided by the rotator cuff led to instability and early glenoid loosening, therefore resulting in unpredictable outcomes with large head hemiarthroplasty or ATSA.^{95,96} The reverse ball and socket ‘Grammont type’ RSA was introduced in 1985 and is based on the biomechanical principles of a medialized joint centre of rotation, distalized humerus, and a semi-constrained design with a constant joint COR.⁹⁷ Contrary to ATSA, in which the humeral head rotates in a spinning motion around itself as the COR lies inside the humeral head, the constant COR in RSA lies inside the glenosphere and leads to a hinged motion of the humerus, making it prone to impingement thereby limiting range of motion (ROM).⁹⁸

Modifications in muscle recruitment

The aforementioned modifications to physiologic shoulder anatomy lead to a 42% increased deltoid lever arm, as well as an increased recruitment of anterior deltoid muscle fibres to perform abduction.⁹⁹ The original design with a 155-degree non-anatomic stem further enhanced the deltoid lever arm by distalization of the humerus.¹⁰⁰ The anterior deltoid becomes consecutively an important contributor to flexion and abduction moment arms.¹⁰¹ In case of a deficient anterior deltoid (i.e. revision surgery with detached or paretic anterior deltoid)¹⁰² compensation for abduction relies on significantly enhanced force of the subscapularis (195%) and middle portion of the deltoid (26%).¹⁰³ There are, however, drawbacks to these anatomic modifications of physiologic moment arms. While the anterior and posterior deltoid as well as pectoralis major are recruited as additional flexors and abductors, the latissimus dorsi, teres major, and lower part of the pectoralis major have increased adductor and extensor moment arms, therefore directly limiting their participation in active internal and external rotation.^{104,105} As lever arms of the anterior and posterior cuff are already decreased secondary to humeral medialization, this adds

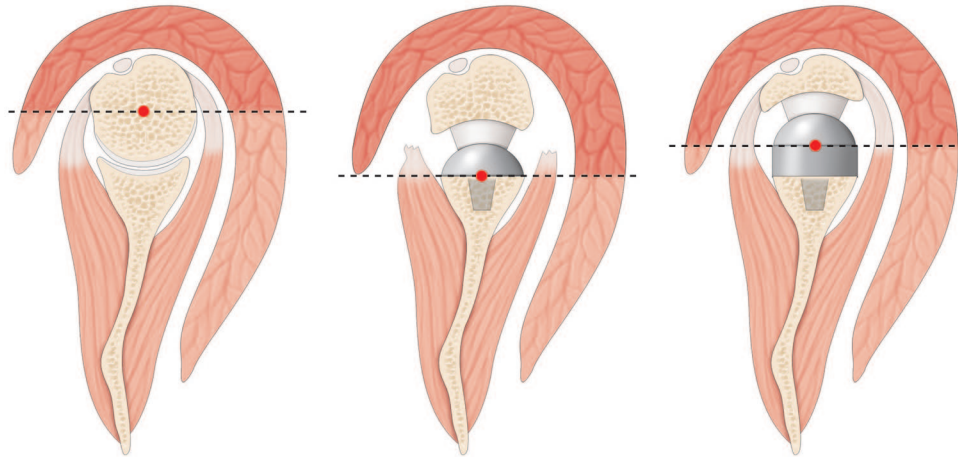


Fig. 6 (A) Native shoulder. The centre of rotation is in the humeral head, and the level of arm of deltoid does not allow consequent deltoid recruitment. (B) Reverse shoulder arthroplasty (RSA) with a medial glenoid/lateral humerus design in case of massive and irreparable rotator cuff lesion. Medialization of the centre of rotation and humeral lateralization allows important deltoid recruitment. (C) Lateral glenoid/medial humerus RSA. As in native shoulders, the bony lateralization of the centre of rotation decreases recruitment of the deltoid for rotation but allows for a retensioning of the rotator cuff.

to a further weakening of active internal and external rotation.^{106,107} This issue can either be addressed by the addition of a tendon transfer or by modifying the classic RSA design to a 'lateralized' one.¹⁰⁸ This modification will preserve rotational moment arms of the subscapularis and teres minor and therefore enhance active range of motion in the axial plane (Fig. 6).¹⁰⁹ Finally, while the postoperative range of motion takes place inside the prosthetic joint, scapulothoracic participation is significantly increased after RSA.¹¹⁰

Medialization of the joint centre of rotation (COR)

The biomechanical benefit of a medialized joint COR is to convert torque forces into compressive forces across the bone–glenosphere interface and therefore provide stability and enhanced component integration.¹¹¹ As the rotator cuff no longer provides its compressive forces, the fixed COR allows the deltoid to compensate and provide the needed compression to stabilize the joint.⁹⁹ While in ATSA joint reaction forces can reach up to 90% of body-weight at 90 degrees of abduction, RSA design reduces both compressive and shear stress and therefore joint reaction forces by up to 42%. This further allows active abduction with a 20% decreased deltoid activity in a cuff deficient shoulder.^{112–114}

There is, however, a major drawback of COR medialization in the form of impingement between the scapular neck and humeral prosthetic component defined as scapular notching.^{115,116} Several technical factors improve impingement-free range of motion. One option is placing the glenosphere (not the baseplate) below the inferior glenoid rim or using an inferior eccentric glenosphere.

De Wilde et al reported that a 5-mm overhang could improve impingement-free adduction by 39 degrees.^{117–119} Abduction is also positively correlated with acromio-humeral distance ($r = 0.93$; $p < 0.001$) which is increased with an eccentric glenosphere.¹²⁰ The ideal amount of overhang relative to the glenoid appears to be about 2.5 mm based on clinical evidence.¹²¹ Alternatively, glenosphere diameter can be increased, therefore upsizing the diameter from 38 to 46 mm was reported to not only increase range of motion by 39% but also stability by a 36% increase in jump distance.¹²² According to a computer simulation of impingement-free range of motion, the single most effective modification in prosthetic design is the change of humeral neck-shaft angle from the classic 155 degrees towards a more anatomic angle.^{123,124}

While joint COR needs to be medialized in regard to the native COR, slight lateralization of the glenosphere from the glenoid can further enhance compressive forces, which are thought to overcome the increased shear forces at the bone–component interface.¹¹¹ Basic science studies show several benefits of lateralization. In both sawbone¹²⁵ and computer models,^{123,126,127} lateralization improves ROM in all directions.¹²⁷ There is an ongoing debate regarding the impact of lateralization on the risk of acromial stress fractures. Finite element analysis has suggested a 17.2% increased acromial stress secondary to 10 mm lateralization.¹²⁸ Clinically, distalization has been implicated as more of a culprit than lateralization.¹²⁹ Glenosphere lateralization has, further, a linear correlation with baseplate micromotion¹³⁰ and therefore exposes patients to the risk of aseptic loosening.¹³¹ Giles et al tested the effect of glenoid and humeral lateralization on deltoid muscle load

in vitro using a simulator. They reported that 10 mm of humeral lateralization was the only parameter that actually decreased deltoid force in abduction ($65 \pm 8\%$), however, they warned that this benefit may not compensate for the negative effects induced by glenosphere lateralization.¹³² Lastly, Boileau et al proposed a bony increased-offset reverse shoulder arthroplasty to lateralize the glenosphere, however, maintaining COR at the prosthesis–bone interface and thereby minimizing torque stress.¹³³

Baseplate design

To allow bone ingrowth, baseplate micromotion must be inferior to 150 μm .¹³⁴ As baseplates are screwed down to the glenoid, research focused on the optimal configuration to enhance initial stability on polyurethane foam models. While increased screw length (> 17 mm inside the glenoid) or screw diameter (3.5 vs. 5.0 mm) was shown to additionally reduce micromotion by up to 30%, inclining screws by 30 degrees (compared to 0 degrees) was the most effective, as it led to a 50% reduction in micromotion.^{111,135} With a central post design, the most important screw in the baseplate is thought to be the inferior one, as tensile forces are the highest at the inferior border secondary to humeral loading. A locking screw should therefore be favoured in this particular location, as a 7% enhanced load to failure was reported compared to standard cortical screws.¹³⁶ Regarding the total number of screws, a cadaveric study comparing a two-peripheral-screw flat-backed baseplate construct (superior and inferior one) with a four-screw construct found no statistical difference regarding motion during cyclic loading.¹³⁷ Regarding baseplate design, the central screw does not seem superior to the post regarding load to failure compared to the central post.¹³⁸ Lastly, Gutiérrez et al investigated optimal baseplate position using a computer model. According to their work, which focused on uniform force distribution, a 15-degree inferior tilt is best suited for a concentric or lateral eccentric glenosphere, and for an inferior eccentric glenosphere a neutral inclination (0 degrees) is the preferred orientation.^{139,140} Superior tilt should always be avoided as stress at the bone interface increases. Boileau et al suggested that superior tilt is commonly underestimated during RSA planification.¹⁴¹ As the baseplate is implanted in the inferior part of the glenoid, they introduced the RSA angle, defined as the angle between the inferior part of the glenoid fossa and the perpendicular to the floor of the supraspinatus. Compared to the ATSA angle (β angle or global glenoid inclination angle), the RSA angle is 8 ± 4 degrees larger.

Stability

The stabilizing effect of the rotator cuff is inexistent in a cuff deficient shoulder, making it prone to instability.¹⁰⁰ In the physiologic state, the glenoid serves as a pillar for the humeral head. During shoulder range of motion,

combined physiologic glenohumeral and scapulohumeral motion keep this pillar beneath the humeral head. Altered muscle balance forces in cuff tear arthropathy shoulders disrupt this dynamic process and explain the eccentric wear pattern encountered in cuff tear arthropathy. The endpoint is reached when the humeral head migrates upward and creates an acetabularization of the acromion, allowing a neutralization of the dynamic instability.¹⁴²

Instability is one of the most cited complications after RSA.¹⁴³ A wide variety of actors potentially influence stability, including glenosphere (eccentricity, diameter, inclination), humeral socket depth, humeral implant version, as well as humeral lateralization and length, as well as remaining subscapularis.^{139,143–146} The arm position most prone to instability is 30 degrees of abduction with neutral or internal rotation.¹⁴⁶ Increasing glenosphere diameter from 38 to 42 mm was reported to augment stability by 32% by increasing joint load and deltoid force.^{146,147} Glenosphere positioning will impact stability as a 2-mm inferior offset enhances stability by 17%.^{119,143} Biomechanical data also suggest that superior tilt exposes patients to a higher risk of instability.^{117,148} Glenosphere lateralization is effective to prevent scapular impingement with the arm in adduction and to increase the force needed for anterior dislocation, the biomechanical benefit of a reduced deltoid force to abduct the arm is unfortunately lost (with lateralization of 15 mm).^{149,150} Comparison of humeral neck-shaft angle (135 vs. 155 degrees) revealed only a minor benefit with higher dislocation forces required in 135-degree stems at 30 degrees of abduction; this effect was, however, negligible compared to a 6–9 mm glenoid lateralization.¹⁴⁹ Avoiding excessive humeral retrotorsion (> 10 degrees) seems to have a higher impact on stability than glenosphere retroversion (> 20 degrees).¹⁵¹ Conformity in radii between the glenosphere and humeral socket present in RSA results in an enhanced joint-reaction force vector tolerance to up to 45 degrees (compared to 30 degrees in the setting of an ATSA).¹³⁰ Lastly, humeral socket depth defined in ratio to glenosphere diameter will increase stability at the potential cost of a reduced range of motion.^{139,144,152}

Distalization of the humerus

While distalization of the humerus is a central point in RSA with the primary goal of increasing the lever arm of the deltoid and improving functional outcomes, there are consequences to lengthening. Optimal lengthening is thought to be around 2 cm but is still debated.¹⁵³ While insufficient lengthening (particularly in the revision setting) has been shown to be a critical factor regarding joint instability,^{153,154} downsides of excessive lengthening include increasing the risk of a neurological lesion (neurapraxia) and over-tensioning resulting in a decreased range of motion as well as increased joint reaction forces.^{155,156} Furthermore, lengthening via an onlay humeral component

has been associated with an increased risk of acromial stress fracture compared to inlay components.¹²⁹ While there is no current consensus regarding the optimal way to increase soft tissue tension while avoiding complications,^{144,157} recent biomechanical data suggest that humeral lateralization could potentially be a solution to improve joint and muscle loading.^{132,158,159} However, one must keep in mind that humeral lateralization also leads to distalization. In addition to the aforementioned consequences, distalization also changes the force vectors of the remaining rotator cuff. The latter may be particularly important in the use of RSA for diagnoses other than rotator cuff arthropathy in which much of the rotator cuff is still functional, such as primary glenohumeral arthritis with posterior subluxation and a biconcave glenoid. Thus, there are not only trade-offs to distalization, but the ideal amount may also vary by diagnosis.

Conclusion

As the number of primary and revision shoulder arthroplasties is projected to progress by up to 322% by 2050, a thorough understanding of the biomechanical principle seems mandatory. The key concepts between these two procedures are yet very different. Reproducing anatomy is at the centre of ATSA philosophy. Therefore, a thorough understanding of premorbid anatomy is crucial to success, as inadequate restoration of the joint centre of rotation will predispose patients to secondary cuff failure and glenoid implant loosening. Further, posterior glenoid bone loss and humeral head subluxation (typically seen in Walch B2 and C glenoids) should be corrected to avoid premature glenoid component failure. While posterior augmented anatomic glenoid implants might solve this issue in the near future, a shift towards RSA in this particular setting can already be observed. With its semi-constraint design, RSA was initially developed to treat cuff tear arthropathy patients. Original indications further expanded towards primary OA with glenoid dysplasia, irreparable rotator cuff tears, three- and four-part fractures as well as revision of failed ATSA. The main complication with the original Grammont design is scapular notching, which might lead to secondary glenoid loosening. Inferior baseplate positioning and therefore inferior glenosphere overhang, bony or metallic baseplate lateralization as well as avoiding superior inclination, all minimize the risk of scapular impingement. Lower humeral neck-shaft angles can further reduce the risk of scapular notching and might enhance deltoid muscle recruitment and cuff tension, thereby potentially improving active external rotation. Current research on optimal RSA design focuses on improved impingement-free ROM. However, increased ROM should not be made at the cost of decreased stability or scapular fractures. One should always keep in mind

that the goal of every arthroplasty is to alleviate pain and restore the best possible function.

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ICMJE CONFLICT OF INTEREST STATEMENT

Dr. Lädermann reports that he is a paid consultant for Arthrex, Wright and Medacta and receives royalties from Stryker. He is the founder of BeeMed.

Dr. Collin reports that he is a paid consultant for Wright, Smith and Nephew and ConMed and receives royalties from Wright, Stortz and Advanced Medical Applications.

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