Edge displacement and deformation of glenoid components in response to eccentric loading. The effect of preparation of the glenoid bone

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Edge Displacement and Deformation of Glenoid Components in Response to Eccentric Loading

The Effect of Preparation of the Glenoid Bone*

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ABSTRACT: The effect of different methods of preparation of glenoid bone on displacement and deformation of a glenoid component under eccentric loading was investigated in a series of scapulae of cadavera. Hand-burring of the osseous surface was associated with less displacement and deformation than simple removal of cartilage with a curet. Reaming resulted in the least displacement and deformation. Substantial posterior deficiency of the bone of the reamed glenoid was not associated with significant increases of displacement and deformation.

Glenohumeral arthroplasty is commonly used for the treatment of pain and loss of function resulting from destruction of the surfaces of the glenohumeral joint. Péan is credited with developing the first total shoulder prosthesis[9]. More recently, Neer[10] developed a prosthetic humeral head that articulated with the residual glenoid bone. This procedure has substantially increased comfort and function in many patients. However, Neer noted problems related to the undisciplined articulation of the humeral head component on a flattened, degenerated glenoid surface. As a result, he, and subsequently others, developed various prostheses for resurfacing of the glenoid. In most systems for glenohumeral arthroplasty, the humeral head is not captured by the glenoid component, but rather it is stabilized on the concave glenoid by the joint capsule and through the compressive effect of the scapulohumeral muscles[11].

The glenohumeral joint-reaction force is substantial, and it changes from an inferior direction at 0 degrees of abduction, to a superior direction at 60 degrees, and back to an inferior direction at 150 degrees[13]. These large, variable, and off-center loads, coupled with the small amount of glenoid bone stock that is available for fixation, contribute to the development of high stresses at the glenoid component-bone interface. These stresses create a potential for loosening of the component. Although Neer et al. found no clinical evidence of loosening in their series[12], other reports have described loosening[1,4,14]. Unfortunately, analysis of these reports is impaired by their inconsistent definitions of evidence of radiographic and clinical loosening of a glenoid component, a problem that was addressed in detail by Franklin et al.

Cofield found radiographic evidence of loosening of eight of seventy-three Neer prostheses, with fifty-two of the other prostheses being associated with some radiolucency at the glenoid bone-cement interface. In a more detailed study, Wilde et al. divided the stem of the glenoid component into three zones and measured the radiolucency in each zone. Radiolucency occurred near the base of the stem in 89 per cent of the components, and the average width of the lucent zone was 1.4 millimeters. Wilde et al. also reported a high prevalence of radiolucency immediately postoperatively, which suggested technical problems with the cementing. Bade et al. suspected technical problems with the cementing as well. Using strict criteria, Barrett et al. reported a 10 per cent rate of loosening of the glenoid component within a follow-up period of two to 7.5 years.

Although a variety of designs of glenoid components are available, there have been few studies of factors that influence the stability of the component. Clarke et al. performed failure tests on glenoid components that had been cemented into scapulae of cadavera and found that the torque to failure was three to four times greater than that predicted to occur in the shoulders of living patients. Fukuda et al. found that glenoid components had substantial resistance to failure by pull-out in a direction perpendicular to the face of the glenoid.

We suggest that, in contrast to a pull-out mechanism of failure, an important mode of loosening of the glenoid component is rocking of the component in response to glenohumeral loads that are not centered on the component[2,5]. Such loads may occur when muscle forces are unbalanced, such as when the rotator cuff is torn[2,5] or when capsular tightness is unbalanced[7,8].

There is little published information on the effect of preparation of the glenoid bone on the stability of the glenoid component. While it is possible that polymethylmethacrylate neutralizes the effect of imperfect prepa-

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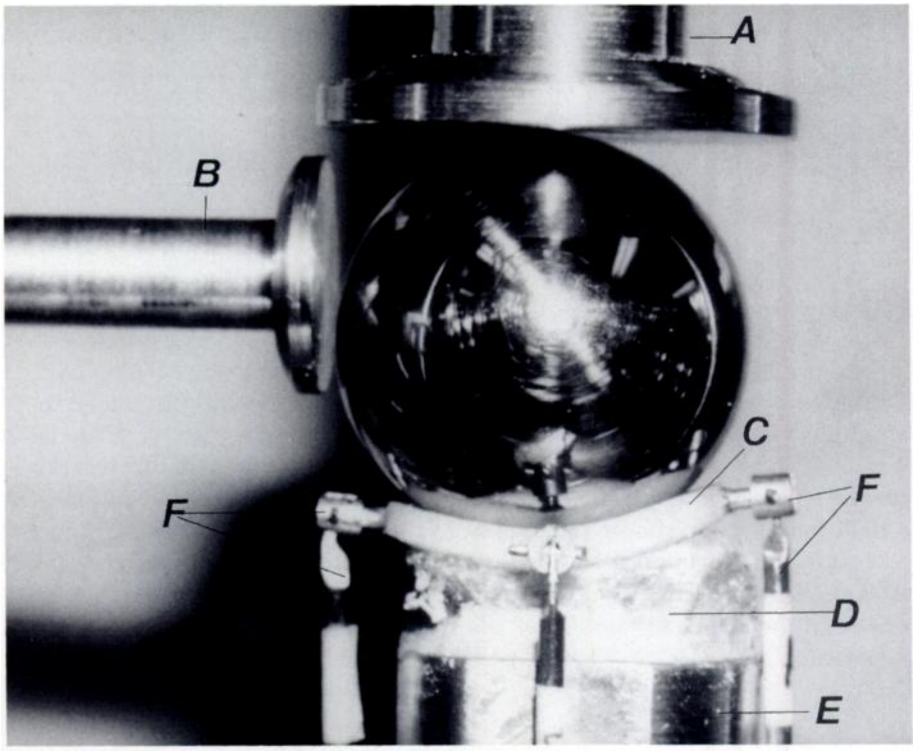

FIG. 1

Photograph of the experimental apparatus, showing the perpendicular load plunger (A), lateral load plunger (B), glenoid component (C), glenoid bone (D), specimen cup (E), and linear variable-differential transducers at the edges of the glenoid component (F).

ration of the glenoid bone, it is also possible that a thin layer of this material is subject to fatigue failure and fragmentation. Theoretically, this risk can be avoided by preparation of the bone so that it directly supports the component without an interposed layer of cement.

We tested the hypothesis that optimum preparation of the surface of the glenoid bone, so that it fits the undersurface of the glenoid component, reduces displacement of the edges of the component and deformation or warp of the component.

Methods

The specific hypotheses to be tested were (1) eccentric loading of the glenoid component results in displacement of the edges of the component and deformation of the component, (2) increasing conformance of the osseous surface to the undersurface of the prosthesis decreases displacement and deformity, and (3) posterior insufficiency of the glenoid bone (such as is often seen in patients who have degenerative disease of the glenohumeral joint) contributes to local deformation of the component under eccentric loading.

These hypotheses were tested with the use of an experimental apparatus in which combined axial and transverse loads were applied to a glenoid component mounted in the scapula of a cadavera while the displacements of the anterior, posterior, superior, and inferior edges of the component were measured. Taken in combination, these measurements reflected the displacement and deformation of the component under load.

Preparation of the Specimen and the Experimental Apparatus

Ten scapulae were removed from five pairs of shoulders of human cadavera. One of the scapulae had a distorted glenoid and was not used. The remaining nine specimens had no evidence of glenohumeral arthritis. These specimens were selected because the surface of each one could be completely covered by the prosthetic component, without overhang. The glenoid and scapular-neck portions of each scapula were potted in a specimen-support cup with fast-setting potting plaster (Labstone Buff; Columbus Dental, St. Louis, Missouri). To permit unconstrained deformation, we used a specially designed non-clinical all-polyethylene glenoid component with a radius of curvature of thirty millimeters and only one four-millimeter-diameter central fixation peg. The component had a rounded-rectangle shape, as do components that are used most commonly in the clinical setting, and it was three millimeters thick. The component was mounted on the glenoid bone after each sequential step of the preparation of the osseous surface. The central peg fit snugly into a hole drilled into the center of the face of the glenoid; this prevented sliding of the component. No cement or other grouting substance was used for glenoid fixation. The peg provided minimum restriction to rocking and no resistance to deformation of the component.

The load was applied to the glenoid through a har-

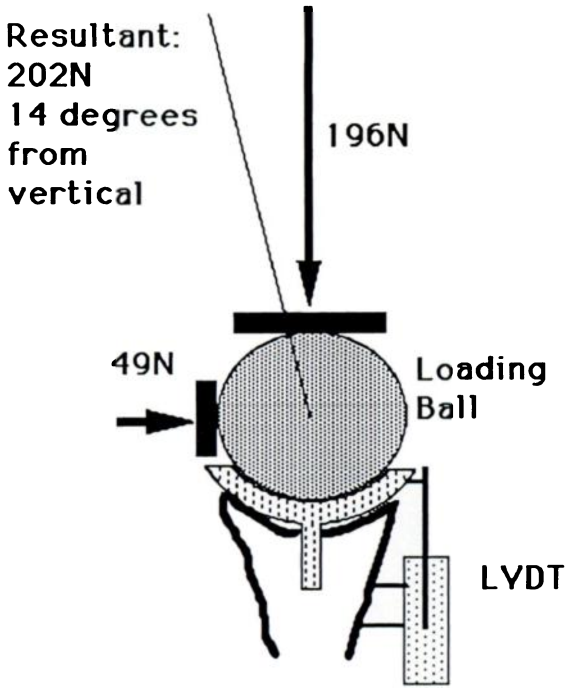

FIG. 2

Schematic diagram showing the magnitudes and directions of the loads applied to the glenoid component through the loading ball. One of the linear variable-differential transducers (LVDT) is shown attached to the glenoid component.

dened steel ball-bearing, with a twenty-five-millimeter radius, centered on the glenoid component (Fig. 1). This slight degree of mismatch between the radii of the ball and the glenoid was selected to avoid the inadvertent loading of the rim of the glenoid component that results from minimum displacements in perfectly conforming humeral and glenoid radii. A force of 196 newtons (30 per cent of average body weight) was applied to the loading ball in a direction perpendicular to the glenoid surface. The load was maintained at a constant 196 newtons with the use of a servohydraulic materials-tester (Bionix, model 828; MTS Systems, Minneapolis, Minnesota) set on load-control. A load transverse to the glenoid face was applied to the ball by a second plunger, connected to a load-cell and a pneumatic cylinder. The cylinder was mounted on one side-post of the materials-tester. By adjustment of the pressure of the cylinder, a transverse load of forty-nine newtons could be maintained. These two applied loads may also have had frictional shear components at the surface of the loading ball. If friction is ignored, the approximate net load on the glenoid was 202 newtons at 14 degrees from the perpendicular to the glenoid surface (Fig. 2). This magnitude of this load was close to that predicted to occur *in vivo* at both 30 and 150 degrees of abduction of the unweighted arm[11].

By rotation of the glenoid-holding apparatus with respect to the transverse load plunger, the glenoid component could be loaded with the transverse component in any of eight orientations: superior, posterior-superior, posterior, posterior-inferior, inferior, inferior-anterior, anterior, and anterior-superior. At each position, the displacements of the anterior, posterior, inferior, and superior edges of the glenoid component were determined with the use of four linear variable-differential transducers (model 050-DCD; Shaevitz Engineering, Pennsauken, New Jersey), as shown in Figures 1 and 2. The core of each linear variable-differential transducer was suspended from the edge of the glenoid component at the location of measurement. Each core floated freely within the barrel of the corresponding transducer, which was attached to the fixture that also held the glenoid bone rigidly. Displacements perpendicular to the face of the glenoid were measured, with the use of a twelve-bit analog digital converter (model DT-2801; Data Translation, Marlborough, Massachusetts) within a personal computer, to within 0.001 volt, corresponding to a resolution of 0.000125 millimeter.

Experimental Sequence

The fixation hole was drilled in the center of the glenoid surface. The stability of the glenoid component was determined for each glenoid after five different preparations of the bone.

The first stage of the preparation of the glenoid was removal of the articular cartilage with a curet, so that only subchondral bone remained. No shaping of the glenoid bone was performed. The glenoid component, with its attached linear variable-differential transducer cores, was mounted on the glenoid bone. With the loading ball resting on the glenoid component, a set of zero-load readings was recorded from each of the linear variable-differential transducers. Then perpendicular and transverse loads were applied while the net displacements were recorded from each of the linear variable-differential transducers. This procedure was repeated with the transverse component of the load oriented in each of the eight different directions.

For the second stage of the preparation, the glenoid component and loading ball were removed, and the osseous surface of the glenoid was carefully contoured to approximate the shape of the back of the glenoid component by an experienced shoulder surgeon using a hand-held power-burr. The glenoid component and the cores of the linear variable-differential transducers were reinstalled and the measurements were made as they had been for the first preparation.

In the third stage, the subchondral bone of the glenoid was reamed, with the use of a custom-designed thirty-millimeter-radius reamer, so that it corresponded to the radius of the back of the glenoid component. The measurements were repeated.

For the fourth stage of the preparation, the posterior 25 per cent of the previously reamed glenoid bone was measured and was removed along a straight vertical line. The testing was repeated. The fifth stage consisted of

TABLE I

DISPLACEMENT OF THE EDGE OF THE GLENOID COMPONENT (IN MILLIMETERS) IN RESPONSE TO LOADING*

	Method of Glenoid Preparation			Comparison Tested‡		
Direction†	Cartilage Removed	Hand-Burred	Reamed	Cartilage Removed/ Hand-Burred	Hand-Burred/ Reamed	Cartilage Removed/ Reamed
Superior	0.16 ± 0.14	0.22 ± 0.23	0.16 ± 0.13	t = −0.51 NS	t = 0.67 NS	t = 0.04 NS
Inferior	0.31 ± 0.27	0.15 ± 0.15	0.13 ± 0.06	t = 1.28 NS	t = 0.36 NS	t = 2.01 p < 0.05
Anterior	0.62 ± 0.17	0.49 ± 0.19	0.21 ± 0.19	t = 1.29 NS	t = 4.30 p < 0.001	t = 4.44 p < 0.001
Posterior	0.39 ± 0.30	0.15 ± 0.10	0.14 ± 0.08	t = 2.24 p < 0.05	t = 0.26 NS	t = 2.23 p < 0.05

*Values are given as average and standard deviation.
†The direction of the transverse load and the edge of the glenoid component at which the displacement was measured.
‡NS = not significant.

removal of the posterior 33 per cent of the glenoid bone, after which the testing was done again.

This sequence of experiments was performed on each of the nine glenoids. Although it would have been desirable to quantitate the quality of each preparation of bone, we did not have access to a method with which to do this.

Results

Displacement of the Edges of the Component

Displacement resulting from loading in eight directions was measured at each of the four edges of the nine glenoid components after each of the five stages of preparation. Displacement was recorded in millimeters, with positive values indicating downward displacement (toward the glenoid surface).

The displacement of the anterior edge of the glenoid component was calculated for each of the nine shoulders after each of three different stages of preparation of the glenoid bone (Fig. 3). It was found that anterior loading almost always produced displacement of the anterior edge toward the bone (a positive value), and in most instances hand-burring and reaming progressively diminished the displacement of the component.

A comparison was done of the effects of three different preparations of the glenoid on the displacement of each edge of the component in response to loading directed toward that edge (for example, displacement of the superior edge in response to superior loading) (Table I). Because we considered both positive displacement (toward the glenoid) and negative displacement (away from the glenoid) to be undesirable, we calculated the means and standard deviations on the basis of the absolute values of the displacements. The paired Student t test was used to calculate significance of the differences resulting from different glenoid preparations. The greatest displacements were seen at the anterior edge with anterior loading, followed by the posterior edge with posterior loading and the inferior edge with inferior loading. In general, the mean displacements were diminished by hand-burring in comparison with simple removal of cartilage and by reaming in comparison with hand-burring.

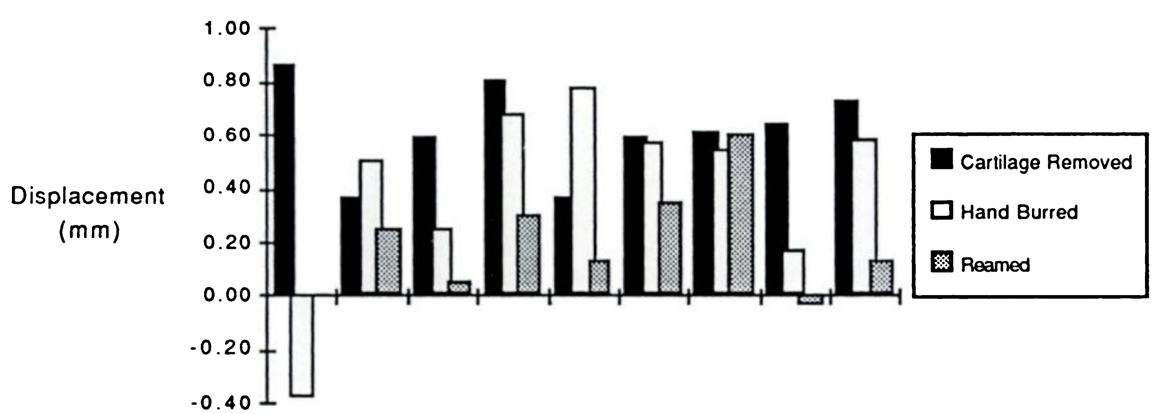

FIG. 3

Displacement of the anterior edge of the glenoid component in response to anteriorly directed loads in nine glenoids after three different types of preparation of the glenoid bone. Positive values indicate displacement toward the glenoid bone and negative values, displacement away from the glenoid bone. Note that the displacement of the component was 0 when the first glenoid was tested in the reamed state.

TABLE II

DISPLACEMENT OF THE POSTERIOR EDGE OF THE GLENOID COMPONENT (IN MILLIMETERS) IN RESPONSE TO POSTERIOR LOADS FOR REAMED GLENOIDS AND FOR REAMED GLENOIDS MADE TWENTY-FIVE AND THIRTY-THREE PER CENT DEFICIENT AT THE POSTERIOR ASPECT*

Method of Glenoid Preparation			Comparison Tested†		
Reamed	25 Per Cent Deficient	33 Per Cent Deficient	Reamed 25 Per Cent Deficient	25 Per Cent/ 33 Per Cent Deficient	Reamed 33 Per Cent Deficient
0.14 ± 0.08	0.17 ± 0.12	0.16 ± 0.18	t = −1.14 NS	t = 0.25 NS	t = −0.6 NS

*Values are given as average and standard deviation.
†NS = not significant.

The mean displacement at each of the four edges when the tangential vector was oriented toward it was calculated for each of the three different preparations (Fig. 4). The displacement of the posterior edge in response to posterior loading after the reamed glenoid had been rendered 25 per cent and then 33 per cent deficient at its posterior aspect was calculated also (Fig. 4). Again, the greatest displacements were seen with anterior, posterior, and inferior loading. Preparation of the glenoid diminished the displacements, and posterior deficiency of the reamed glenoid did not significantly increase the displacement at the posterior edge.

A substantial loss of posterior bone from the reamed glenoid did not significantly increase the displacement at the posterior edge in response to posteriorly directed loads (Table II). We calculated the means and standard deviations on the basis of the absolute values obtained from the nine glenoids. The paired Student t test was used for the statistical comparisons.

Data were collected from each of the four edges of the component with eight different directions of loading. Figure 5 shows, as an example, the effect of eight directions of loading on the displacement at the four edges of the component after the cartilage had been removed from the glenoid bone. The greatest displacements in this preparation occurred at the anterior and posterior edges in response to anterior and inferior-anterior loading.

We were interested in whether the glenoid component deformed under the loads that were applied in this investigation. If the glenoid did not deform under a given load, the vector sum of the anterior and posterior displacements would be equal to the vector sum of the superior and inferior displacements. (This can be verified with a piece of cardboard moved relative to the top of a table.) The extent to which these sums were not equal reflected the deformity induced in the component by the load. We defined the difference in these sums as warp. Thus, warp for a given loading condition equals (displacement of the anterior edge + displacement of the posterior edge) (displacement of the superior edge + displacement of the inferior edge).

Our data suggested that the displacements of the anterior and posterior edges of the glenoid component were not always reciprocal and that these displacements were not always accompanied by corresponding similar displacements of the superior and inferior edges (Fig. 5). We calculated the warp of the glenoid component in each shoulder for each loading condition and each glenoid preparation. We found that the component deformed substantially under certain circumstances. Since any

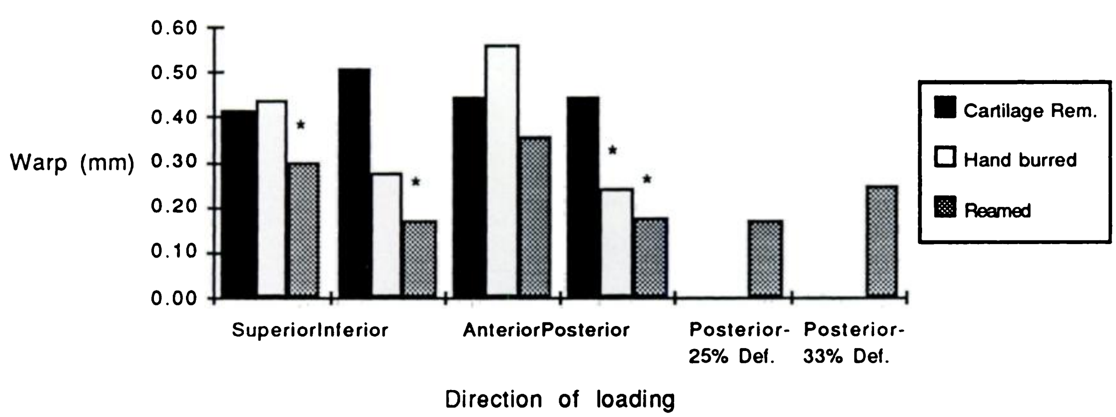

FIG. 4

Displacement of each of the four edges of the glenoid component in response to loads directed toward that edge. The results are shown for three different preparations of glenoid bone and for the reamed glenoid bone after it had been rendered 25 and 33 per cent deficient at the posterior aspect. The results are the means of the absolute values for the nine glenoids. The values that are significantly different ($p < 0.05$) from those recorded after only the cartilage had been removed are designated with an asterisk.

TABLE III

WARP OF THE GLENOID COMPONENT (IN MILLIMETERS) IN RESPONSE TO FOUR DIRECTIONS OF LOADING FOR THREE DIFFERENT GLENOID PREPARATIONS*

	Method of Glenoid Preparation			Comparison Tested†		
Direction	Cartilage Removed	Hand-Burred	Reamed	Cartilage Removed/Hand-Burred	Hand-Burred/Reamed	Cartilage Removed/Reamed
Superior	0.41 ± 0.49	0.44 ± 0.40	0.30 ± 0.38	t = −0.20 NS	t = 1.51 NS	t = 2.26 $p < 0.01$
Inferior	0.51 ± 0.70	0.27 ± 0.58	0.17 ± 0.11	t = 1.53 NS	t = 2.11 $p < 0.05$	t = 3.73 $p < 0.005$
Anterior	0.45 ± 0.58	0.56 ± 0.62	0.36 ± 0.42	t = −0.67 NS	t = 1.40 NS	t = 0.70 NS
Posterior	0.44 ± 0.50	0.24 ± 0.28	0.18 ± 0.24	t = 2.58 $p < 0.05$	t = 0.69 NS	t = 2.31 $p < 0.05$

*Values are given as average and standard deviation.
†NS = not significant.

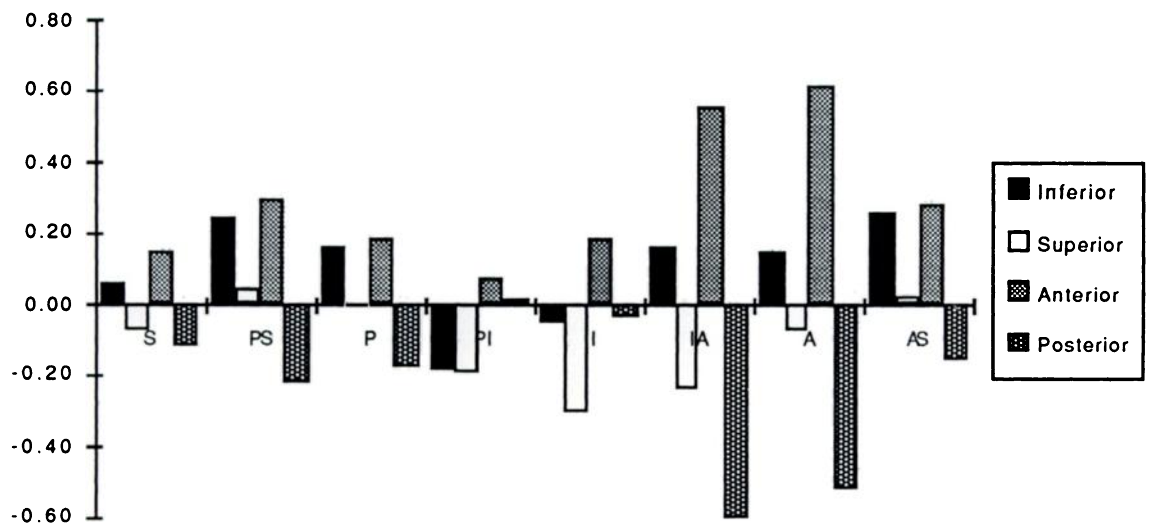

FIG. 5

The displacements at each of the four edges of the glenoid components in response to loading in eight directions: superior (S), posterior-superior (PS), posterior (P), posterior-inferior (PI), inferior (I), inferior-anterior (IA), anterior (A), and anterior-superior (AS). The results are the means of the values for the nine glenoids that had been prepared with removal of the cartilage only.

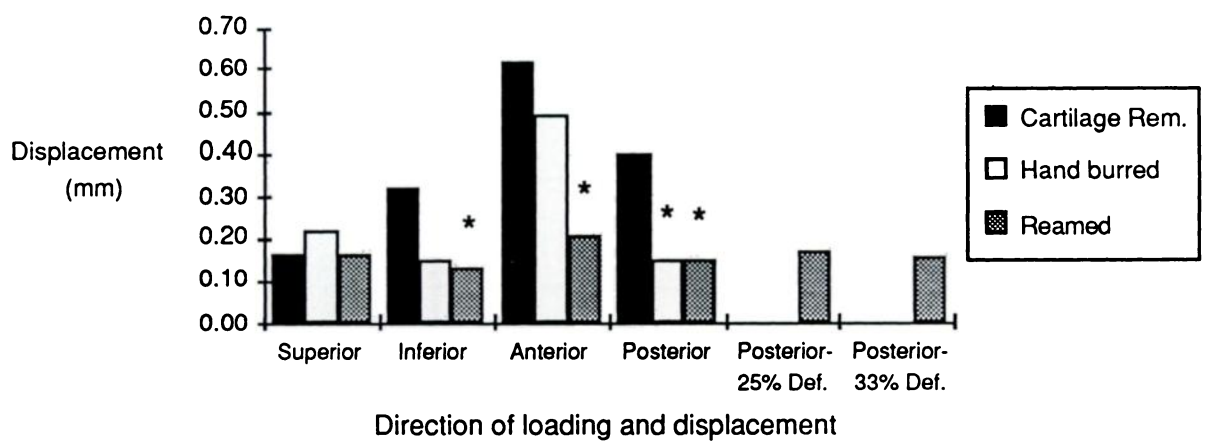

FIG. 6

The warp of the glenoid components in response to different directions of loading after different preparations of the bone. The values are the means of the absolute values of warp. The values that are significantly different ($p < 0.05$) from those recorded after only the cartilage had been removed are designated with an asterisk.

warp is undesirable, we considered the absolute value of the warp in our statistical analysis. We found that warp occurred under loads in four different directions after three different stages of preparation and for posterior loading with the two different states of posterior deficiency of the glenoid (Fig. 6 and Table III). An increase in the conformance of the glenoid surface to the shape of the component diminished the warp, and posterior deficiency in the reamed glenoid preparation did not significantly increase the warp of the glenoid component under posteriorly directed loads.

Discussion

Many factors contribute to the clinical stability of a glenoid component. Some of these factors include the design of the prosthesis, the adequacy of soft-tissue balance, the cementing technique, the integrity of the rotator cuff, and the loads that the patient applies to the prosthetic joint. The objective of this study was to explore only the effect of the preparation of the glenoid bone on the displacement and warp of the glenoid component. To enhance our ability to detect displacement and warp, we used a thin, all-polyethylene component that had only one small, central, uncemented fixation peg. Therefore, this component did not have the benefits of cement, metal backing, fixation with screws, a keel, or multiple pegs. It was stabilized only by the single peg and by virtue of the quality of the fit against the glenoid bone.

Our clinical experience has suggested that an important mechanism of loosening of the glenoid component is rocking in response to off-center or eccentric loads. Thus, our mode of loading included a transverse component to produce an off-center resultant force. In our experimental system, this type of loading displaced the glenoid component as much as 0.62 millimeter when only the cartilage had been removed from the glenoid bone. Displacements at the anterior, posterior, and inferior edges were reduced by more than 50 per cent when the glenoid bone had been prepared so that it conformed better to the undersurface of the prosthesis.

Use of the polyethylene component permitted observation of deformation in response to loading. A perfectly supported component deforms little under load, whereas non-conforming support allows the component to warp under load. The warp of the component was approximately one-half millimeter with loading in the anterior, posterior, superior, or inferior direction.

Posterior deficiency of the glenoid is common in shoulders that are to be treated with arthroplasty, especially if the diagnosis is osteoarthrosis or arthritis that developed after the anterior part of the capsule was tightened for the treatment of recurrent instability. In these patients, excessive loss of bone posteriorly may lead to the use of a bone graft for complete support of the glenoid component. It is difficult to know how much of an osseous deficiency merits bone-grafting. In this study, displacement at the posterior edge of the component in response to a posteriorly directed load was not significantly increased by a 25 per cent or even a 33 per cent deficiency of the reamed glenoid bone. Similarly, the warp of the glenoid component was not significantly increased by posterior deficiency of the reamed glenoid.

The results of this study suggest that careful preparation of the glenoid bone so that it matches the contour of the back of the glenoid component helps to stabilize the component against the eccentric loads that are encountered during the daily use of a prosthesis. A substantial degree of stability of the glenoid component appears to be achievable even without the use of cement, screws, a metal backing, or a keel.

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