Influence of glenohumeral conformity on glenoid stresses after total shoulder arthroplasty

Alexandre Terrier, PhD,[a] Philippe Büchler, PhD,[a] and Alain Farron, MD,[b] *Lausanne, Switzerland*

Glenohumeral conformity has been reported to be one of the most critical implant-related features that may affect the occurrence of glenoid loosening. This study evaluated the mechanical effects of this parameter with a 3-dimensional finite element model of a prosthetic shoulder, which included the scapula, the humerus, and the rotator cuff muscles. Aequalis humeral and glenoid components were implanted numerically according to manufacturer's recommendations for 2 different orientations of the glenoid component (0° and 15° of retroversion). Different values of glenohumeral conformity (1–15 mm of radial mismatch) were tested by a progressive flattening of the glenoid surface. Free and countered rotation movements were simulated. Glenohumeral contact pressure, cement stress, shear stress, and micromotions at the bone-cement interface were calculated. At 0° of retroversion, conformity had only a slight effect, whereas at 15° of retroversion, all quantities increased by more than 200% and exceeded critical values above 10 mm of mismatch. (J Shoulder Elbow Surg 2006;15:515-520.)

Although glenohumeral arthroplasty has proved to be an effective procedure, glenoid loosening is a frequent complication after prosthetic replacement of the shoulder.[35,41] Among the possible causes, glenohumeral conformity is one of the implant-related features that may affect the occurrence of glenoid loosening.[10,31]

Glenohumeral conformity is usually defined as the difference between the radii of curvature of the glenoid and the humeral head surfaces. It may be related to 2 mechanical aspects of the joint: the glenohumeral contact surface and the glenohumeral obligate translations. Basically, conforming designs present a greater contact area and, therefore, a smaller contact pressure,[39] reducing the stress within implant, cement, and bone, as well as at their interfaces, and finally reducing the risk of wear and fatigue of the polyethylene and cement, as well as the reliability of the bone-cement interface. In parallel, through their natural geometric constraint, conforming designs are assumed to improve joint stability.[39] On theother hand, conforming implants reduce the natural level of obligate translations between the articular surfaces.[9,12,16-18,28] These translations are constrained by eccentric forces, which may create excessive rim stress[15,31] and may lead to implant loosening.[5] Therefore, because glenohumeral conformity is related to opposite mechanisms, an ideal value may be hypothesized. Finally, it seems obvious that the stress pattern at the glenohumeral interface influences the longevity of the joint replacement with respect to stability, loosening of the glenoid component, and wear of the components.

From cadaveric studies, it was found that a radial mismatch of 4 mm best reproduced the glenohumeral translation.[13,16] Collins *et al*[5] recommended 3 to 5 mm of mismatch, whereas Walch *et al*,[39] in a retrospective multicenter clinical study, recommended 6 to 10 mm. Friedman[7] emphasized the risk of polyethylene fracture with radial mismatch exceeding 10 mm. However, despite several clinical,[11,39] experimental,[10,13,31] and numerical studies,[21,33] the mechanical effects of glenohumeral conformity are not yet completely understood,[6,16] and recommendations for an ideal mismatch are still uncertain.[39]

Therefore, the aim of this study was to evaluate the influence of glenohumeral conformity on glenoid stress by use of a finite element model of a prosthetic shoulder. In addition, because retroversion of the glenoid component is often reported,[38] this parameter was included in this study. For that reason, a rotation movement was chosen for this analysis, because it was more appropriate to reveal critical joint contacts caused by the coupled effect of conformity and retroversion.

From the [a]Division of Orthopaedic Research, Swiss Federal Institute of Technology, and [b]Hôpital Orthopédique de la Suisse Romande, University of Lausanne

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Reprint requests: Alexandre Terrier, PhD, Bldg AA-B, Station 15, Orthopedic Research Center, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland (E-mail:alexandre.terrier@epfl.ch).

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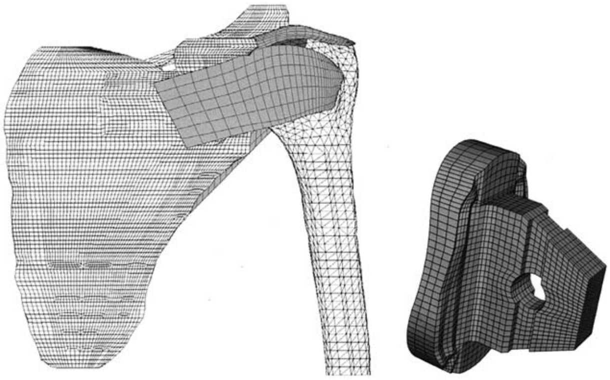

Figure 1 Finite element mesh of prosthetic shoulder and detail view of glenoid component.

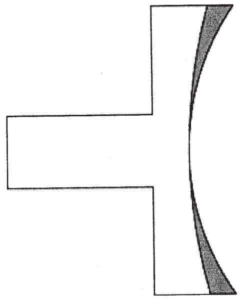

Figure 2 The variation in glenohumeral conformity was obtained by a progressive flattening of the spherical glenoid surface (*gray zone* in this horizontal view), maintaining its central point on a fixed position.

MATERIALS AND METHODS

A fresh-frozen cadaveric shoulder without any evidence of pathology was scanned every 1 mm, from the acromion to the humeral midshaft. Thereafter, careful dissection was performed to measure (Fastrak stylus, Polhemus Inc., www.polhemus.com) the exact insertion zones of the major rotator cuff muscles: infraspinatus, supraspinatus, and subscapularis.[2,3] The 3-dimensional geometry of the scapula and humerus was obtained from computed tomography segmentation, whereas the muscles were reconstructed from the measured insertions[2,3] and general anatomic considerations. Humeral and glenoid components (Aequalis, Tornier, Montbonnot, France) were implanted numerically into the virtual shoulder in 2 different glenoid orientations: 0° and 15° of retroversion. The glenoid component was an all-polyethylene, keeled, and flat-back design (Figure 1). It was surrounded by a uniform cement layer of 0.5 mm (recommended by the manufacturer). The material property of the glenoid, cement, and scapula was linear elastic.[3] The elastic modulus of the scapula was related to bone density,[34] which was derived from computed tomography. The muscles were characterized by hyperelastic law, based on an exponential strain energy potential.[26] The humerus and humeral component were rigid. The implant-cement interface was perfectly bonded, whereas the Coulomb friction law governed the bone-cement interface. The friction coefficient (μm, 0.6) corresponded to a cement–compact bone interface.[29,40] The scapula was fixed at the insertion points of the trapezius and rhomboid muscles and at some points of its anterior side, corresponding to contact with the thorax. The movements of the humerus were restricted by fixing the elbow and avoiding abduction/adduction and flexion/extension. Rotation was simulated by the direct action of the muscles, starting from a position of neutral rotation and abduction of the arm, when the humeral component faced the glenoid component. In a first step, the humerus was fixed, and all muscles were pretensioned with a I = N force. Then, the humerus was released, and the glenohumeral contact was achieved. Finally, a displacement of the scapular extremity of the subscapularis was imposed to generate 60° of internal rotation; in the same way, a displacement of the infraspinatus extremity generated external rotation. In addition, a countered movement was obtained by attaching an axial spring to the humerus, in the diaphyseal direction. This spring passively induced an increasing torque on the humerus as rotation occurred and corresponded to about 10 N of traction in the hand (the forearm being perpendicular to the arm) at 60° of rotation.

Glenohumeral conformity variations were obtained by a progressive flattening of the glenoid surface to reproduce 7 values of radial mismatch: 1, 3.5, 6, 8.5, 10, 12, and 15 mm (Figure 2). For each of these glenoid components, free and countered rotations were simulated, with and without retroversion. Different mechanical variables were calculated: the glenohumeral contact pressure, the cement stress, the shear stress, and relative micromotions at the bone-cement interface. Finite element analyses and postprocessing were achieved with the Abaqus software suite (Abaqus Inc, http://www.abaqus.com.

RESULTS

During the full range of motion, the results followed the same trend in internal rotation as in external rotation. However, the effect was maximal at 60° of internal rotation. Therefore, the calculated quantities were only presented at this extreme position. Spatial distributions (Figures 3 and 4) and maximal values (Figure 5) were considered.

Glenohumeral contact pressure

Glenohumeral contact pressure increased by about 300% as mismatch increased from 1 to 15 mm, independent of the retroversion angle or the countered force. The contact pressure was amplified by 10% to 20% when retroversion was added and increased drastically from 12 mm of mismatch when the countered force and retroversion were combined (black curve, top right graph of Figure 5). The contact position remained symmetrically centered on the glenoid surface in the free/no-retroversion case, but it moved posteriorly with the countered force or with retroversion (Figure 3). When the countered force and retroversion were combined, the contact point reached the posterior rim of the glenoid surface.

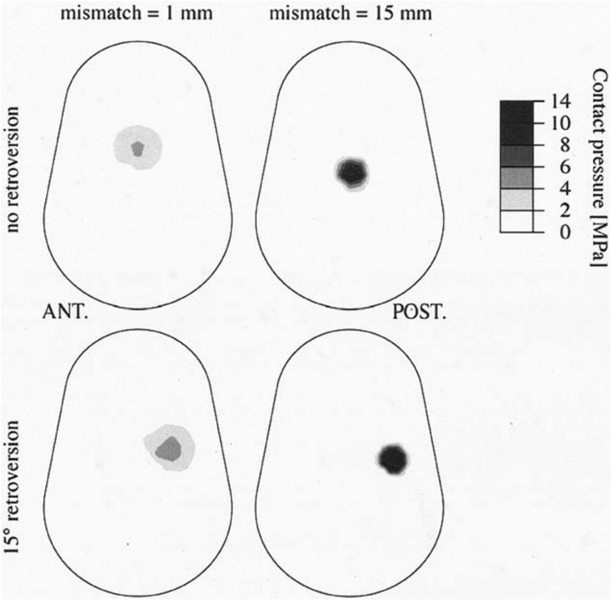

Figure 3 Glenohumeral contact pressure for extreme mismatch values (1 and 15 mm) at 60° of free internal rotation with 0° and 15° of retroversion. *ANT,* Anterior; *POST,* posterior.

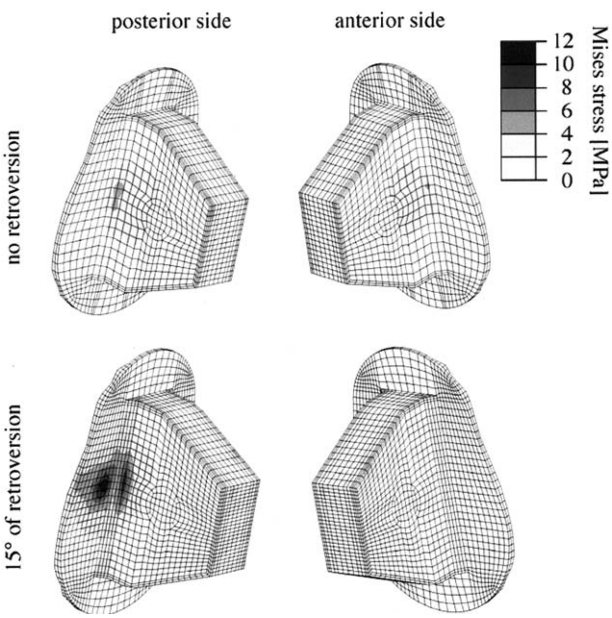

Figure 4 von Mises stress in cement layer for 15 mm of mismatch at 60° of free internal rotation with 0° and 15° of 15° of retroversion.

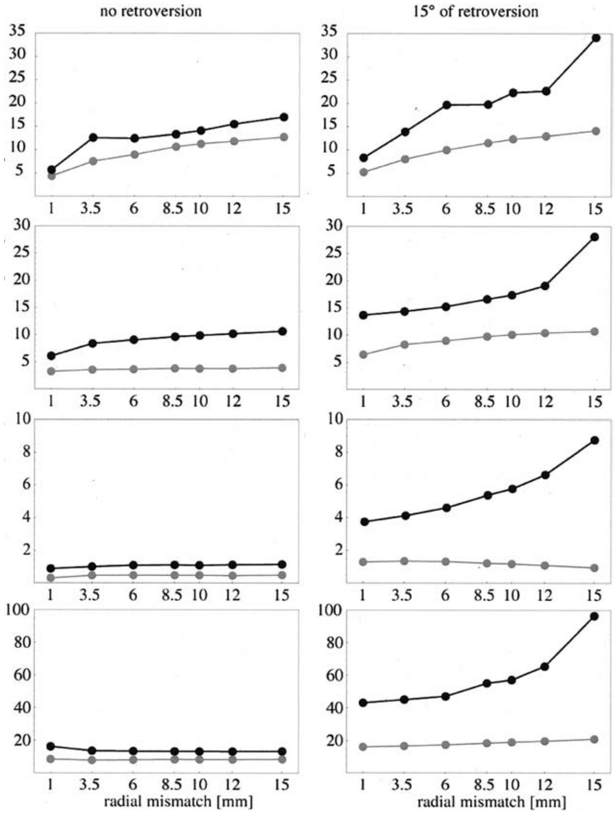

Figure 5 Maximal value of glenohumeral contact pressure, cement von Mises stress, bone- cement interfacial shear stress, and bone-cement interfacial micromotions at 60° of free (*gray*) and countered (*black*) internal rotation with 0° (*left*) and 15° (*right*) of retroversion.

Cement stresses

A similar behavior was observed in the cement layer. Indeed, von Mises stress increased in all cases by about 200% as mismatch increased. This increase was slight in the free/no-retroversion case but became important in the countered/retroversion case and also severe above 12 mm of mismatch in the countered/retroversion case. As for contact pressure, the stress distribution was symmetric and centered in the free/no-retroversion case but moved posteriorly in the countered or retroversion case (Figure 4).

Bone-cement interfacial shear stress

Bone-cement interfacial shear stress was almost not sensitive to mismatch except in the countered/retroversion case, where it increased exponentially. It was about 10 times higher in the countered/retroversion case compared with all other cases. At 0° of retroversion, its peak value was located near the keel-plate edges; it moved behind the keel tip when the glenoid was retroverted by 15°.

Bone-cement relative micromotions

Without retroversion, the bone-cement relative micromotions were almost not influenced by mismatch. Conversely, at 15° of retroversion, micromotions increased as mismatch increased. This increase was only important with the countered force and, in this case, increased rapidly above 10 mm of mismatch.

DISCUSSION

Glenohumeral conformity is reported as one of the implant features that might influence glenoid loosening after total shoulder arthroplasty. Because findings from the clinical and biomechanical studies on this topic are still unclear, there is a need to investigate this feature further. In this study, the effect of this parameter was analyzed in parallel with glenoid retroversion. Indeed, the angle of retroversion of the glenoid component is often difficult to correct or to set precisely during the surgical procedure, and it also modifies the glenoid articular surface concurrently with glenohumeral conformity. Because glenoid retroversion mainly occurs in the horizontal plane, a rotation movement was more appropriate to reveal critical joint contact stresses. Therefore, a rotation movement was simulated by means of a 3-dimensional finite element model of a shoulder to analyze the mechanical effect of glenohumeral conformity on sensitive aspects of glenoid loosening (ie, glenohumeral contact pressure, von Mises stress within the cement, shear stress, and micromotions at the bone-cement interface). These variables were chosen because they might be related to polyethylene wear, cement cracks, and reliability of the bone-cement interface.

Our results showed that, as mismatch increased, glenohumeral contact pressure increased significantly (300% from 1 to 15 mm), and as a result, stress within the polyethylene increased, as reported by other studies.[33] The contact pressure was maximal in the countered or retroversion case. From 10 mm of mismatch, it exceeded the polyethylene yield strength,[20,36] and consequently, damage accumulation and a reduced fatigue life of the component could be expected. Moreover, because contact pressure is related to wear, we can assume that a mismatch increase will also produce a wear increase.

Cement stress also increased as mismatch increased; however, the cement stress increase was only severe for the countered or retroversion case and above 10 mm of mismatch. This value of 10 mm was already reported as a limit value for radial mismatch.[7] Except for the free/no-retroversion case, cement stresses were high enough (>5–7 MPa) to induce cement failure.[15] This result indicates that the stress within the cement is an important point to account for in designing shoulder implants or implantation techniques.

In a cadaveric study, Nyffeler *et al*[24] measured the pullout strength of cemented glenoid component pegs for different surfaces and macrostructures. Because failure occurred at the polyethylene-cement interface for all cases except one (occurring at the bone-cement interface), the maximum pullout strength can be used to minimize the failure strength of the bone-cement interface. This rough estimate gives a failure strength of at least 3 MPa, which is in the range of reported values (2–12 MPa) of shear strength at the bone-cement interface.[22] In the countered or retroversion case, this value was exceeded at the tip of the keel. This may suggest that debonding begins at this location.

Above 10 mm of mismatch, in the countered/retroversion case, micromotions reached a reported limit for the formation of fibrous tissue,[14] which is known to promote implant loosening. Moreover, when the implant starts to debond, cement particles, resulting from microfractures, may migrate toward regions of high slipping and accentuate the effect of the micromotions on fibrous tissue formation.[1]

In a cadaveric study with various glenoid designs, Severt *et al*[31] reported that reaction forces to fixed displacements of the humeral head were higher in conforming designs. In the same way, Walch *et al*,[39] in a retrospective multicenter clinical study of the Aequalis implant, reported that a radial mismatch of less than 6 mm induced higher radiolucency scores and concluded that, for this implant, the ideal radial mismatch should range between 6 and 10 mm. Conversely, in a clinical study on retrieved glenoid components. Hertel and Ballmer[11] observed that the newly formed concavity of the glenoid component due to wear perfectly matched the radius of the prosthetic head. These observations confirmed those of other researchers[8,30] and assume that full articular conformity would be preferable.

The present model has some limitations. First, it is based on a single shoulder, having no degenerative alterations, instead of multiple arthritic shoulders, which usually present degenerative changes such as posterior glenoid erosion. This method may, however, be valid to analyze the general biomechanical effects and trends of the phenomenon. Moreover, it should be noted that, providing a correct description of the different material properties, the finite element technique is commonly accepted for calculating the motion and stress state of deformable structures without further experimental assessments.[23,25,32] The cement layer surrounding the glenoid was uniform, and the contact law did not include a stress failure criterion in tension, accounting for adhesion of the cement to the bone. Only rotations were simulated in this work, inducing lower contact forces and stresses than abduction. Nevertheless, by use of an axial spring, simulating a countered movement, the glenohumeral contact force reached 250 N, which is between one half and one third of the maximal abduction force.[19,27,37] However, although large translations of the humeral head were observed, the expected increase in interface stresses associated with a conformity increase[15,39] was not observed. In our opinion, this phenomenon is mainly caused by tangential forces associated with important forces of the stabilizer muscles, which occur, for instance, during standing up, pushing, pulling, or carrying loads. Despite these limitations, our model can be used to obtain minimum conditions, at least valid in the case of countered rotation, which is a relatively frequent movement during activities of daily living.

In summary, all mechanical variables that were related to bone-cement interface reliability were altered by a decrease in conformity. Without retroversion, the glenohumeral contact forces were almost centered and aligned to the implant axis. With retroversion, the contact forces became eccentric, increasing the stresses at the posterior part of the implant-cement-bone complex. Finally, although an ideal mismatch could not be established, we confirm that radial mismatch above 10 mm should be avoided.

The clinical conclusion of this study confirms the importance of glenoid component orientation and, thus, the importance of the surgeon's ability to reproduce the natural glenohumeral joint. Moreover, we conclude that posterior wear of the glenoid, uncorrected with a prosthesis implanted in retroversion, may accelerate the mechanisms of glenoid loosening.[4]

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