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Biomechanics of reverse total shoulder arthroplasty

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Reverse total shoulder arthroplasty is an effective procedure for treatment of glenohumeral joint disease among patients with severe rotator cuff deficiency. Improvements in prosthetic design are the result of an evolved understanding of both shoulder and joint replacement biomechanics. Although modern generations of the reverse shoulder prosthesis vary in specific design details, they continue to adhere to Grammont's core principles demonstrated by his original Delta III prosthesis. This review article discusses the biomechanics of reverse total shoulder arthroplasty with a focus on elements of implant design and surgical technique that may affect stability, postoperative complications, and functional outcomes.
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Keywords: Reverse total shoulder arthroplasty; biomechanics; implant design; surgical technique; scapular notching; instability; functional outcomes

History

Since its conception, reverse total shoulder arthroplasty (RTSA) has gained significant popularity because of its ability to treat glenohumeral joint disease in patients with severe rotator cuff deficiency. Considerable improvements in prosthetic design are the result of an evolved understanding of both shoulder and joint replacement biomechanics. Early versions of RTSA were designed as a targeted solution to the shortcomings of the Neer total shoulder replacement among patients with absent or damaged periarticular structures. As a result, the original RTSA designed by Neer (the Mark I) was an inherently stable, highly constrained prosthesis replicating the biomechanical design of other weight-bearing joints (Fig. 1).[10,29,53] The Mark I, along with numerous other reverse prosthesis designs of the 1970s, resulted in implant breakage and glenoid component loosening because of an underlying design flaw.[27,29] Lateralization of the shoulder's center of rotation along with the highly constrained design of the prosthesis resulted in unacceptable forces at the bone-implant interface.

Paul Grammont's original reverse prosthesis introduced in 1985 revolutionized shoulder arthroplasty with its novel design. This system focused on 4 key principles necessary to provide a stable construct while allowing the deltoid to compensate for an absent rotator cuff: (1) the center of rotation must be fixed, distalized and medialized to the level of the glenoid surface; (2) the prosthesis must be inherently stable; (3) the lever arm of the deltoid must be effective from the start of movement; and (4) the glenosphere must be large

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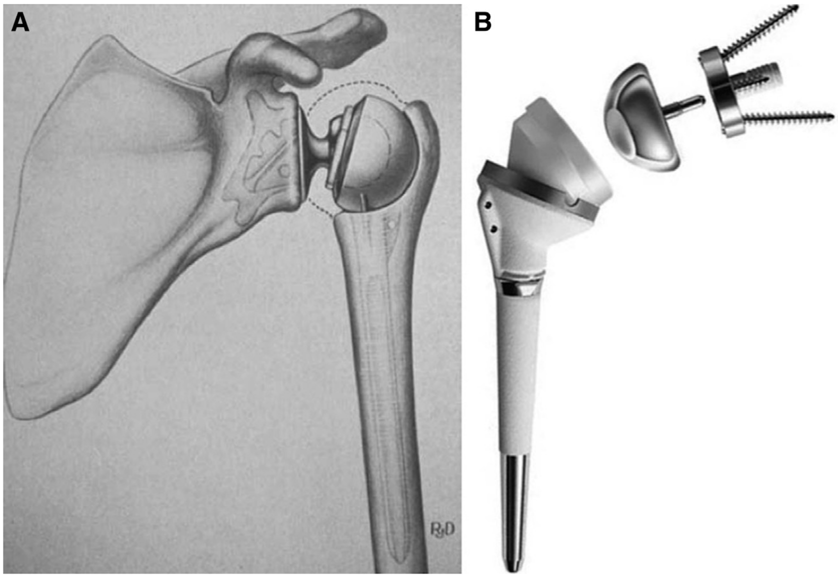

Figure 1 (**A**) Mark I reverse prosthesis. (Illustration by Robert J. Demarest. With permission.) (**B**) The Grammont Delta III prosthesis has 5 parts: the glenoid baseplate (metaglenoid), the glenosphere, the polyethylene cup, the humeral neck, and the humeral stem. (Reproduced from Boileau P, Watkinson DJ, Hatzidakis AM, Balg F. Grammont reverse prosthesis: design, rationale, and biomechanics. J Shoulder Elbow Surg 2005;14(Suppl):147S-161S. © 2005 Journal of Shoulder and Elbow Surgery Board of Trustees. With permission.)

and the humeral cup small to create a semiconstrained articulation.[7,33] Although the glenohumeral joint's center of rotation was medialized in the initial design, it remained lateral to the native glenoid surface. Grammont's second-generation prosthesis, the Delta III, corrected for this limitation by changing the glenosphere from two thirds of a sphere to a hemisphere.[10] The baseplate included a central press-fit peg and two divergent 3.5-mm screws specifically angled to resist the shear forces at the bone-implant interface. The humeral component featured a small cup, covering less than half of the glenosphere, oriented almost horizontally with a nonanatomic neck-shaft angle of 155° (Fig. 1). Although modern generations of the reverse shoulder prosthesis vary in specific design details, they continue to adhere to Grammont's core principles.

The following sections address advancements in our understanding of RTSA biomechanics in relation to Grammont's 4 original principles.

Center of rotation

The anatomy of a native glenohumeral joint results in a variable center of rotation throughout the arc of motion. Movement of the humeral head on the glenoid occurs successively around 2 main centers of rotation, both of which exist in a location close to the center of the humeral head.[28] RTSA components create a fixed center of rotation secondary to increased constraint and matched radii of curvature. Movements of the shoulder produce a resultant force vector, composed of both compressive and shear forces, that varies throughout the range of motion but that consistently passes through the joint's fixed center of rotation (Fig. 2). Because all joint reactive forces are transmitted through a new fixed center of rotation, the design of a reverse prosthesis must maximize compressive forces while minimizing shear forces at the bone-implant interface. The effect of lateralizing the joint's center of rotation is an increase in the distance between this point and the bone-implant interface (Fig. 2). This distance is equal to the lever arm through which destabilizing forces act on the glenosphere, resulting in increased torque. By creating a glenoid component shaped as a hemisphere, Grammont reduced the system's center of rotation directly to the bone-implant interface. This medialized the joint's center of rotation and stabilized the bone-implant interface by converting the shear forces that challenge glenoid fixation into compressive forces.[60]

However, medialization of the shoulder's center of rotation has been associated with scapular notching, reduced range of motion, and loss of shoulder contour.[9,10,45] Scapular notching is thought to result from mechanical impingement of the superomedial humeral prosthesis against the inferior scapular neck during adduction. Rates of scapular notching are significant, occurring in up to two thirds of patients within 2 years of reverse shoulder arthroplasty.[63,79,82] Numerous technical strategies have been proposed to avoid scapular notching, including eccentric (inferior) glenosphere position, implanting of the glenoid component in a position with inferior inclination, increased lateral offset, and decreased inclination (neck-shaft angle) of the humeral component.[30,69]

Eccentric (inferior) positioning

Cranial-caudal positioning of the glenosphere is appealing in particular because it can be altered without distancing

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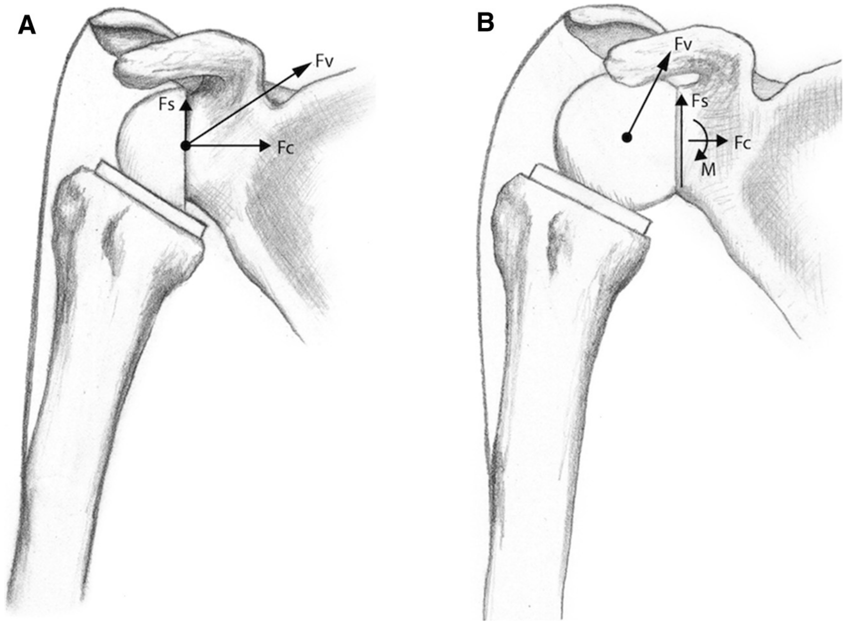

Figure 2 (**A**) The resultant force vector (*Fv*) is composed of both compressive (*Fc*) and shear (*Fs*) forces, all of which act through the joint's fixed center of rotation located at the bone-implant interface on the surface of the glenoid. (**B**) Lateralization of the joint's center of rotation results in a reduction in compressive forces, a longer lever arm for destabilizing shear forces, and a new moment (M) at the bone-implant interface. Lateralization also provides for a larger impingement-free range of motion. (Illustrations by Julianne Ho.)

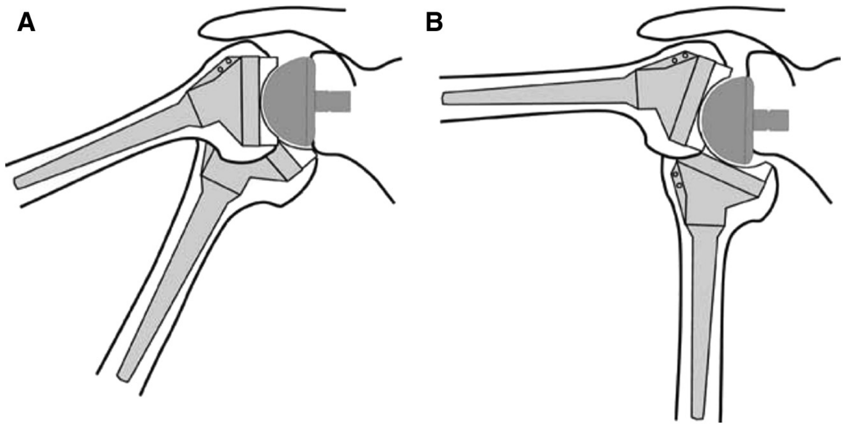

Figure 3 (**A**) With a centered glenosphere, range of motion in the coronal plane is limited relative to a glenosphere with eccentric positioning. Adduction is limited by direct contact of the polyethylene cup on the inferior glenoid rim; abduction is limited by subacromial or subcoracoid impingement. (**B**) Eccentric positioning affords increased range of motion in both adduction and abduction. (Reproduced from Nyffeler RW, Werner CM, Gerber C. Biomechanical relevance of glenoid component positioning in the reverse Delta III total shoulder prosthesis. J Shoulder Elbow Surg 2005;14:524-8. With permission).

the joint's center of rotation from the glenoid surface. Inferior overhang of the glenosphere provides a space between the glenosphere and the scapular neck that may decrease notching (Fig. 3). It also creates additional clearance between the greater tuberosity and coracoacromial arch, allowing greater impingement-free range of motion during abduction. Eccentric positioning of the glenosphere improves the adduction deficit by allowing approximately 11° to 39° of additional adduction.[14,21,41,65,69] In vitro studies have demonstrated a direct correlation between inferior eccentric positioning and progressively larger impingement-free range of motion during both abduction and adduction.[14,41,65,69]

Data regarding the efficacy of eccentric glenosphere positioning at reducing rates of scapular notching generally favor inferior positioning. Mizuno et al, in a prospective study of 57 RTSAs with a mean follow-up of 30.4 months, found no significant difference in the rate of inferior scapular notching or postoperative Constant scores between patients implanted with either a concentric or eccentric glenosphere.[66] However, among patients who developed scapular notching, those who received a concentric glenosphere had a worse severity of notching. A separate study found that both craniocaudal positioning and inclination of the glenosphere were significantly correlated with scapular notching, with craniocaudal positioning exerting more of an effect by a factor of approximately 8.[78] De Biase et al, in a prospective comparison of concentric vs eccentric glenospheres, found a convincing difference among the rates of scapular notching between the 2 groups, with radiographic evidence of scapular notching in 42% of the concentric group vs 0% of the eccentric group.[18] Other retrospective studies have also shown a significant correlation between glenosphere overhang and reduced rates of scapular notching.[24]

Inferior inclination

Despite promising results from biomechanical studies, clinical studies have not validated the advantage of glenosphere component inferior inclination. In a cadaveric study by Nyffeler et al, glenoid components implanted with an inferior inclination of 15° had both increased abduction and adduction impingement-free range of motion compared with a component placed in neutral position.[69] However, inferior (eccentric) positioning of the glenosphere on the glenoid was even more effective at eliminating adduction deficit. In a prospective randomized controlled trial of 42 patients, Edwards et al compared cohorts with glenoid components implanted in either a neutral position or with a 10° inferior inclination; all components were placed with 3 mm of inferior translation.[22] Their results showed no benefit of inferior inclination with regard to notch ratings or clinical outcomes. Similar results were described in a retrospective study of 71 shoulders.[58]

Lateral offset

Lateralization relative to this new medialized center of rotation provides for a larger impingement-free range of motion but creates an additional destabilizing torque at the bone-implant interface. Grammont's Delta III glenosphere was designed with 19 mm of lateral offset. Harman et al demonstrated in vitro that glenospheres with increased lateral offsets of 23 and 27 mm generate 44% and 69% more torque, respectively, at the baseplate interface.[44] Progressively increasing offset demonstrates a linear correlation with baseplate motion.[44,48,52,85] Glenoid implant complications are common, occurring in 0% to 60% of cases, and are believed to be secondary to excessive motion at the baseplate interface.[10,11,31,56,79] These complications include glenosphere unscrewing, baseplate loosening, and migration of the glenosphere.

Lateralization may improve shoulder range of motion after RTSA. Medialization of the shoulder's center of rotation slackens the rotator cuff muscles and decreases their respective moment arms by as much as 36%.[47] Lateralization has been shown to offset this effect by lengthening the origin to insertion distance of the subscapularis and teres minor.[35,83] Furthermore, limited postoperative shoulder rotation after RTSA may be, in part, related to the limited excursion of the cup around the medialized glenosphere as well as mechanical impingement of the tuberosities against the coracoid process in internal rotation and the scapular spine in external rotation. Gutierrez et al, in an in vitro study analyzing multiple factors of component positioning, found that lateralization had the greatest effect on range of motion by improving both abduction and adduction deficits.[41] However, lateralization may be less important if the glenosphere is placed in an eccentric (inferior) position. De Wilde et al demonstrated that with 1 mm or more of eccentric positioning, the incremental benefit of lateralization on maximum adduction is eliminated.[21] Boileau et al proposed the bony increased-offset reversed shoulder arthroplasty (BIO-RSA) designed to harness the potential advantages of component lateralization while limiting the known disadvantages of distancing the rotational center from the bone-implant interface.[8] In a prospective study of 42 patients having undergone BIO-RSA implantation with a mean follow-up of 28 months, the authors reported a 98% autograft incorporation rate, inferior scapular notching in 19% of patients, and sufficient internal rotation to reach above the sacrum in 86% of patients.

Neck-shaft angle and humeral component version

Because of the inherent design of the reverse total shoulder as a nonanatomic prosthesis, optimal version and neck-shaft angle of the humeral component differ from a normal shoulder and are not yet defined. Compared with the normal humerus' mean neck-shaft angle of 135° to 140°, Grammont's humeral component is designed with a nonanatomic humeral neck inclination of 155°. Variations in the humeral component's neck-shaft angle affect clinical range of motion. With increasing neck-shaft angle, the polyethylene cup is positioned in a more horizontal orientation, resulting in progressive mechanical conflict between the cup and inferior scapular neck[21] (Fig. 4). Gutierrez et al, in a Sawbones biomechanical study, evaluated the effect of 4 independent factors on abduction range of motion and impingement.[41] Neck-shaft angle had the largest effect on inferior scapular impingement and adduction deficit. A retrospective review of 65 patients after RTSA compared 2 cohorts with varying neck-shaft angles and glenoid offsets. The group with a smaller neck-shaft angle (143° vs 155°) and larger glenosphere offset (2.5 mm vs 0 mm) had a significantly lower incidence of notching (16.2% vs 60.7%).

Increasing humeral component retroversion increases the amount of external rotation and decreases the amount of internal rotation before impingement during in vitro testing.[5] However, it does not appear to affect the muscle forces required for abduction.[37,46] Stephenson et al, in a cadaveric study, showed that humeral retroversion between 20° and 40° most closely restores a functional range of motion.[80] Placing the humeral component in neutral version or anteversion results in greater than physiologic internal rotation while increasing the risk of posterior notching. As

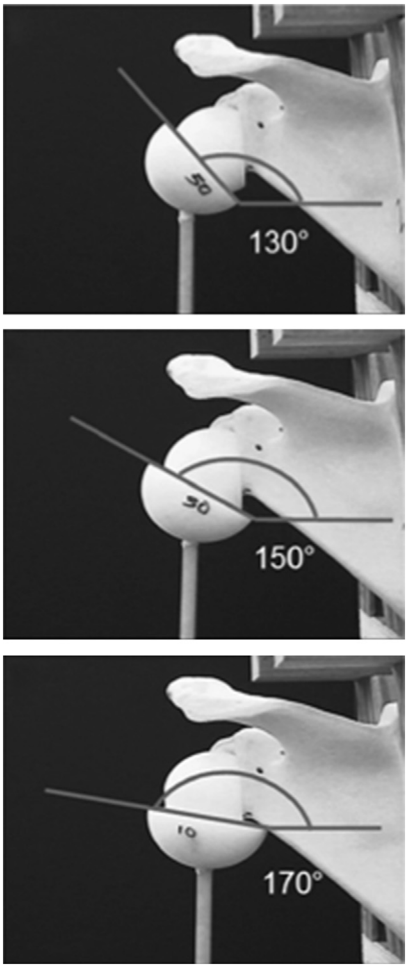

Figure 4 Varying humeral neck-shaft angles demonstrate progressive inferior impingement and resulting adduction deficit. (Reproduced from Gutierrez S, Levy JC, Frankle MA, Cuff D, Keller TS, Pupello DR, et al. Evaluation of abduction range of motion and avoidance of inferior scapular impingement in a reverse shoulder model. J Shoulder Elbow Surg 2008;17:608-15. With permission.)

the shoulder is abducted in the scapular plane, mechanical limitations on internal and external rotation diminish. At 60° of abduction, the humeral bearing is able to rotate unimpeded around the glenosphere; and at 90° of abduction, supraphysiologic internal rotation and external rotation are possible.[37] Berhouet et al, in a cadaveric study, demonstrated that humeral component retroversion may also affect adduction range of motion.[5] However, the authors caution that rotational range of motion should be the primary consideration in deciding humeral component version.

Inherent stability

A quantitative measure of glenohumeral joint stability is the balance stability angle, defined as the maximal angle that the net joint reaction force can form with the concavity

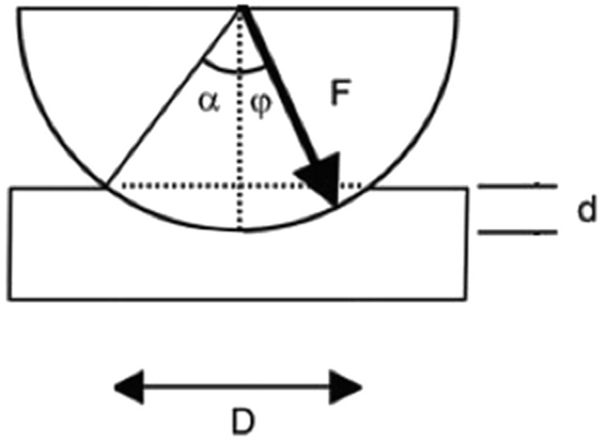

Figure 5 Balance stability angle is defined as the maximal angle that the net joint reaction force can form with the concavity before dislocation occurs. A prosthetic shoulder is stable as long as the net joint reaction force (*F*, *arrow*) points inside the concave component ($\varphi < \alpha$). Increasing cup depth (*d*) results in larger α values. For reverse total shoulder arthroplasty components, α is equal to approximately 45°.

before dislocation occurs[64] (Fig. 5). In conventional total shoulder arthroplasty, the net humeral joint-reaction force vector must be directed within 30° of the glenoid centerline to avoid dislocation.[71] This value is a result of the component's inherent design. Unequal radii of curvature between the humeral and glenoid components as well as the system's limited constraint confer impingement-free range of motion at the cost of intrinsic stability. Comparatively, Grammont's reverse prosthesis, designed with equal radii of curvature, is able to tolerate a joint-reaction force vector of up to 45°.[64] Increased constraint secondary to the deeper and more conforming concavity of the humeral articular surface prevents glenohumeral translation while providing sufficient stability for functional range of motion. This high degree of intrinsic stability frees the reverse total shoulder prosthesis from dependence on active stabilization by concentric compression and provides a stable fulcrum for the remaining musculature.

A second quantitative measure of joint stability is the stability ratio, defined as the maximum allowable subluxation force/joint compression force. The normal glenohumeral joint has a stability ratio of approximately 0.5, whereas total shoulder arthroplasty has a ratio of approximately 1.0.[43,54] In contrast, RTSA has a stability ratio >2.0. With the glenohumeral joint in 90° of abduction, the reverse total shoulder is approximately 4 to 5 times more stable than a normal joint and 2 to 3 times more stable than a conventional total shoulder prosthesis.[26] Despite this, the semiconstrained design is susceptible to anterior instability in the fully adducted position, a complication reported in 1.5% to 31% of patients.[17,32,36,57,64,79,84] The stability ratio increases approximately 60% with the glenohumeral joint at 90° of abduction and decreases with the arm in a fully adducted position.[16] Relative instability in the fully adducted position is likely due to inferior impingement, which, through a levering effect, can generate distractive forces. Increasing the humeral cup's depth to radius ratio exponentially improves the inherent stability of the reverse prosthesis.[40] In contrast, varying glenosphere size has no notable effect on joint stability.[16,40]

In a study evaluating the hierarchy of stability factors in the reverse shoulder, Gutierrez et al found that the net compressive force acting on the glenohumeral articulation is the most significant element of stability.[40] In a rotator cuff–deficient reverse shoulder, joint compressive forces are largely the product of soft tissue, primarily deltoid, tensioning. This may be accomplished by multiple intraoperative techniques, including lowering the humerus relative to the native glenoid, lengthening the humerus by inserting a thicker polyethylene humeral component, and retaining as much proximal humerus as possible. Results are conflicting as to whether subscapularis repair augments glenohumeral joint stability by providing additional anterior restraint.[15,23]

Stability also depends on glenoid component positioning. Glenosphere retroversion >20° has been shown to reduce anterior stability while the arm is in the resting position.[26] However, optimizing fixation through screw length and avoiding undesirable tensile forces on the metaglene-baseplate interface should probably take priority over glenosphere version. In addition, placing the glenosphere in a position of inferior offset has been shown to increase stability by approximately 17%.[16] Humeral component version has little effect on stability. Although a noncadaveric shoulder simulator demonstrated that version of the humeral component had a significant effect on stability, a conflicting study using cadaveric shoulders, which provide an additional element of soft tissue constraint, showed that humeral component version did not significantly alter dislocation forces.[26,46] Similarly, with the arm in a position of neutral rotation, humeral component neck-shaft angle did not affect anterior instability in a cadaveric model.[70] In the clinical setting, stability is a complex interworking of multiple variables including both active and passive constraints and the position of the shoulder at the time of dislocation.

Deltoid function

Grammont fittingly chose to name his reverse shoulder prosthesis the Delta, emphasizing the importance of the deltoid muscle.[33] It was developed to optimize functional outcome by making better use of the patient's remaining musculature. The system is designed both to re-tension and to reposition the deltoid in relation to the joint's center of rotation. A medialized center of rotation increases the deltoid's moment arm by 20% to 42% and recruits additional fibers of the anterior and posterior deltoid to serve as abductors.[7,60,81] Compared with native anatomy, the deltoid's abduction moment arm in a reverse shoulder has much greater fluctuation peaking at 90° of abduction, the position at which the weight of the arm creates its largest adducting moment[60] (Fig. 6). The enhanced torque-producing capacity of the deltoid, particularly in early abduction, may compensate for impairment in the initiation of torque resulting from supraspinatus deficiency. A distalized center of rotation restores tension to a shortened deltoid in the setting of cuff tear arthropathy, effectively improving the muscle's efficacy by approximately 30%.[33,46,81] In addition, distalization of the center of rotation is necessary to provide space for the proximal humerus, allowing less restricted range of motion.

RTSA results in significant increases in the abductor moment arms of the anterior and middle deltoid subregions, with maximum abduction moment arms of all 3 subregions occurring in the coronal plane.[3,76] In contrast to the anatomy of the native shoulder, in which the anterior deltoid subregion is mainly a flexor, the middle deltoid subregion an abductor, and the posterior deltoid subregion an extensor, all 3 deltoid subregions demonstrate primarily abductor function after RTSA. RTSA lowers the muscle forces required to generate the torque necessary to abduct and to flex the shoulder, allowing the deltoid's lever arm to be effective from the start of movement. Deltoid muscle forces required to achieve 90° of abduction are approximately 50% of body weight in the native shoulder. This value is reduced to 36.8% in the reverse shoulder.[2] Similarly, RTSA significantly reduces the forces in the middle and anterior deltoid during flexion.

The recruitment of additional deltoid muscle fibers to initiate flexion and abduction comes at the expense of axial rotation. Each subregion's direction of axial rotation changes after RTSA. The inferior-most portion of the anterior deltoid loses its internal rotation and adduction capacity and becomes a flexor-abductor, the posterior deltoid loses its external rotation and adductor moment and functions as an extensor-abductor, and the middle deltoid acts as an even stronger abductor.[3] Ackland et al[1] demonstrated in a cadaveric model that after reverse shoulder arthroplasty, the superior pectoralis major and anterior deltoid demonstrate larger flexion moment arms during early flexion than they did in a native shoulder, indicating prominent flexion-initiation capacity. Clinical outcomes after RTSA suggest that the deltoid's axial rotation moment arms are significantly affected by changes in the joint's center of rotation. Cadaveric studies specifically designed to measure the change in axial rotation moment arms after RTSA found that all subregions of the deltoid had smaller axial moment arms, with the most significant decrease in the posterior subregion of the deltoid.[1] Therefore, in the reconstructed shoulder, the rotator cuff is the only appreciable contributor to external rotation, which may explain why patients with cuff tears or fatty infiltration may have reduced external rotation after RTSA.[77] This has led some

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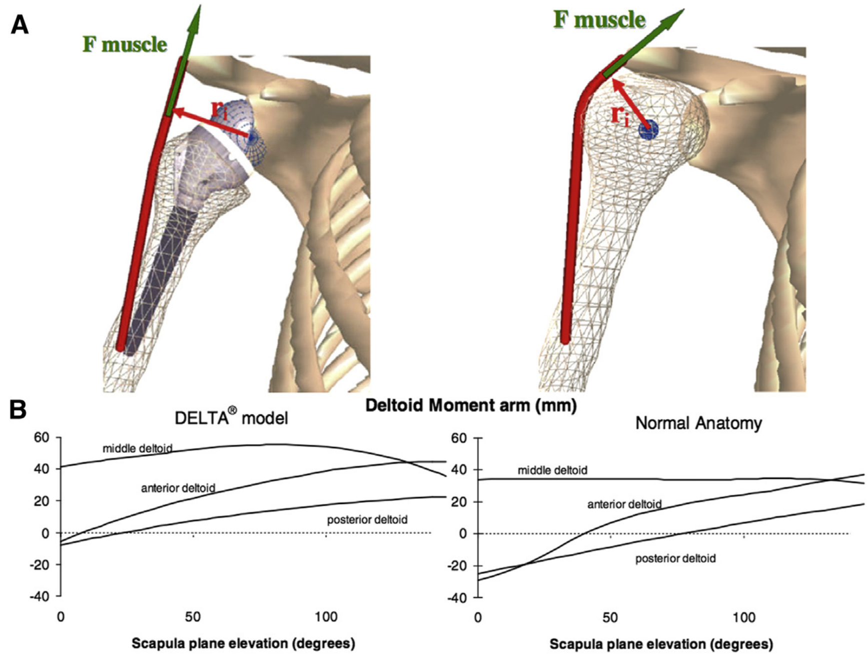

Figure 6 (**A**) The consequence of a medialized center of rotation is a lengthened deltoid moment arm (r_i) compared with normal anatomy. (**B**) Compared with a native shoulder's middle deltoid moment arm, which demonstrates a nearly constant value throughout abduction, the reverse shoulder's moment arm has much greater fluctuation peaking at approximately 90° of abduction, where the weight of the arm creates its largest adducting moment. (Reproduced from Kontaxis A, Johnson GR. The biomechanics of reverse anatomy shoulder replacement—a modelling study. Clin Biomech (Bristol, Avon) 2009;24:254-60. With permission).

clinicians to perform a latissimus dorsi transfer during primary RTSA, a technique that has proved effective at restoring external rotation in biomechanical studies.[25] However, further research is needed regarding the usefulness of the latissimus dorsi as a consistent external rotator.

Although good functional outcomes after RTSA are dependent on the function of the deltoid, prior shoulder surgery may compromise the muscle's integrity.[6,50] Schwartz et al, using a cadaveric model, demonstrated that the anterior deltoid is crucial for balanced abduction and flexion in the reverse shoulder.[76] When this subregion of the deltoid is deficient, the shoulder relies more heavily on compensatory contributions from both the subscapularis, if it is viable, and the middle deltoid.[38]

The consequences of a repositioned glenohumeral joint center of rotation extend beyond the deltoid, affecting the rotator cuff and shoulder girdle muscles. Despite most patients' improvement in flexion and abduction, active internal rotation and external rotation often remain unchanged or reduced, negatively affecting the patient's ability to perform activities of daily living.[10,34,86] This is the result of decreased rotational moment arms of the subscapularis and teres minor after RTSA.[47] The muscles are further compromised by decreased origin to insertion distance, resulting in muscle detensioning. Attempts have been made to counteract these unfavorable changes. A lateralized prosthesis has been shown to maintain tension within the subscapularis and teres minor while also preserving rotational moment arms.[35] These results may explain clinical outcome studies' results showing superior rotational capability after lateralized RTSA compared with non-lateralized RTSA.[8,67,83]

After RTSA, the most prominent glenohumeral joint force during both abduction and flexion changes from compression by the rotator cuff to superior shear forces generated by the deltoid.[2] In a normal shoulder, the rotator cuff muscles and latissimus dorsi contribute inferior shear as well as joint compression, opposing the superior shear generated by the deltoid.[3] In the absence of the rotator cuff's compensatory inferior shear force, the latissimus dorsi must act alone, resulting in significantly more superior shear force.[2] In the anterior-posterior plane, the pectoralis major generates the largest component of anterior shear, counteracting the significant posterior shear forces of the middle and posterior deltoid. These findings highlight the importance of preserving the shoulder girdle muscles as well as postoperative strengthening to promote joint stability and to reduce premature prosthesis wear, subluxation, and dislocation.

Functional limitations and range of motion after RTSA are primarily secondary to a lack of generated muscle force and not due to mechanical limitations.[4] Consequently, alterations in scapulohumeral rhythm occur as a compensatory mechanism. Multiple studies have shown that after RTSA, scapulothoracic motion contributes a proportionately larger amount of total arm elevation, especially at lower angles of abduction.[19,59,62] During resistance exercises, which more closely mimic activities of daily living, the scapulothoracic contribution to arm elevation is even greater.

Semiconstrained design

In contrast to all previous reverse ball-and-socket prostheses, the Grammont glenoid component is a hemisphere with a large diameter of 36 or 42 mm, creating a greater potential arc of motion.[14] When it is centered on the glenoid, use of the 42-mm glenosphere, compared with the 36-mm glenosphere, has been shown to increase average abduction amplitude by approximately 5° and to provide an additional 22° of adduction before inferior impingement occurs.[5] Similar findings have been demonstrated with the use of computer modeling.[42] However, increasing glenosphere size does not result in improved rotational range of motion.[55] Use of a large-diameter glenosphere can be difficult in practice, in part because good surgical exposure is required to ensure proper positioning.[20] The humeral component is reduced in size, covering less than half of the glenosphere. This semiconstrained design allows significantly improved range of motion.

Glenohumeral joint contact forces have been shown to be less than those of a normal shoulder.[61] In the normal shoulder, maximum joint forces occur at 90° of elevation and then steadily decrease with further elevation. In a reverse shoulder, maximum joint forces occur at approximately 60° to 70° and remain fairly constant with further elevation.[61,74] This is consistent with in vitro cyclical loading of RTSA constructs demonstrating maximum micromotion at 60° of elevation.[61] During cyclical loading, micromotion of the baseplate remains below 62 to 113 µm, which is less than the 150-µm threshold demonstrated to be necessary for bone ingrowth into total hip arthroplasty femoral components.[12,44,48,52,61,73] However, the presence of scapular notching may increase baseplate micromotion above 150 µm.[75] Stability can be enhanced with an inset baseplate that increases glenosphere contact with glenoid bone. Average micromotion at the baseplate-bone interface has been shown to decrease by approximately 37% when the glenosphere is in contact with glenoid bone, with a direct correlation between the size of the glenosphere and the resulting increase in stability.[68]

Initial baseplate screw fixation is the most important factor leading to long-term fixation through osseous integration.[39,48,72] Scapular anatomy has been closely studied in an effort to determine optimal screw placement. The scapula is often conceptualized as three bony columns attached to the glenoid. Regions away from these columns provide little structural stability because they are composed of bone thinner than the diameter of a screw. The three columns are the (1) base of the coracoid, (2) scapular spine, and (3) scapular pillar, which correspond to placement of the superior, anterior, and inferior screws, respectively. Cadaveric studies have defined both optimal baseplate rotation and individual screw trajectory to capture the maximum amount of scapular bone.[49,72] Scapular bone quality has a significant effect on the stability of initial fixation, an important consideration in patients with osteoporotic bone.[13,48] A reduction in bone stiffness of 50% results in an increase in baseplate micromotion of approximately 70%.[48]

Screw type and location affect baseplate stability and resistance to micromotion. Locking screws create a more stable construct and reduce baseplate micromotion in vitro compared with similar diameter nonlocking screws.[13,44] An in vitro study testing a 4-screw glenoid implant's load to failure showed that each screw position within the baseplate had a varying effect on initial fixation.[13] If the inferior locking screw, which is the screw nearest the point of load application and therefore most important, is absent, then the load to failure is reduced by 35%. In the absence of an inferior *non*-locking screw, load to failure is reduced by 28%.[13] James et al implanted flat-backed glenoid baseplates into human cadaveric scapulae with either 2 screws, placed in the inferior and superior holes, or 4 screws to determine differences in stability. No statistical difference in average peak central displacements existed during cyclical loading in both inferior-to-superior and anterior-to-posterior directions.[51] This suggests that although anterior and posterior screws may be considered for use, they should not be relied on for baseplate stability. Hopkins et al, using finite element analysis, concluded that optimal screw inclination is more effective at reducing micromotion than using larger diameter screws.[48]

Conclusion

Despite changes in modern implant design, RTSA biomechanics remain based on Grammont's core principles. Glenoid component positioning, most importantly eccentric (inferior) placement, can affect rates of scapular notching. Initial baseplate screw fixation is the most important factor leading to long-term fixation through osseous integration. Reduced humeral component neck-shaft angle minimizes inferior scapular impingement and notching. Repositioning of the shoulder's center of rotation recruits additional deltoid muscle fibers to initiate flexion and abduction at the expense of rotator cuff mechanics and axial rotation. It is therefore important to preserve the remaining shoulder girdle musculature, which functions to counteract increased shear forces generated by the deltoid. Joint stability is dependent primarily on soft tissue tensioning but is also affected by glenoid component positioning. Future RTSA implant design and surgical technique will use these principles as well as our improved understanding

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of biomechanics to optimize postoperative function while minimizing complications such as scapular notching, instability, and component failure.

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