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Total shoulder arthroplasty: Downward inclination of the glenoid component to balance supraspinatus deficiency

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Hypothesis: Supraspinatus deficiency associated with total shoulder arthroplasty (TSA) provokes eccentric loading and may induce loosening of the glenoid component. A downward inclination of the glenoid component has been proposed to balance supraspinatus deficiency.
Methods: This hypothesis was assessed by a numeric musculoskeletal model of the glenohumeral joint during active abduction. Three cases were compared: TSA with normal muscular function, TSA with supraspinatus deficiency, and TSA with supraspinatus deficiency and downward inclination of the glenoid.
Results: Supraspinatus deficiency increased humeral migration and eccentric loading. A downward inclination of the glenoid partly balanced the loss of stability, but this potential advantage was counterbalanced by an important stress increase within the glenoid cement. The additional subchondral bone reaming required to incline the glenoid component indeed reduced the bone support, increasing cement deformation and stress.
Conclusion: Glenoid inclination should not be obtained at the expense of subchondral bone support.
Level of evidence: Basic science study.

Keywords: Glenoid inclination; subchondral bone support; total shoulder arthroplasty; supraspinatus tendon deficiency

Total shoulder arthroplasty (TSA) with anatomic prostheses is an accepted treatment for degenerative pathologies of the glenohumeral joint with functional rotator cuff muscles. Degenerative changes in the supraspinatus tendon are also sometimes associated with osteoarthritis, leading to partial or complete deficiency of the supraspinatus tendon. A deficient supraspinatus muscle induces an increased upward migration of the humeral head during abduction, which induces more eccentric loading of the glenoid implant (rocking horse phenomenon), and precludes the long-term survival of the glenoid component.[10,13,19]

Because the supraspinatus deficiency induces an upward migration of the humerus, several studies have supported the idea that a downward inclination of the glenoid component could help restore the loss of joint stability. A cadaveric study showed humeral upward migration increased after rotator cuff deficiency but reduced after a downward inclination of the glenoid (closed wedge osteotomy).[8] This cadaveric measurement of the humeral translation was later completed by a biomechanical analysis of the resultant muscle force and the joint reaction force, which confirmed theoretically the stabilizing effect of the downward inclination of the glenoid.[9] Conversely, the

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upward inclination of the glenoid has been associated with an increase of the upward migration humeral head in a cadaveric study[25] and in a numeric study.[5] In addition, an experimental study that tested cyclic loading on glenoid components cemented on artificial bone reported an improved glenoid fixation with a downward inclination of the glenoid.[14]

According to these studies, the downward inclination of the glenoid component should be advantageous for glenohumeral joint stability when muscles of the rotator cuff are deficient. It has indeed been shown that the upward migration of the humerus can be balanced by the glenoid inclination, but this potential advantage has not yet been confirmed for the stability of the articular contact pattern.

Two objectives were pursued in the present study. First, we aimed to confirm that a downward inclination of the glenoid component balances the upward migration of humerus when the supraspinatus muscle is deficient. Second, we analyzed the effect of a downward inclination of the glenoid component on the contact pattern on the glenoid surface and on the stress distribution within the cement mantel surrounding the glenoid component.

Materials and methods

A 3-dimensional musculoskeletal model of the glenohumeral joint based on computed tomography (CT) images and dissection data of a normal shoulder was used for this analysis (Figure 1).[22] The segmentation of the CT images was performed with Amira (Mercury Computer Systems Inc, Chelmsford, MA) to isolate the bony structures. A solid model of the scapula and humerus was then constructed using Geomagic Studio (Geomagic Inc, Research Triangle Park, NC). These 2 bones were reimported into Amira to assess the accuracy of the final geometric reconstruction compared with the original CT images. Six muscles were considered in the musculoskeletal model: the middle deltoid, the anterior deltoid, the posterior deltoid, the supraspinatus, the subscapularis, and the infraspinatus combined with the teres minor. The geometry of the muscles consisted of rubber-like shapes. The dimensions of the muscles were estimated from general anatomic observations. The locations of the attachment of the muscles were obtained during a dissection of the same shoulder with a magnetic stylus.[2]

An active movement of abduction was simulated in the plane of the scapula, from 0° to 150° of abduction. The muscles actively achieved the motion of the arm, but also the stability of the glenohumeral joint. The activation of the muscles was controlled by a feedback algorithm, assuming constant muscle force ratios that were roughly estimated from electromyography (EMG) and physiologic cross-section area as initially proposed by Poppen and Walker.[15] The details of this algorithm are described in 2 previous articles and can be summarized as follows.[22,23] The elevation movement is controlled through a shortening of the middle deltoid. The force induced within the middle deltoid is then considered as the reference force to constrain the force within the other muscles, according to the predefined muscle ratios. This feedback process was implemented in a user subroutine within Abaqus (Dassault Systèmes, Simulia, Vélizy-Villacoublay, France), which solves the mechanical equilibrium, the contact stability, and the muscle ratio. This method ensures that the mechanical equilibrium and the muscle ratio constrain are satisfied simultaneously during the entire elevation movement.

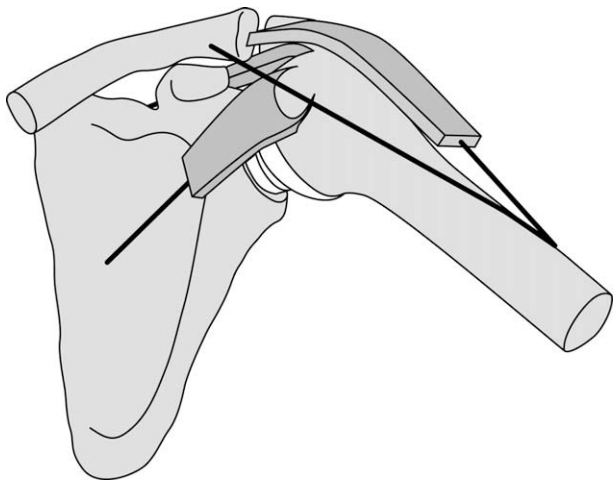

Figure 1 Schematic illustration shows the numeric musculoskeletal model used in this study.

The stability of glenohumeral joint was also achieved by the muscles. The contact forces produced by the muscles wrapping around the humeral head stabilized the joint, together with the reaction contact forces of the articular surfaces. This stabilizing mechanism, which mimics the natural stabilization of the joint, allowed for the natural translation of the humeral head relative to the glenoid. The muscle and joint forces calculated by the algorithm balanced the arm weight, which was set to 37.5 N (5% of the body weight) and an additional weight of 10 N was placed in the hand. During the abduction of the arm in the scapular plane, the rotation of the scapula was constrained with a constant scapulohumeral rhythm of 2:1.

The Aequalis anatomic prosthesis (Tornier Inc, Edina, MN) was inserted in the shoulder model according to the manufacturer's recommendations. The glenoid component was keeled, convex, and made of polyethylene. Its size was chosen to best fit the glenoid bone. The articular surfaces of each component were spherical, with radius of curvature of 30 mm for the glenoid and 24 mm for the humeral head. The glenoid and humeral components were positioned according to the manufacturer's recommendation by a senior orthopedic surgeon. A uniform cement mantel of 0.5 mm around the glenoid implant was considered. The virtual reaming, cementing, and positioning of the implants were performed with the standard modeling tools of the computer-aided design software SolidWorks (Dassault Systèmes, SolidWorks, Concord, MA).

The elasticity modulus E of the glenoid bone was related to bone density,[4] which was derived from CT Hounsfield data.[11,17] Its Poisson ratio ν was 0.3. The polyethylene glenoid implant was also elastic ($E = 500$ MPa, $\nu = 0.4$), as was the cement ($E = 2000$ MPa, $\nu = 0.3$), but the humeral metallic component was assumed to be rigid.

Abaqus was used for all numeric simulations. The glenoid component and surrounding cement was meshed with linear hexahedral elements, whereas the scapula was meshed with

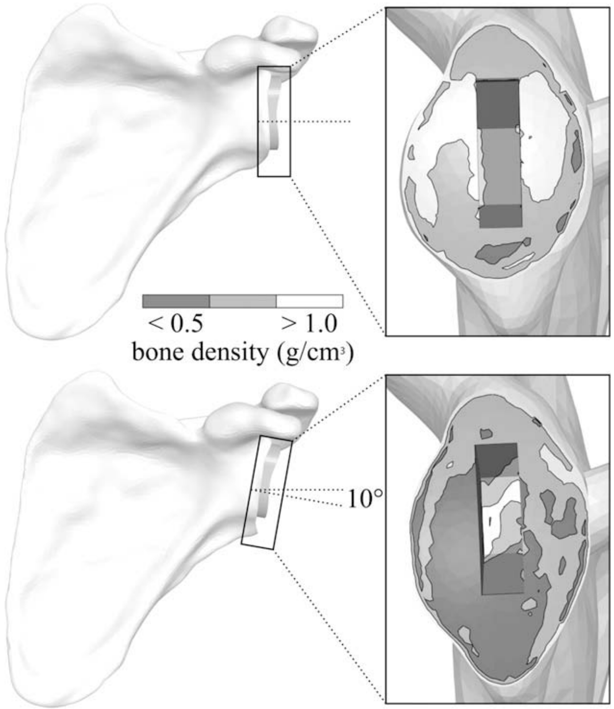

Figure 2 Positioning of the glenoid component with **(top)** a standard inclination and with **(bottom)** 10° of downward inclination. **(Left)** The view in the plane of the scapula is completed by **(rightl)** a zoom view facing the reamed glenoid bone. With a standard inclination (case A and B), the glenoid component was positioned to best fit the articular surface and preserve the subchondral bone. The downward inclination of the glenoid component (case C) required an additional reaming of the inferior glenoid.

quadratic tetrahedral elements. The bone–cement and cement–implant interfaces were fully bounded. A standard hard-contact algorithm was used to solve the contact between the articular surfaces and the contact between muscles and bones.

Three cases were compared: a reference case with normal functional muscles and a standard glenoid inclination (case A), a deficient supraspinatus with a standard glenoid inclination (case B), and a deficient supraspinatus with a downward inclination of the glenoid (case C). For cases A and B, the inclination of the glenoid component corresponded to the natural upward inclination of the glenoid bone, which was approximately 5° relative to the medial border of the scapula. For cases B and C, the supraspinatus was fully deactivated. For case C, the glenoid was inclined downward by 10° by an additional reaming of the inferior side of the glenoid bone (Figure 2).

The following quantities were calculated for each case: the inferior–superior translation of the humerus, the contact pressure on the glenoid surface, and the tensile stress (maximum principal invariant) within the glenoid cement. The translation of the humerus was defined as the position of the humeral head center point relative to an axis parallel to the glenoid bone and also parallel to the scapular plane. This was referred to as inferior–superior translation, although it was always relative to this axis, which was fixed to the scapula that rotated during abduction. Zero translation corresponded to a perfect centering of the humeral head within the glenoid fossa. The same axis and zero reference were used in case C.

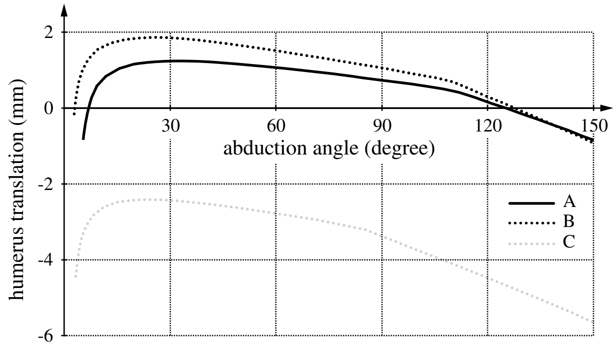

Figure 3 Inferior–superior humerus translation during abduction. The humeral translation corresponds to the position of the humeral head center relative to an axis parallel to the normal glenoid surface and fixed to the scapula. Zero translation corresponds to a perfect centering of the humeral head in the glenoid component with the standard inclination. The same reference was used to describe the humerus translation when the glenoid was inclined. Compared with the standard situation (case A, *black line*), the supraspinatus deficiency (case B, *black dotted line*) slightly increased the upward translation of the humeral head, but the downward inclination of the glenoid (case C, *gray dotted line*) displaced the humeral head inferiorly by more than 4 mm relative to the scapula.

The contact pressure pattern on the glenoid component was also calculated during the entire abduction movement but was presented only for some typical positions. The stress distribution within the glenoid cement was analyzed every 30° of abduction, but only the situation at 60° of abduction is represented here. The complex distribution of the cement stress was represented by a volume fraction histogram.

Results

An upward translation of the humeral head was demonstrated in all cases during the first 30° of abduction, followed by a downward translation thereafter. According to the axis fixed to the scapula, the highest position of the humeral head was 1.7 mm above the ideal centering in case A, reached 2 mm in case B, but was about 4 mm below in case C (Figure 3).

The pattern of contact pressure on the glenoid surface was similar for each case (Figure 4). During the abduction movement, the contact pattern was initially located in the inferior side of the glenoid, but rapidly moved to the superior–posterior side during the first 30° of abduction. From 30° to 150° of abduction, the contact pattern moved back to the inferior side and was centered at approximately 120° of abduction. Overall, the deficiency of the supraspinatus produced a slightly higher contact pressure and a more eccentric location of the contact pattern. The average contact pressure reached 13.0 MPa in case A and

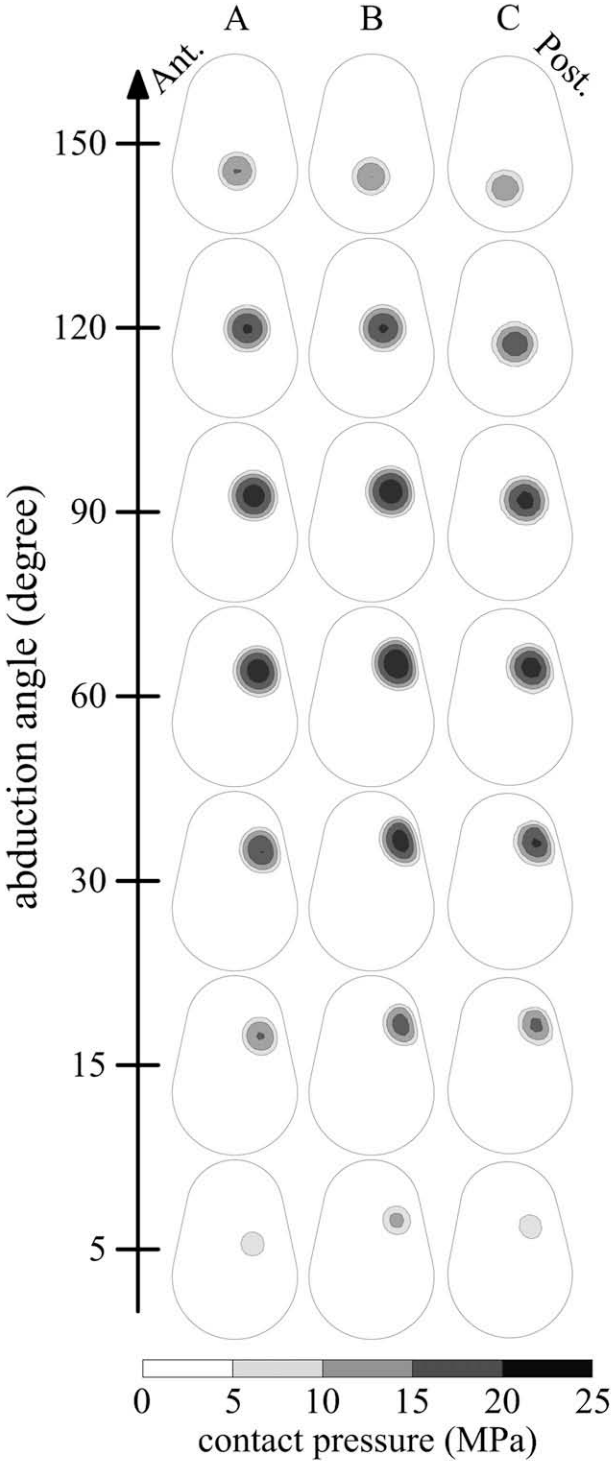

Figure 4 Contact pressure on the glenoid surface during abduction, for the reference (case A, *left column*), when the supraspinatus was deficient (case B, *middle column*), and when the supraspinatus deficiency was balanced by a downward inclination of the glenoid component (case C, *right column*).

13.1 MPa in case B. The center of the contact area was approximately 2 mm more eccentric relative to the center of the glenoid component in case B than in case A. This adverse effect of the supraspinatus deficiency was partly balanced by the downward inclination of the glenoid, which reduced the maximum average contact pressure to 12.8 MPa and recentered the contact pattern by about 1 mm.

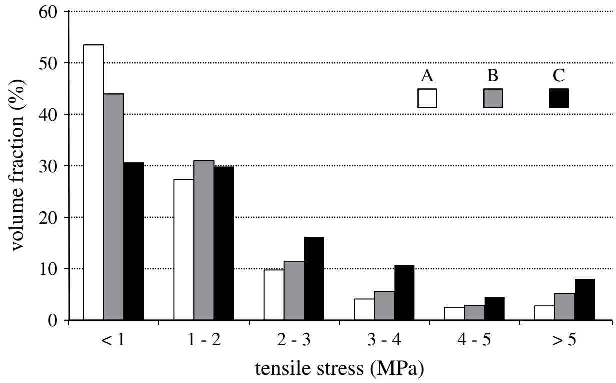

Figure 5 Volumetric distribution of stress within the cement mantel at 60° of abduction (maximal stress). Each bar represents the volume fraction (percentage of the total cement volume) associated with a specific stress range. Compared with the standard situation (case A, *white bar*), the volume of cement sustaining a stress above 1 MPa increased when the supraspinatus was deficiency (case B, *gray bar*), but this volume increased even more when the glenoid was inclined downwards (case C, *black bar*).

Within the cement, the tensile stress was maximal at 60° of abduction (Figure 5). It reached 8.7 MPa in case A and increased to 10.2 MPa in case B and to 13.0 MPa in case C. The maximal stress value increased, as did the volume of cement sustaining higher stress. The relative volume of cement bearing stress above 1 MPa corresponded to 47% of the cement volume in case A, to 56% in case B, and up to 69% in case C. In the same way, the cement volume with stress above 5 MPa was 3% in case A, 5% in case B, and 8% in case C. Regarding the cement stress, the adverse effect of supraspinatus deficiency was not balanced but was worse after glenoid inclination.

Discussion

A deficiency of the supraspinatus muscle when associated with anatomic TSA increases the upward migration of the humeral head. This lack of the stabilizing function of the supraspinatus muscle induces eccentric loading on the glenoid surface, which can increase the risk of glenoid loosening and limit the long-term success of the arthroplasty. A downward inclination of the glenoid component has been proposed to balance this deleterious effect,[20] but the advantage of a downward inclination of the glenoid surface for TSA associated to supraspinatus deficiency is not clearly assessed, particularly its effect on the stress within the cement surrounding the glenoid component.

The present numeric musculoskeletal model predicted a higher upward migration of the humeral head when the supraspinatus is deficient. It also predicted that the upward migration of the humerus is reduced when the glenoid component is oriented downwards. The contact stress pattern on the glenoid surface was also more important and eccentric when the supraspinatus was deficient, but almost back to normal after a glenoid inclination. The kinematic advantage of the glenoid inclination was, however, counterbalanced by an increase of the cement stress. The supraspinatus deficiency increased the cement stress, but it further increased after glenoid inclination.

The deficiency of the supraspinatus muscle produced a resultant muscular force that was more upward oriented because the supraspinatus muscle is approximately always oriented perpendicular to the glenoid surface. This upward orientation of the muscle resultant force increased the upward migration of the humeral head during the abduction. The supraspinatus deficiency also reduced the stabilizing role of the rotator cuff muscles, which required a higher force of the remaining muscles to stabilize the joint and thus a higher reaction force and a higher contact pressure. This effect has already been observed in a previous study.[22] The downward inclination of the glenoid component obviously recentered the contact pattern because it realigned the contact surface more perpendicularly to the altered muscle resultant force. More importantly, the glenoid inclination displaced inferiorly the center of the humeral head by more than 4 mm. The glenoid inclination also increased the muscle moment arm of the deltoid, also reducing the required muscle force, the resulting joint force, and the contact pressure. The joint force was maximal at approximately 90° of abduction, when the arm weight moment force is maximal.[22,23] However, the contact pressure was maximal at approximately 60° of abduction, because the contact pattern was less centered than at 90° of abduction.

Although the downward inclination of the glenoid component partly balanced the supraspinatus deficiency regarding joint stability, this potential advantage was counterbalanced by an important increase of the cement stress. The additional cement stress increase after the glenoid inclination was not directly related to the glenoid contact pressure, which was lower and more centered. The cement stress increased because of a loss of underlying bone support. The downward inclination of the glenoid component indeed required an additional resection of the inferior glenoid bone, which removed a significant volume of hard subchondral bone (Figure 1). The glenoid component and the surrounding cement mantel were thus lying on a softer bone. This lack of bone support of course induced higher deformation and stress within the cement.

The prediction of the glenohumeral kinematics was consistent with previous studies. The calculated natural translation of the humerus was indeed very similar to cadaveric and in vivo measurements.[6,8,13,16] The predicted effect of the supraspinatus deficiency and the glenoid inclination also corresponded to previous cadaveric measurements.[10] In particular, this cadaveric study also reported that the translation of the humerus was inferior to a normal shoulder when the glenoid was inclined downwards.[10] The predicted movement of the contact pattern was also consistent with previous theoretic estimation of glenohumeral force direction.[21,22,24] This movement of the contact pattern was observed in a cadaveric model and recently confirmed by an in vivo study.[12,18]

The effect of glenoid inclination on glenoid and cement stress has already been estimated by the finite element method.[7] The advantage of the present model is to account for the motor and stabilizing function of the muscles within the same model. The glenohumeral contact pattern obviously depends on the abduction angle, but also on the supraspinatus efficiency and the glenoid inclination. To analyze this dependency, it was essential to reproduce the natural translation of the humerus, which is the uniqueness of this model. In addition, it was also crucial to account for the inhomogeneous elasticity of glenoid bone to observe the stress increase after glenoid inclination.

Although the inhomogeneous bone elasticity was estimated from CT data of a normal scapula, it is clear that it may vary from one person to another, particularly for an osteoarthritic glenoid. We verified, however, that the predicted elasticity corresponded with experimental measurements.[1,11] The hypothesis of constant muscle force ratios during abduction could be a limitation of the model, but it seems to be rather reasonable according to EMG studies, particularly for abduction in the scapular plane. We do not know, however, exactly how these ratios would be altered when the supraspinatus is fully deficient. Contrary to what was assumed here, the remaining rotator cuff muscles could balance the supraspinatus deficiency in a nonproportional way through complex proprioceptive mechanisms. However, this hypothesis is used in most cadaveric models and seems reasonable because it is consistent with clinical observations.[3] The model also assumes a constant rotation of the scapula during elevation, which is most often accepted, but again might be affected with partial deficiency or the rotator cuff muscle.

This numeric study confirmed the deleterious effect of the supraspinatus deficiency on glenoid implant survival after TSA. The downward inclination of the glenoid restored the glenohumeral kinematics but significantly increased the cement stress. This phenomenon is due to the resection of the subchondral bone at the inferior part of the glenoid. Accordingly, our main clinical recommendation is that the downward glenoid inclination should not be achieved at the expense of subchondral bone reaming.

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