Version Correction via Eccentric Reaming Compromises Remaining Bone Quality in B2 Glenoids: A Computational Study

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Abstract

Background Version correction via eccentric reaming reduces clinically important retroversion in Walch type B2 glenoids (those with substantial glenoid retroversion and a second, sclerotic neoglenoid cavity) before total shoulder

arthroplasty (TSA). Clinically, an increased risk of glenoid component loosening in B2 glenoids was hypothesized to be the result of compromised glenoid bone quality attributable to eccentric reaming. However, no established guidelines exist regarding how much version correction can be applied without compromising the quality of glenoid bone.

Questions/Purposes (1) How does version correction correlate to the reaming depth and the volume of resected bone during eccentric reaming of B2 glenoids? (2) How does version correction affect the density of the remaining glenoid bone? (3) How does version correction affect the spatial distribution of high-quality bone in the remaining glenoid?

Methods CT scans of 25 patients identified with Walch type B2 glenoids (age, 68 ± 9 years; 14 males, 11 females) were selected from a cohort of 111 patients (age, 69 ± 10 years; 50 males, 61 females) with primary shoulder osteoarthritis who underwent TSA. Virtual TSA with version corrections of 0° , 5° , 10° , and 15° was performed on 25 CT-reconstructed three-dimensional models of B2 scapulae. After simulated eccentric reaming at each version correction angle, bone density (Hounsfield units [HUs]) was analyzed in five adjacent 1-mm layers under the reamed glenoid surface. Remaining high-quality bone (> 650 HUs) distribution in each 1-mm layer at different version corrections was observed on spatial distribution maps.

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Results Larger version corrections required more bone resection, especially from the anterior glenoid. Mean bone densities in the first 1-mm bone bed under the reamed surface were lower with 10° (523.3 ± 79.9 HUs) and 15° (479.5 ± 81.0 HUs) version corrections relative to 0° (0°, 609.0 ± 103.9 HUs; mean difference between 0° and 15°, 129.5 HUs [95% CI, 46.3–212.8 HUs], $p < 0.001$; mean difference between 0° and 10°, 85.7 HUs [95% CI, 8.6–162.9 HUs], $p = 0.021$) version correction. Similar results were observed for the second 1-mm bone bed. Spatial distribution maps qualitatively showed a decreased frequency of high-quality bone in the anterior glenoid as version correction increased.

Conclusions A version correction as low as 10° was shown to reduce the density of the glenoid bone bed for TSA glenoid fixation in our computational study that simulated reaming on CT-reconstructed B2 glenoid models. Increased version correction resulted in gradual depletion of high-quality bone from the anterior region of B2 glenoids.

Clinical Relevance This computational study of eccentric reaming of the glenoid before TSA quantitatively showed glenoid bone quality is sensitive to version correction via simulated eccentric reaming. The bone density results of our study may benefit surgeons to better plan TSA on B2 glenoids needing durable bone support, and help to clarify goals for development of precision surgical tools.

Introduction

As a degenerative disease, shoulder osteoarthritis (OA) usually leads to pathologic changes to the bony morphologic features and bony properties of the shoulder. Walch type B2 glenoid deformities are characterized by substantial glenoid retroversion and formation of a second, sclerotic neoglenoid cavity [14, 21, 23]; this morphologic feature is present in approximately 15% of all patients with primary shoulder OA [23]. The pathogenesis of the biconcave glenoid also is associated with stiffening of subchondral bone on the surface of the neoglenoid cavity [5, 14, 21]. Although total shoulder arthroplasty (TSA) is one successful surgical treatment for end-stage OA [11, 13, 20, 23], the excessive retroversion and asymmetric bone density distribution in the subchondral bone of a type B2 glenoid poses a challenge for TSA glenoid component fixation.

Severe glenoid retroversion often coincides with posterior migration of the humeral head, generating a posteriorly directed glenohumeral contact force [11, 19, 24]. One of the main surgical goals is to correct the retroversion and place the glenoid component in neutral version, thus establishing a more-centralized glenohumeral contact, better joint stability, and more durable fixation [6, 11, 13].

To achieve this version correction, surgeons use eccentric reaming by asymmetrically reaming the anterior glenoid such that it is even with the eroded posterior glenoid [6, 11, 13]. The desired effect is to mitigate the posteriorly directed contact seen at higher retroversion [6, 7, 18]. Although eccentric reaming may be an effective method in achieving more-centralized glenohumeral alignment, the procedure often requires a substantial amount of bone resection [15, 17, 21, 28] and could lead to glenoid-vault violation by the implant's pegs and keel [17]. More recently, eccentric reaming has been associated with violation of the high-quality bone stock, therefore compromising initial glenoid fixation owing to weakened bone support [2, 4, 7, 12, 15, 28]. However, no established guidelines exist regarding how much version correction can be applied without compromising the quality of the remaining bone that provides a foundation for glenoid component fixation.

The purpose of our study was to determine how the amount of version correction via eccentric reaming affects the amount of bone resection and the quality of remaining bone in B2 glenoids before TSA. In particular, we focused on three research questions: (1) How does version correction correlate to the reaming depth and the volume of resected bone during eccentric reaming of B2 glenoids? (2) How does version correction affect the density of the remaining glenoid bone? (3) How does version correction affect the spatial distribution of high-quality bone in the remaining glenoid?

Materials and Methods

CT Examination and Three-dimensional Reconstruction

The CT datasets of 25 patients (mean age, 68 ± 9 years; 14 males, 11 females) used in this study were selected from the preoperative CT scans of 111 patients (mean age, 69 ± 10 years; 50 males, 61 females) seen at the Hospital for Special Surgery during a period of more than 3 years (from April 2011 to December 2014). All patients received a diagnosis of primary shoulder OA by experienced surgeons (JB and LVG). All CT datasets were further examined by two operators (JB and ASR), 25 were identified to have type B2 glenoid morphologic features according to Walch classification [23]. All CT scans were taken under settings of 100 to 240 mA, 100 to 140 mVs, with 0.5 to 1 mm slice thickness, and 512×512 pixels per slice (resulting in a mean pixel size of 0.4 ± 0.1 mm). The retrospective review of patients' preoperative CT scans was approved by the Hospital for Special Surgery institutional review board (IRB # 13101). The CT datasets were uploaded to Mimics® software

(Materialise, Leuven, Belgium) for segmentation and reconstruction of scapular geometries. Automatic gray-value thresholding with a minimum value of 200 Hounsfield units (HUs) allowed initial segmentation of bony materials from other tissues [14]. Manual segmentation was done to refine and finalize the boundaries of the scapular geometries. Three-dimensional (3-D) volume meshes of scapulae were generated using scan-defined CT voxels (averaged $0.4 \times 0.4 \times 0.5 \text{ mm}^3$ across all scapulae).

Simulated Version Correction via Eccentric Reaming

Native B2 glenoid retroversion and tilt were measured by two operators (JB and ASR) according to a previously published method [10, 17] (Fig. 1A). The original 3-D CT datasets were resliced in the Mimics software to realign with the scapular plane defined by three bony landmarks: center of the glenoid fossa [25], most medial point on the spinal border of the scapula, and most distal point on the inferior angle of the scapula. Native glenoid version was measured in the 2-D axial plane that is perpendicular to the resliced scapular plane [10] (Fig. 1A). Native glenoid tilt was measured in the 2-D coronal plane using a similar technique. Our observers achieved good interobserver reliability (mean difference between observers in glenoid version, $1.8^\circ \pm 1.1^\circ$), similar to values reported by Friedman et al. [10]. For further simulations of version correction, we chose to use the measurements from only one observer (ASR), to simplify the methodology and focus our analysis on bone density.

3-D models of commercially available four-peg all-polyethylene TSA glenoid components (available in three sizes: small, medium, and large; Comprehensive® Total Shoulder System; Zimmer Biomet, Warsaw, IN, USA) were positioned on the 25 3-D scapula models. Although available in different lengths and widths, all three sizes of glenoid components share identical curvatures at the front and back surfaces (38-mm radius at the front surface, 52-mm radius at the back surface) and identical peg configuration. Initially, each scapula model was virtually implanted with all three sizes of the glenoid component. Each sized glenoid component was first aligned to match the native B2 retroversion (0° version correction, Fig. 1B) of each glenoid with 0° glenoid tilt. Progressive version corrections of 5° , 10° , and 15° (Fig. 1C) then were applied to each glenoid while maintaining the tilt of the glenoid component. Version corrections that resulted in overcorrected (anteverted) glenoids were not used.

We developed an automated algorithm for glenoid component fitting and eccentric reaming using custom code in MATLAB® (MathWorks, Natick, MA, USA). During simulated eccentric reaming, a best-fit glenoid component

Fig. 1A–C (A) B2 retroversion and tilt were measured on the resliced CT scans aligned to the scapular plane. The scapular plane was defined by three bony landmarks: center of the glenoid (GC), most medial point of the scapular spine (TS), and the inferior angle of the scapula (AI). Glenoid tilt was measured in the two-dimensional coronal plane, and version was measured in the two-dimensional axial plane. Version correction was applied relative to the native B2 retroversion. Placement of the glenoid component is shown at (B) the native B2 retroversion (0° version correction) and (C) 15° version correction.

(among three available sizes) was chosen for each glenoid (reconstructed from a patient's CT scan) at each version correction angle. At each version correction angle, eccentric reaming was simulated by removing glenoid bone using a spherical reamer (the reamer matched the radius and the dimension of the back surface of the glenoid component), starting at the most lateral tip of the glenoid rim, and moving medially in steps of 0.5 mm (Fig. 2A). After each step of simulated reaming, the coverage of the back surface of the glenoid component by the glenoid bone was calculated via the algorithm. The 0.5-mm-step reaming of the glenoid bone did not stop until the back surface of the glenoid component could be fully covered by the

remaining glenoid bone. Meanwhile, the algorithm ensured stoppage of simulated reaming once full support of the glenoid component was reached. The algorithm then selected the largest possible size of the glenoid component that achieved full support of the back of the glenoid component by remaining glenoid bone. After automated component fitting, the chosen glenoid component was examined manually (XC and ASR) to ensure full support of the back surface by remaining glenoid bone. This manual confirmation also ensured there was no overhanging of the chosen glenoid component. Reaming depth and volume of resected bone were calculated for each glenoid and correlated with version correction angle.

One-way ANOVA with post hoc Bonferroni analysis was performed to determine differences in reaming depth and volume of resected bone across different version correction angles. An alpha value less than 0.05 was considered statistically significant.

Bone Density Analysis

We examined bone density for each glenoid after simulated reaming at each version correction angle. Starting from the reamed fixation surface, bone density (mean and SD) was

analyzed in five adjacent 1-mm parallel layers under the reamed fixation surface in the footprint of the glenoid component (Fig. 2B). For each analyzed layer, mean and SD of bone density of the entire layer was determined from HU values across all voxels in the layer (approximately 9000 voxels in each layer). Each layer was further divided in anterior, posterior, superior, and inferior subregions, where bone densities (means and SDs) were analyzed separately for each subregion (Fig. 2B).

One-way ANOVA with post hoc Bonferroni analysis was performed to determine differences in mean bone density of each 1-mm parallel layer and its subregions at different version correction angles across all subjects. An alpha value less than 0.05 was considered statistically significant. Power analysis was done for the resulting comparisons that had an alpha value less than 0.05.

Spatial Distribution of High-Quality Bone After Eccentric Reaming

The aim of our study was not only to understand how bone quality is affected after eccentric reaming, but also to assess where the strong high-quality bone is distributed. In the analyzed CT scans of B2 glenoids, bony voxels with density greater than 650 HUs were identified as “high-quality” bony voxels [1]. The threshold of 650 HUs allowed separation of subchondral cortical bone and cortical bone from the less-dense subchondral trabecular bone and the trabecular bone in the glenoid vault [1, 14, 22]. Spatial distribution maps compiling the locations of remaining high-quality bone in the entire cohort were generated at different version correction angles using a custom algorithm developed in MATLAB. Distribution of high-quality bone was analyzed in five consecutive 1-mm layers beneath the reamed fixation surface.

At each version correction angle, in a specified 1-mm analysis layer, our algorithm registered the location and HUs of all bony voxels of each reamed glenoid to a standardized 3-D grid with equal-sized cubic cells (Fig. 3A). The frequency of high-quality bony voxels inside each cell was calculated (Fig. 3A), indicating the incidence of high-quality bone at the location of each cell. After registering voxels from all the reamed glenoids, the spatial distribution map of high-quality bone for a specified bone layer was generated (Fig. 3B). Each spatial distribution map summarized the percentage of incidence of high-quality bone at a given location inside one specified layer in the cohort of B2 glenoids (Fig. 3B). Spatial distribution maps of high-quality bone were generated at different version correction angles to compare

Fig. 2A–B (A) Eccentric reaming was simulated at different version corrections (VC) until a flush fixation surface was achieved. (B) Bone density was analyzed in five adjacent 1-mm bone layers beneath the reamed fixation surface in the footprint of the glenoid component. Mean bone density was calculated for the full layer and as the anterior (A), posterior (P), superior (S), and inferior (I) subregions.

Fig. 3A–B (A) Distribution of high-quality bone from one patient is shown for bone layer 1 at 15° version correction. Distribution of high-quality bone was analyzed in the footprint of the glenoid component. The frequency of high-quality bone (> 650 HUs) in each grid cell was calculated. (B) A spatial distribution map of high-quality bone for bone layer 1 at 15° version correction is shown. Voxels of bone layer 1 from 14 analyzed glenoids were registered to the three-dimensional grid. By averaging the frequency of high-quality bone at each grid cell, the gray scale of each grid cell indicates the mean frequency of high-quality bone across all glenoids that underwent 15° version correction.

the distribution of high-quality bone after eccentric reaming.

Results

Reaming Depth and Volume of Resected Bone

The mean glenoid retroversion of all 25 scapulae was $14^\circ \pm 5^\circ$. All scapulae were reamed at 0° (native B2 retroversion) and 5° version corrections, whereas 18 scapulae had 10° version correction, and 14 underwent 15° version correction. The mean glenoid tilt across 25 scapulae was $4^\circ \pm 6^\circ$ (positive indicated superior tilt). Reaming depth and volume of resected bone had strong positive linear correlations with version correction angles ($R^2 = 0.97$ and $p <$

Fig. 4 The mean reaming depth and volume of resected bone fit to linear trend lines correlate with version correction angles. Error bars = SD; Reaming depth: * $p < 0.001$ for 0° version correction (VC) versus 15° VC; † $p = 0.005$ for 0° VC versus 10° VC; ‡ $p < 0.001$ for 5° VC versus 15° VC; Volume of resected bone: * $p < 0.001$ for 0° VC versus 15° VC; † $p = 0.004$ for 0° VC versus 10° VC; ‡ $p < 0.001$ for 5° VC versus 15° VC; $n = 25$ at 0° VC; $n = 25$ at 5° VC; $n = 18$ at 10° VC; $n = 14$ at 15° VC.

0.001 for reaming depth against version correction; $R^2 = 0.98$ and $p < 0.001$ for the volume of resected bone against version correction; Fig. 4). For every 5° increment of version correction, reaming depth increased by 1.4 mm, whereas an extra 550 mm^3 bone was resected, predominantly from the anterior glenoid (Fig. 4).

Bone Density Analysis

In the first 1-mm bone layer (bone layer 1), mean bone density at 15° version correction (479.5 ± 81.0 HUs) showed reductions compared with 0° version correction (0° , 609.0 ± 103.9 HUs; mean difference between 0° and 15° , 129.5 HUs [95% CI, 46.3–212.8 HUs], $p < 0.001$, power = 0.95) (Fig. 5) and 5° version correction (5° , 576.9 ± 93.4 HUs; mean difference between 5° and 15° , 97.4 HUs [95% CI, 14.5–180.7 HUs], $p = 0.013$, power = 0.86) (Fig. 5). Ten-degree version correction (523.3 ± 79.9 HUs) showed bone density reduction compared with 0° version correction in bone layer 1 (mean difference, 85.7 HUs; [95% CI, 8.6–162.9 HUs]; $p = 0.021$; power = 0.74) (Fig. 5). In bone layer 2, only 15° version correction (449.9 ± 80.4 HUs) showed lower bone density compared with 0° version correction (0° , 530.8 ± 96.9 HUs; mean difference between 0° and 15° , 80.9 HUs [95% CI, 2.3–159.4 HUs], $p = 0.040$, power = 0.68) (Fig. 5).

The decreased bone density in the first two bone layers as a function of version correction was restricted predominantly to the anterior and superior subregions (Fig. 6). In the anterior subregion, compared with 0° version correction, 15° version correction showed reductions of bone

Fig. 5 Mean bone densities are shown at each version correction (VC) angle in five adjacent 1-mm bone layers beneath the full reamed fixation surface. Error bars = SD; Layer 1: * $p < 0.001$ for 0° VC versus 15° VC; † $p = 0.021$ for 0° VC versus 10° VC; ‡ $p = 0.013$ for 5° VC versus 15° VC; Layer 2: * $p < 0.040$ for 0° VC versus 15° VC; $n = 25$ at 0° VC; $n = 25$ at 5° VC; $n = 18$ at 10° VC; $n = 14$ at 15° VC; HUs = Hounsfield units.

density in layer 1 (0°, 588.1 ± 165.3 HUs; 15°, 352.0 ± 106.7 HUs; mean difference, 236.0 HUs [95% CI, 115.5–356.6 HUs], $p < 0.001$, power = 0.99) and layer 2 (0°, 477.4 ± 125.5 HUs; 15°, 355.0 ± 102.3 HUs; mean difference, 122.4 HUs [95% CI, 21.6–223.3 HUs], $p = 0.009$, power = 0.87). Similar trends were seen for 10° version correction compared with 0° version correction in the anterior subregion (Fig. 6). In the superior subregion, compared with 0° version correction, 15° version correction resulted in lower density in layer 1 (0°, 640.9 ± 143.2 HUs; 15°, 443.5 ± 101.9 HUs; mean difference, 197.3 HUs [95% CI, 78.4–316.3 HUs], $p < 0.001$, power = 0.98) and layer 2 (0°, 535.8 ± 136.0 HUs; 15°, 396.6 ± 95.0 HUs; mean difference, 139.2 HUs [95% CI, 35.4–243.0 HUs], $p = 0.003$, power = 0.90). Similarly, mean bone density in the superior subregion at 15° version correction was lower compared with 5° version correction in layers 1 and 2 (Fig. 6).

Spatial Distribution of High-Quality Bone After Eccentric Reaming

In the first two bone layers beneath the reamed fixation surface, the spatial distribution maps qualitatively showed

decreased frequency of high-quality bone in the anterior glenoid at 10° and 15° version corrections (Fig. 7). In deeper layers (layers 3, 4, and 5), spatial distribution maps showed a similar pattern across different version correction angles with high-quality bone clustered in the posterior glenoid.

Discussion

Correction of substantial B2 glenoid retroversion via eccentric reaming before TSA has been associated with an increased risk of early glenoid component loosening, which was hypothesized to be the result of compromised glenoid bone quality attributable to excessive reaming [2, 4, 7, 12, 15, 28]. Our simulation study sought to investigate how much version correction can be applied without compromising the quality of remaining bone in B2 glenoids after eccentric reaming. We quantified and compared the remaining bone quality while assessing the amount of bone a surgeon needs to resect to correct highly retroverted B2 glenoids. We found that increased version correction resulted in increased reaming depth and required more bone resection. The spatial distribution maps qualitatively showed gradual depletion of high-quality bone from the anterior glenoid as version correction increased. This asymmetric bone resection resulted in reductions in bone density, especially in the anterior and superior subregions of the glenoid, in the first 2 mm of bone beneath the reamed surface for fixation of the TSA glenoid component.

Several limitations regarding the scope of our study need to be considered. We focused our study on the clinically challenging type B2 glenoid. Considering the characteristic bony morphologic features and bony property, the results of our study only apply to B2 glenoids. We also simulated one specific design of glenoid component and spherical glenoid reamer. Our results may not be applicable to a reaming result using other reamer designs, especially reamers that generate a flat surface. However, our automated simulation of reaming and glenoid component fitting can be modified and applied to other reamer and implant designs. We analyzed the effect of version correction on remaining glenoid bone quality by maintaining the same 0° tilt during simulations of eccentric reaming. Tilt correction before TSA also can affect remaining bone quality; however, the same methodology developed in our study can be used to investigate the effect of tilt correction for TSA on B2 and other types of OA glenoids. In addition, we simulated idealized eccentric reaming of type B2 glenoids before TSA in a computational (simulated) environment. With precision surgical tools and subject-specific surgical guides, future studies should investigate

Fig. 6 Mean bone densities are shown in anterior (A), posterior (P), superior (S), and inferior (I) subregions of five adjacent 1-mm bone layers beneath the reamed fixation surface at different version correction (VC) angles. Error bars = SD; Anterior subregion layer 1: $^{\circ}p < 0.001$ for 0° VC versus 15° VC; $^{\dagger}p < 0.001$ for 0° VC versus 10° VC; $^{\ddagger}p = 0.016$ for 5° VC versus 15° VC; layer 2: $^{\circ}p = 0.009$ for 0°

VC versus 15° VC; $^{\dagger}p = 0.009$ for 0° VC versus 10° VC; Superior subregion layer 1: $^{\circ}p < 0.001$ for 0° VC versus 15° VC; $^{\ddagger}p = 0.002$ for 5° VC versus 15° VC; layer 2: $^{\circ}p = 0.003$ for 0° VC versus 15° VC; $^{\dagger}p = 0.036$ for 0° VC versus 10° VC; $^{\ddagger}p = 0.039$ for 5° VC versus 15° VC; $n = 25$ at 0° VC; $n = 18$ at 10° VC; $n = 14$ at 15° VC; HUs = Hounsfield units.

the accuracy of reaming and its effect on remaining glenoid bone quality in the clinical setting.

Other limitations also may be considered regarding the methods used in our study. Owing to the variability in patients' native glenoid retroversion, the number of analyzed patients decreased at the 10° and 15° version corrections. In addition, we retrospectively analyzed preoperative CT datasets of patients with B2 shoulder OA; therefore, CT phantoms were not used at the time of scanning. We used 650 HUs as the threshold for high-quality bone, based on reported thresholds that separated cortical bone from trabecular bone on clinical CT scans

[22] and in an anatomic study that correlated CT HUs to cortical bone anatomy [1]. Future studies using CT phantoms would convert CT HUs to bone mineral density, because bone mineral density is the more-relevant parameter describing the quality of bone. Finally, we only analyzed 5 mm of glenoid bone beneath the reamed fixation surface, although the pegs in many TSA glenoid implants extend beyond this depth. Because our analysis was done after simulating eccentric reaming, we restricted our analysis to a depth of 5 mm to avoid considering the scapular geometry medial to the region of the glenoid vault. Previous studies showed that the depth of the glenoid

Fig. 7 Spatial distribution maps consolidated distribution of high-quality bone across all glenoids at each version correction (VC) angle. Maps for three of the five 1-mm bone layers beneath the reamed fixation surface are shown. The gray scale bar indicates the frequency of high-quality bone at any given location in the maps. Data from layers 4 and 5 were similar as the trend seen in layer 3. $n = 25$ at 0° VC; $n = 25$ at 5° VC; $n = 18$ at 10° VC; $n = 14$ at 15° VC.

vault averaged less than 7 mm adjacent to the border of glenoid in all directions [3, 23]. In addition, glenoid bone strength and mechanical behavior tend to be more closely related to the denser, more-superficial bone plate [3, 8, 16, 21], for which our analysis was appropriate.

Our results suggest that as version correction is increased, eccentric reaming of the B2 glenoid could result in reduction of bone density in the bone bed close to the reamed surface, compromising the support for TSA glenoid fixation. A Walch type B2 glenoid is commonly characterized by the formation of a posteriorly located neoglenoid cavity that has higher mineral deposition in the subchondral bone compared with other regions of the glenoid [5, 14, 21]. Correction of B2 retroversion could lead to excessive reaming of subchondral bone from the anterior glenoid, which can be a concern for the remaining bone quality at the fixation surface [15, 24, 27]. Previous indentation studies on cadaveric nonarthritic glenoids have shown that the modulus and the mechanical strength of glenoid bone decrease rapidly from the subchondral layer to the trabecular bone in the glenoid vault [3, 8]. In particular, the average strength of glenoid bone decreased by 25% 1 mm under the subchondral plate, whereas the strength decreased by 70% at a depth of 2 mm [8]. Studies also have shown correlations between reduction of CT HUs

and decrease in glenoid bone modulus and strength [3, 9, 16]. Our results show that by asymmetrically reaming the anterior glenoid at 10° to 15° version corrections, the mean bone density in the anterior and superior subregions of the glenoid decreased by approximately 200 HUs in the first 1 mm of the bone bed beneath the reamed surface. The asymmetric reduction in bone density in the anterior and superior glenoid may indicate considerable weakening of mechanical strength at and adjacent to the fixation surface for a TSA glenoid component [3, 4, 8, 9, 16, 27]. Based on our findings, future finite element and biomechanical studies would be useful to provide more in-depth information regarding the mechanical strength of the remaining glenoid bone.

The reduction of bone density in the superior subregion of B2 glenoids may be the result of our method for dividing the glenoid into subregions, where portions of bone in the superior and inferior subregions were removed during simulated eccentric reaming. Mean bone density in the inferior subregion was not sensitive to version correction, whereas our study and other studies [14, 21] showed higher mean bone density in the inferior glenoid.

Our findings of decreased bone density at the reamed glenoid bone surface are consistent with clinical findings of increased complication rates when treating B2 glenoids

with TSA. Intermediate clinical followups (averaging 77 months) showed that TSAs on B2 glenoids resulted in greater than 20% loosening of the glenoid component [26]. In particular, subsidence and posterior tilting of the glenoid component were associated with eccentric reaming [26]. By simulating a medially directed glenohumeral contact load, a finite element study suggested a linear correlation between increased risk for cement failure and the amount of trabecular bone exposure after version correction [27]. We found a reduction of 200 HUs in the anterior glenoid at 10° and 15° version corrections, which may explain the high incidence of subsidence of the glenoid component attributable to crushing of the weak anterior bone after eccentric reaming. In addition to compromised bone strength in the reamed anterior glenoid, recurrence of a posteriorly directed glenohumeral contact load [26] and the rocking horse loading pattern experienced by the TSA glenoid component [7, 27] may further increase the risk of glenoid component loosening in B2 glenoids. Although we only found asymmetric reduction of bone density in the first 2 mm of bone beneath the reamed fixation surface, compromised bone strength at the reamed glenoid surface may initiate loosening of the TSA glenoid.

Previous computational studies suggested a version correction limit of 12° to 18° of glenoid retroversion by only considering glenoid vault penetration by the glenoid component pegs [7, 17, 27]. However, one of those studies used a cadaveric shoulder without any macroscopic or radiologic signs of disease for the computational modeling of TSA [7]; other studies did not specifically study the sclerotic type of B2 glenoids [17, 27]. Our results showed specifically that bone quality tradeoffs in Walch type B2 glenoids begin as low as 10° version correction. Although greater than 10° version correction is often necessary to achieve centralized glenohumeral contact, increased eccentric reaming will result in unbalanced bone strength adjacent to the reamed glenoid surface. Considering the tradeoffs between more-centralized glenohumeral alignment and the bone strength adjacent to the implant fixation surface, our study suggests that a version correction limit of 10° should be considered.

In addition to potentially compromised bone quality in the B2 glenoid, substantial bone resection at high version correction angles may result in medialization of the glenohumeral center of rotation after TSA, which may create slackness in the glenohumeral capsule and rotator cuff muscles. Future studies may consider the medialization of glenohumeral center of rotation to investigate the effect of eccentric reaming on shoulder stability.

Through simulations of eccentric reaming on CT-reconstructed type B2 glenoids, we showed quantitatively that eccentric reaming with increased version correction resulted in more asymmetric bone resections, which

consequently led to reductions of bone quality in the anterosuperior subregions of the first 2 mm of the bone bed beneath the reamed fixation surface of B2 glenoids. A version correction angle as low as 10° resulted in reductions of bone density. We developed a methodology to describe and analyze the spatial distribution of high-density bone in a cohort of B2 glenoids after simulated eccentric reaming. According to the spatial distribution maps of high-quality bone, we were able to elucidate a general trend of decreased frequency of high-quality bone in the anterior glenoid with increased version correction. This trend was most prominent in the first 2 mm of bone beneath the reamed fixation surface, supporting findings from other investigators [2, 4, 12, 15, 21, 28]. This cohort-based analysis of spatial variations of high-density bone provides a means to perceive the generalized bone quality variations of a B2 glenoid after surgical interventions. Future work will be able to advance these approaches toward developing a generalized finite element model, with cohort-based bone quality distributions, for analysis of implant fixation in B2 glenoids.

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