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Three-Dimensional Scapular Border Method for Glenoid Version Measurements

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Background: Variations among methods to measure glenoid version have created uncertainty regarding which method provides the most consistent measurements of morphology. Greater deformity may also make accurate depiction of the native morphology more challenging. This study examined 4 current methods (Friedman, corrected Friedman, Ganapathi-Iannotti, and Matsumura) and an experimental scapular border-derived coordinate system method, to compare measurement inconsistencies between methods and reference systems and assess the impact of glenoid deformity on measured glenoid version.

Methods: Three-dimensional scapulae were created from computed tomography (CT) scans of 74 shoulders that had undergone arthroplasty (28 A2, 22 B2, 10 B3, and 14 C glenoids) and 34 shoulders that had not undergone arthroplasty. Glenoid version measurements were made in Mimics using the 4 methods. For the experimental method, scapulae were reconstructed, and 3 orthogonal global coordinate planes (GCPs) were derived from the medial and lateral borders. Version was measured as the angle between the sagittal reference plane and an anterior-posterior glenoid vector. The intraclass correlation coefficient (ICC) was calculated for the Friedman and corrected Friedman methods. Inconsistencies were assessed for all methods using the interquartile range, mean and standard deviation, and repeated-measures analysis of variance. Concordance correlation coefficients (CCCs) were calculated to assess agreement among the methods.

Results: Scapular plane-based methods (experimental, Friedman, and corrected Friedman) yielded an average version between $-10°$ and $-12°$, with average measurement differences among these methods of $<2°$. Vault methods (Ganapathi-Iannotti and Matsumura) overestimated or underestimated version by an average of 5° to 7° compared with scapular plane-based methods, and showed significant differences of $>12°$ when compared with each other. Scapular plane-based methods maintained consistency with increasing deformity.

Conclusions: The other methods of version measurement using the scapular planes as the reference were highly comparable with the corrected Friedman method. However, when the reference plane was the glenoid vault, version measurements were inconsistent with scapular plane-based methods, which is attributed to differences in the reference systems. In surgical planning, the coordinate system utilized will impact version measurements, which can result in variations in the planned surgical solutions. Additionally, as glenoid deformity increases, this variation resulting from the utilization of different coordinate systems is magnified.

An accurate understanding of premorbid glenoid morphology is imperative for glenoid component placement in shoulder arthroplasty. Even small discrepancies in glenoid version correction have implications with respect to shoulder stability, postoperative biomechanics, and implant loosening[1-6]. Several 2D and 3D methods using computed tomography (CT) scans have improved the accuracy and reliability of glenoid version measurements, but have certain limitations.

Friedman et al. described the first method using a line defined by the scapular spine and the center of the glenoid (the Friedman line) on 2D CT rather than a line defined using the scapular body[7,8]. However, this simplistic method does not account for the orientation of the CT image, causing unwarranted variability in version measurements. The corrected Friedman method, using a scapular plane derived from 3 points, was designed to reduce inconsistencies by correcting images to their "true" axial positioning[9-15].

Two-dimensional vault-based methods using either a glenoid vault line (Matsumura method) or a vault triangle (Poon-Ting method) often overestimate glenoid retroversion[16,17]. Additional methods using a glenoid sphere (Lewis-Armstrong method) or ellipse have improved accuracy and subjectivity by automating the definition of the glenoid center, but remain limited by their reliance on a reference plane defined by the

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grader[18,19]. A 3D glenoid vault implant can be used for measuring pathological and native glenoid version, as described by Codsi et al. (Ganapathi-Iannotti method)[20-22]. The Ganapathi-Iannotti method improves on the limitations of the 2D vault methods by eliminating use of the reference plane in the version measurement, but remains subjective because of the need for accurate placement of a glenoid line[22].

Several of these methods are likely utilized in surgical planning platforms; however, research has shown measurement inconsistencies among platforms using different software[23-25]. Webb et al. emphasized that differences in reference systems, glenoid deformity, presence of osteophytes, labral calcifications, and CT artifacts are all key contributors to morphological measurement inconsistencies[25]. While there is no consensus on the method used to measure glenoid version, discrepancies among current methods have necessitated a more precise method for understanding native glenoid morphology.

This research presents an experimental 3D method using the medial and lateral borders of the scapula to determine the degree of glenoid version in patients with and without primary osteoarthritis (OA). The proposed method was compared with the Friedman, corrected Friedman, Ganapathi-Iannotti, and Matsumura methods to assess whether it could reliably define version angles. The primary objective was to evaluate the inconsistencies of version measurements between methods and reference systems. The secondary objective was to evaluate the effect of glenoid deformity on the inconsistencies of version measurements. The hypotheses were that (1) there would be significant inconsistencies between version methods, (2) measurement inconsistencies would be greater between methods utilizing different reference systems, (3) inconsistencies would be greater in glenoids with OA than in those without OA, and (4) inconsistencies between methods would be dependent on the glenoid wear pattern.

Materials and Methods

Study Criteria and Cohort

Patient files and preoperative shoulder CT scans were acquired from the registry of a fellowship-trained upper-extremity surgeon (M.A.F.) and screened on the basis of primary and secondary criteria for inclusion in the study group of shoulders with OA. Primary criteria included a patient age of ≥18 years, an OA diagnosis, primary elective total or reverse shoulder arthroplasty, and no detectable scapular or humeral fractures (acute or previous) or previous shoulder surgeries. Secondary criteria

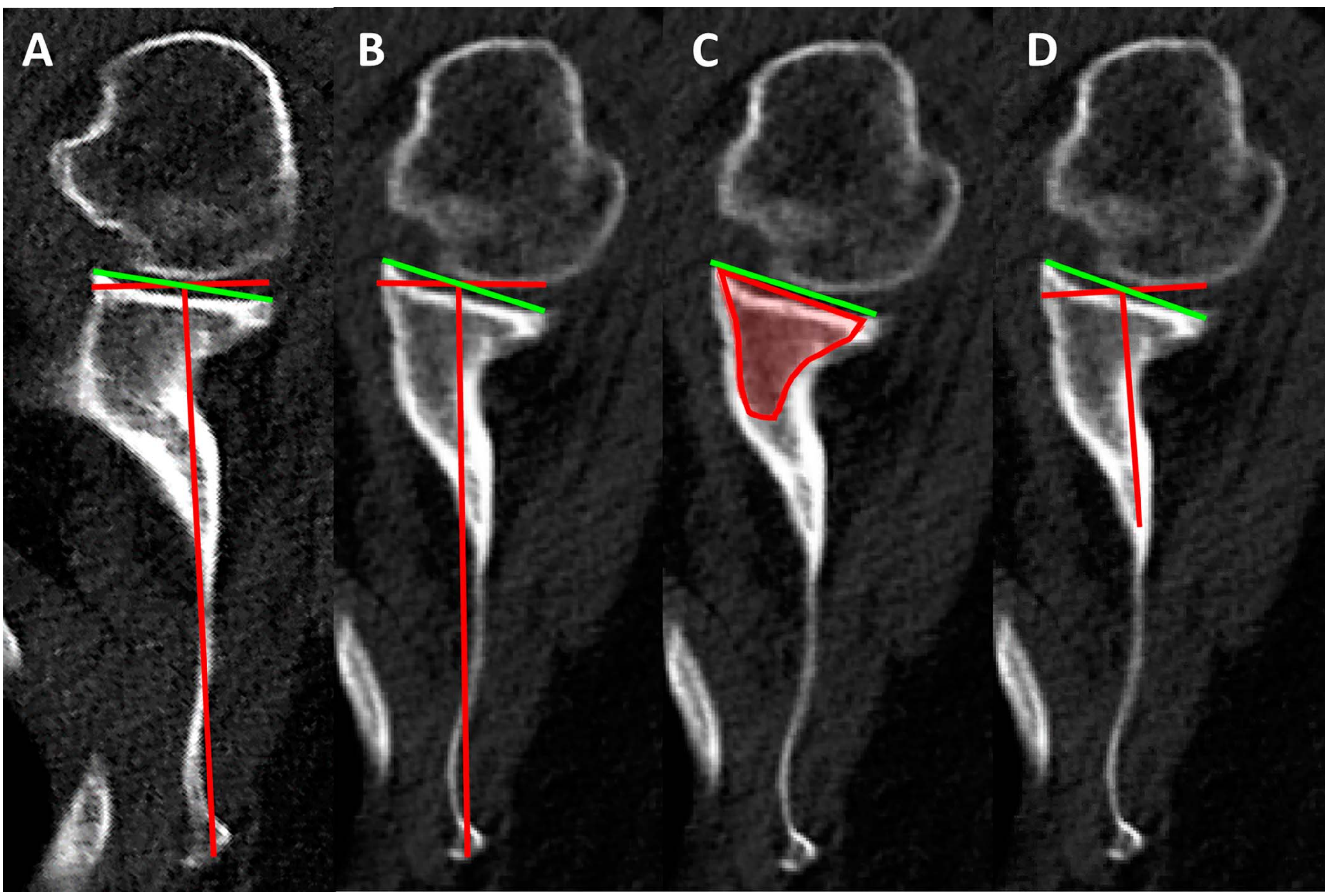

Fig. 1

Glenoid version measurements in Mimics software using the Friedman (**Fig.1-A**), corrected Friedman (**Fig. 1-B**), Ganapathi-Iannotti (**Fig. 1-C**), and Matsumura (**Fig. 1-D**) methods.

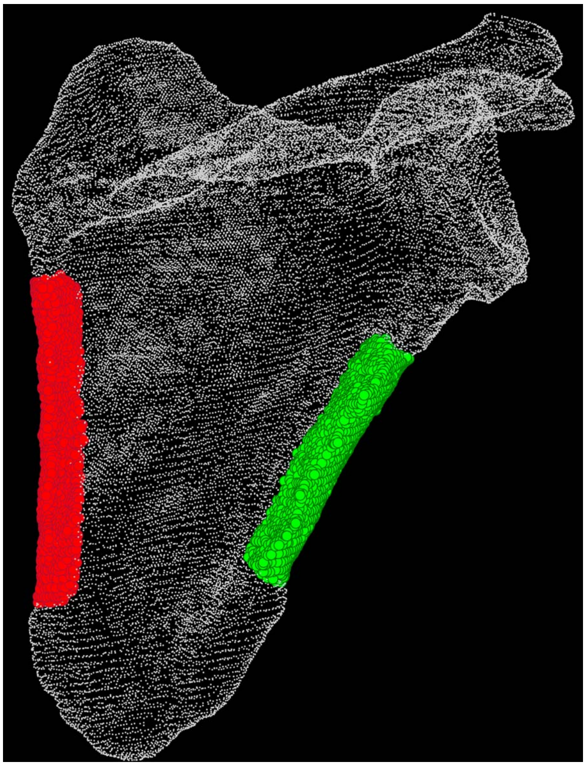

Fig. 2

The experimental method. Scapular point cloud with extracted medial and lateral borders reconstructed in MATLAB.

included preoperative CT scans with no metal artifacts or scapular truncation, and a Walch glenoid classification of type A2, B2, B3, or C. Walch types A1 and B1 were excluded from the study because such groups exhibit minimal glenoid erosion.

In addition, patient files were screened for the following criteria for inclusion in the non-OA comparison group: a patient age of ≥18 years; absence of OA, with no articular cartilage degeneration and no diagnosis of inflammatory, post-infectious, or posttraumatic arthritis; and no detectable scapular or humeral fracture (acute or previous) or previous shoulder surgeries. Scans were further evaluated and excluded if they exhibited scapular truncation or metal artifacts.

Consequently, a set of 74 preoperative CT scans of shoulders with OA and 34 preoperative CT scans of shoulders exhibiting no visible signs of OA were included. The shoulders in the OA group were further grouped according to their Walch classification (28 A2, 22 B2, 10 B3, and 14 C) by a postgraduate year-3 resident and confirmed by the fellowship-trained upper-extremity surgeon[26,27].

Image Reconstructions and 3D Modeling

DICOM (Digital Imaging and Communications in Medicine) files for each patient were loaded in Mimics software (version 14.0; Materialise), and complete 3D scapulae were rendered using a slice thickness of 1.25 mm. Glenoid version measurements were calculated using the Friedman, corrected Friedman, Ganapathi-Iannotti, Matsumura, and experimental methods[7,16,22,28].

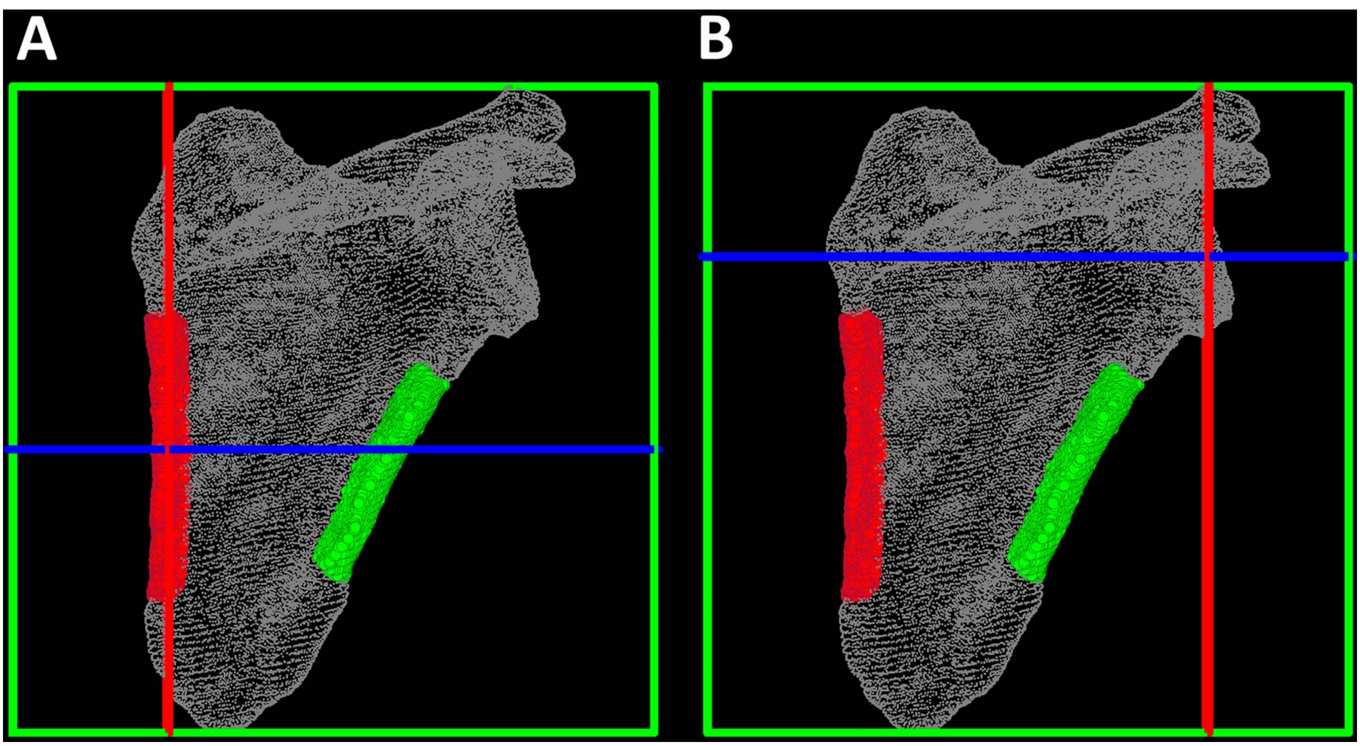

Fig. 3

The experimental method. **Fig. 3-A** Coronal view of the global coordinate planes (GCPs) positioned at the center of the medial border and extending along the length of the scapular spine. **Fig. 3-B** Coronal view of the reference coordinate system produced by translation of the GCPs to the center of the glenoid fossa.

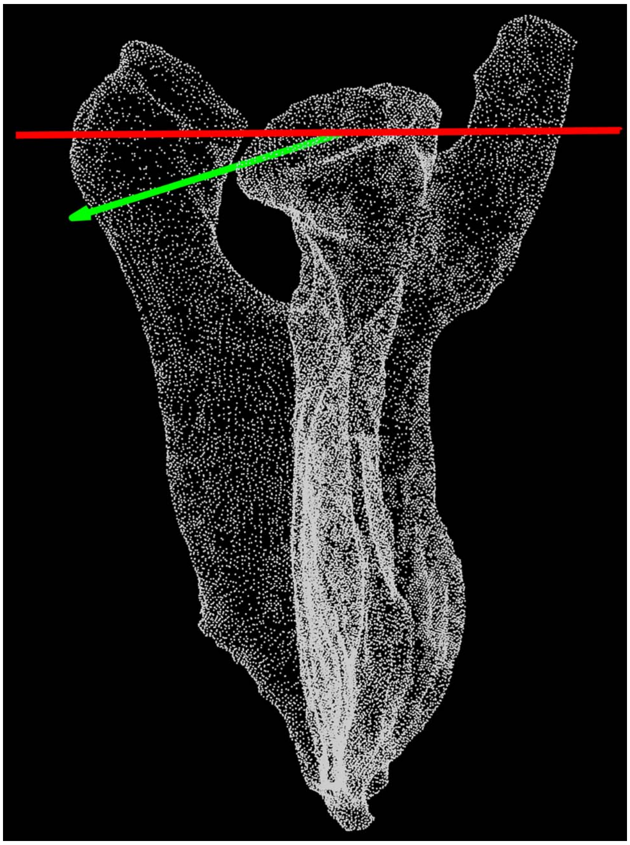

Fig. 4
The experimental method. Transverse view showing glenoid version measurement as the angle formed between the sagittal reference plane and the anterior-posterior glenoid vector. Glenoid lines extending medially from the reference plane denote retroversion, and angles extending laterally denote anteversion.

Friedman Method

Version measurements were obtained according to the methodology of Friedman et al.[7]. For each scapula, a mid-glenoid axial image was selected for measurement, and a glenoid line connecting the anterior and posterior cortices was drawn. The Friedman line was drawn from the medial tip of the scapular spine to bisect the glenoid line. Version was measured as the posterior-side acute angle between the glenoid line and a reference line normal to the Friedman line (Fig. 1-A). Version angles were positive (anteversion) if the glenoid line was lateralized relative to the reference line, and negative (retroversion) if it was medialized.

Corrected Friedman Method

Version measurements were obtained according to the corrected Friedman method (correction of the CT orientation using a 3D multiplanar reslice)[7,28]. Three points were selected for the reslice: the scapula trigonum, inferior pole, and approximated glenoid center[9,15,16,22,28-30]. A mid-glenoid axial image was selected after reslicing, and glenoid, Friedman, and reference lines were drawn. Version was recorded as the posterior-side acute angle between the glenoid and reference lines (Fig. 1-B).

Ganapathi-Iannotti Method

Three-dimensional vault models were scaled and positioned for each 3D scapula following the published methodology for the Ganapathi-Iannotti method[20-22,31-33]. Using the previously defined CT reslice, axial image, and glenoid line, a vault line was drawn across the lateral vault surface. A reference line was drawn at the center of the glenoid line and parallel to the vault line. Version was recorded as the posterior-side acute angle between the glenoid and reference lines (Fig. 1-C)[20,22,29].

Matsumura Method

Version measurements were obtained following the methodology of Matsumura et al.[16]. Using the previously defined CT reslice, axial image, and glenoid line, a vault line was drawn from the medial apex of the glenoid vault and bisecting the glenoid line. A reference line was drawn perpendicular to the vault line. Version was measured as the posterior-side acute angle between the glenoid and reference lines (Fig. 1-D).

Experimental Method

For the experimental method, 3D scapulae were exported as point clouds and loaded into custom-written software for precise volumetric segmentation. The interior glenoid fossa and the medial and lateral borders were extracted. Scapulae and extracted point cloud files were reconstructed in MATLAB (R2020b; MathWorks), and left scapulae were mirrored to right scapulae (Fig. 2). Principal component analysis was used to define the glenoid centroid and sets of 3D vectors in the inferior-superior, anterior-posterior, and medial-lateral directions representing the orientations of the medial and lateral borders of the scapula. Three orthogonal global coordinate planes (GCPs) were derived, using the vectors of the medial and lateral borders, and were positioned at the center of the medial border along the scapular spine (Fig. 3-A). The GCPs were translated to the glenoid center to produce a reference coordinate system for version measurements (Fig. 3-B). Glenoid version was calculated as the posterior-side acute angle between the sagittal reference plane and the anterior-posterior glenoid vector (Fig. 4).

Statistical Analysis

An a priori power analysis was performed in G*Power software (version 3.1.9.4; Heinrich Heine Universität Düsseldorf) using an F test for within-factors repeated-measures analysis of variance (ANOVA). Using a Cohen effect size of 0.16 and type-1 and type-2 error probabilities of 0.05, the minimum sample size needed was calculated to be 100 patients[28].

Two observers assessed glenoid version using the Friedman and corrected Friedman methods. For each method, the interrater reliability of the measurements was assessed by the intraclass correlation coefficient (ICC) and its 95% confidence interval (CI), calculated with 2-way mixed effects for consistency[34,35]. An ICC of <0.5 was considered to indicate poor reliability; 0.5 to 0.75, moderate; >0.75 to 0.9, good; and >0.9, excellent[35]. The interquartile range width (IQR), mean and standard deviation (SD), and repeated-measures

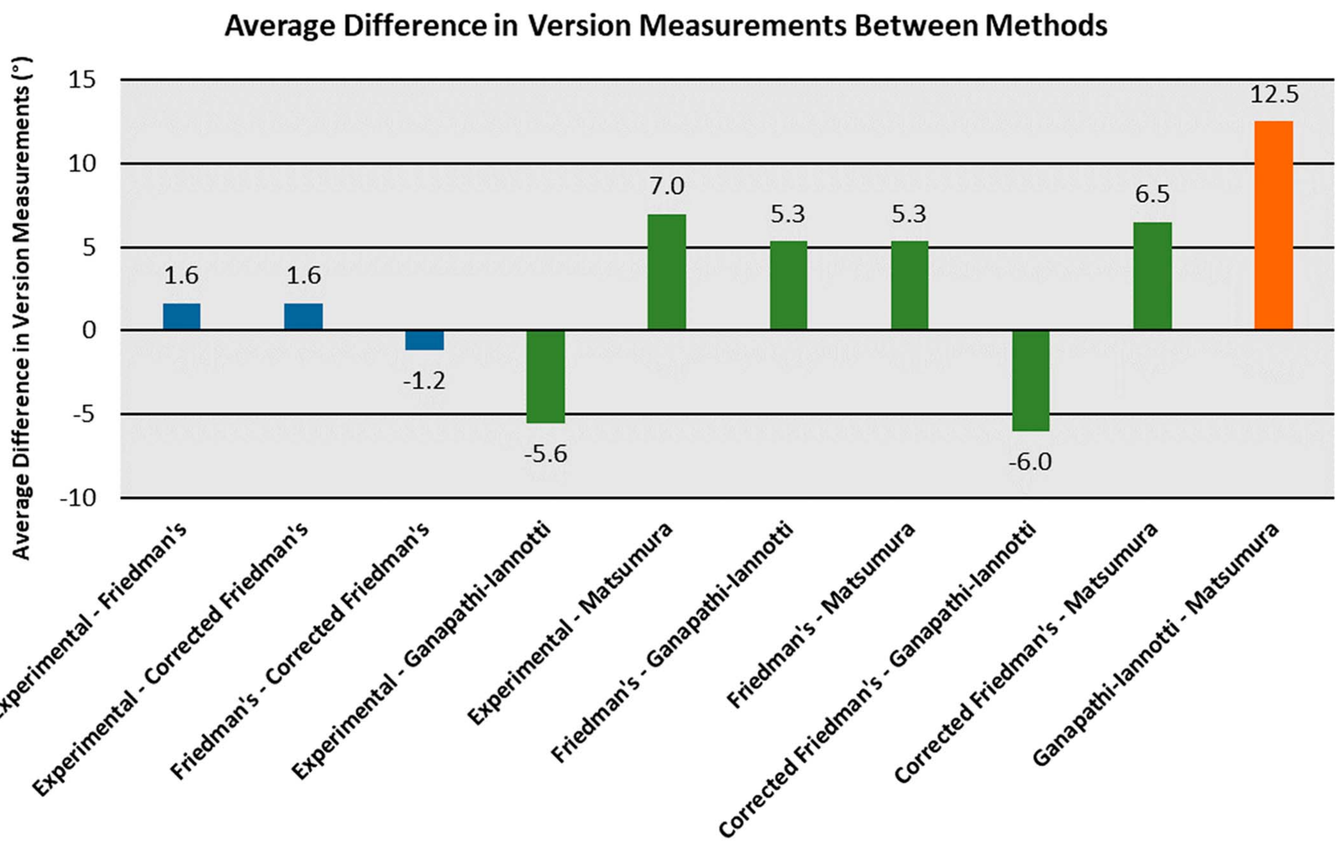

Fig. 5

Average differences in version measurements between pairs of methods, grouped according to the compared reference systems: blue = SPBA versus SPBA, green = SPBA versus vault, orange = vault versus vault.

ANOVA were analyzed for all groups and methods. Agreement between pairs of methods was evaluated using the concordance correlation coefficient (CCC), which was reported with its 95% CI[36-38], and the average differences between the version measurements made with those methods were computed (Fig. 5). A p value of <0.05 was considered significant. Statistical analyses were performed using SPSS (version 26; IBM) and Excel (Microsoft).

Source of Funding

No external funding was received for this study.

Results

Comparison of the measurements by the 2 raters revealed moderate to excellent reliability for the Friedman method (ICC = 0.57 to 0.91) and good to excellent reliability for the corrected Friedman method (ICC = 0.87 to 0.96) (Table I).

Inconsistency of Version Measurements Between Methods and Reference Systems

The inconsistency within a method was highest (IQR = 17.2°) for the corrected Friedman method and lowest (IQR = 11.4°) for the Ganapathi-Iannotti method (Table II). The scapular plane-based methods (SPBAs; namely the experimental, Friedman, and corrected Friedman methods) yielded a mean of 10° to 12° of retroversion. Compared with this, the vault methods (Ganapathi-Iannotti and Matsumura) overestimated or underestimated the version by an average of 5° to 7° (Table III). The highest concordance (CCC = 0.96; 95% CI = 0.93 to 0.97) was between the experimental and corrected Friedman methods, and

TABLE I ICC Analysis of Consistency Between 2 Observers*

Version Method	Non-OA Group	A2 Glenoids	B2 Glenoids	B3 Glenoids	C Glenoids
Friedman	0.85 (0.70 to 0.93)	0.57 (0.07 to 0.80)	0.91 (0.79 to 0.96)	0.88 (0.53 to 0.97)	0.88 (0.63 to 0.96)
Corrected Friedman	0.89 (0.78 to 0.94)	0.87 (0.71 to 0.94)	0.92 (0.80 to 0.97)	0.87 (0.48 to 0.97)	0.96 (0.88 to 0.99)

*The values are given as the ICC with the 95% CI in parentheses, calculated using 2-way mixed effects. N = 34 for the non-OA group, 28 for the A2 glenoid group, 22 for the B2 group, 10 for the B3 group, and 14 for the C group.

TABLE II IQRs of Version Angle Measurements by Method and Glenoid Type*

Version Method	All	Non-OA	A2	B2	B3	C
Experimental	16.4	7.2	8.1	7.4	8.2	11.0
Friedman	14.5	4.4	9.6	6.1	8.3	12.7
Corrected Friedman	17.2	5.8	9.1	11.1	7.6	11.8
Ganapathi-Iannotti	11.4	10.7	10.6	9.0	5.2	14.1
Matsumura	14.6	4.5	10.8	10.8	11.8	11.3

*The values are given as the IQR width in degrees. N = 108 for the entire cohort, 34 for the non-OA group, 28 for the A2 glenoid group, 22 for the B2 group, 10 for the B3 group, and 14 for the C group.

the lowest concordance (CCC = 0.40; 95% CI = 0.29 to 0.49) was between the 2 vault methods (Table IV).

A comparison of the reference systems revealed mean version differences of <2° between individual SPBAs, 5° to 7° between individual SPBA and vault methods, and >12° between the 2 vault methods (Fig. 5). The greatest agreement in version measurements was between individual SPBAs (CCC = 0.86 to 0.96) (Table IV). SPBA measurements showed greater discordance with the Ganapathi-Iannotti method (CCC = 0.54 to 0.59) than with the Matsumura method (CCC = 0.72 to 0.77).

Effect of Glenoid Deformity on the Inconsistency of Version Measurements

When the individual glenoid types were compared with the glenoids without OA (Table II), inconsistency (as indicated by the width of the IQR) was greater in the presence of deformity for the experimental (by 0.2° to 3.8°), Friedman (1.7° to 8.3°), corrected Friedman (1.8° to 6°), and Matsumura (6.3° to 7.3°) methods. The Ganapathi-Iannotti method demonstrated greater inconsistency for C glenoids (by 3.4°) and less inconsistency for A2 (0.1°), B2 (1.7°), and B3 (5.5°) glenoids. Inconsistency showed a dependency on the wear pattern among the more retroverted glenoid types, specifically B2, B3, and C, for the experimental (IQR = 7.4° to 11.0°) and Friedman (IQR = 6.1° to 12.7°) methods. The remaining version methods did not exhibit the same pattern.

The SPBAs yielded a mean retroversion of 3° to 4° for the non-OA glenoid group and 2° to 31° for the OA group overall; values for the individual glenoid types (including the non-OA group) differed <5° among the 3 SPBAs. Compared with the SPBA methods, the Ganapathi-Iannotti vault method underestimated version by 5° to 6° for non-OA glenoids and 1° to 14° for the individual osteoarthritic glenoid types, whereas the Matsumura vault method overestimated version by 7° to 8° for non-OA glenoids and 3° to 8° for the osteoarthritic glenoid types (Table III).

Repeated-measures ANOVA indicated that the vault methods were significantly different from all SPBAs for non-OA ($p < 0.001$), B2 ($p \le 0.009$), and B3 glenoids ($p \le 0.040$). Additionally, the Matsumura method was significantly different from all SPBAs ($p \le 0.004$) for A2 glenoids and from the experimental and corrected Friedman methods ($p < 0.001$) for C glenoids. The Ganapathi-Iannotti method was significantly different from all SPBAs ($p \le 0.001$) for C glenoids and from the Friedman method ($p = 0.019$) for A2 glenoids.

An analysis of the CCCs showed that the experimental and corrected Friedman methods exhibited the highest and most consistent agreement among version methods (CCC = 0.79 to 0.86) (Table V). Furthermore, the Ganapathi-Iannotti method had the lowest concordance when compared with the Friedman method for non-OA glenoids (CCC = 0.01), with the Matsumura method for A2 (CCC = 0.16) and C (CCC = 0.16) glenoids, and with the experimental method for B2 (CCC = −0.02) and B3 (CCC = 0.05) glenoids.

Discussion

Understanding the variation in glenoid deformity shapes in degenerative shoulder diseases provides insight into the pathophysiology of these acquired disorders. Additionally, outcomes of shoulder arthroplasty are highly dependent on accurately defining glenoid morphology. The introduction of surgical planning software could theoretically provide a clinical benefit if it permits developing a surgical strategy that will ideally balance the glenohumeral articulation even in shoulders with asymmetric acquired bone loss. Implicit in this method is an agreed-upon reference for defining various degrees of deformity. This study assessed the concordance and variability of a newly devised method for measuring a glenoid morphological feature, version, with those of 4 existing methods.

TABLE III Mean Version Angle Measurements by Method and Glenoid Type*

Version Method	All	Non-OA	A2	B2	B3	C
Experimental	−10.2 ± 10.7	−3.6 ± 5.4	−1.5 ± 5.4	−17.2 ± 6.1	−18.9 ± 6.8	−25.7 ± 6.5
Friedman	−11.8 ± 11.7	−3.2 ± 4.5	−4.9 ± 7.1	−18.8 ± 6.9	−17.8 ± 6.5	−31.0 ± 8.1
Corrected Friedman	−10.6 ± 11.2	−3.6 ± 4.7	−1.9 ± 5.1	−18.1 ± 6.7	−18.2 ± 6.6	−27.9 ± 8.3
Ganapathi-Iannotti	−4.6 ± 9.3	1.9 ± 5.8	−0.7 ± 6.8	−9.9 ± 7.5	−8.0 ± 3.4	−17.3 ± 8.1
Matsumura	−17.1 ± 10.5	−11.0 ± 4.0	−9.0 ± 6.0	−23.8 ± 6.3	−22.9 ± 7.2	−33.5 ± 8.2

*The values are given as the mean and SD in degrees. N = 108 for the entire cohort, 34 for the non-OA group, 28 for the A2 glenoid group, 22 for the B2 group, 10 for the B3 group, and 14 for the C group.

TABLE IV Concordance Between Methods in Entire Cohort

Method Pairs	CCC (95% CI)
SPBA vs. SPBA	
Experimental vs. Friedman	0.86 (0.80 to 0.91)
Experimental vs. corrected Friedman	0.96 (0.93 to 0.97)
Friedman vs. corrected Friedman	0.90 (0.85 to 0.94)
SPBA vs. vault	
Experimental vs. Ganapathi-Iannotti	0.58 (0.44 to 0.69)
Experimental vs. Matsumura	0.72 (0.62 to 0.79)
Friedman vs. Ganapathi-Iannotti	0.54 (0.40 to 0.65)
Friedman vs. Matsumura	0.75 (0.65 to 0.82)
Corrected Friedman vs. Ganapathi-Iannotti	0.59 (0.46 to 0.69)
Corrected Friedman vs. Matsumura	0.77 (0.69 to 0.83)
Vault vs. vault	
Ganapathi-Iannotti vs. Matsumura	0.40 (0.29 to 0.49)

This study partially confirmed the first hypothesis, that significant inconsistency exists between version methods. Vault method measurements were significantly different from SPBAs for most glenoid types. SPBAs yielded a mean retroversion of 10° to 12°; compared with these SPBA-based values, version was underestimated using the Ganapathi-Iannotti method and overestimated using the Matsumura method by an average of 5° to 7°.

The second hypothesis, that measurement inconsistencies were greater between methods utilizing different reference systems, was also confirmed. SPBAs use a similar methodology (the scapular plane) for the reference system, as highlighted in Figures 6-A and 6-B, contributing to the <2° observed differences in mean version among the SPBA methods in the overall cohort. There was greater discordance between measurements using SPBAs and vault methods (5° to 7° differences), but this was notably less than the discordance observed between vault methods (>12° difference). The 2 vault methods utilize diverse reference methods. The Ganapathi-Iannotti method relies on appropriate scaling and positioning of a novel vault implant (Fig. 6-C), but observed inconsistencies may be attributed to gender-related scalability issues. Merrill et al. discussed significant differences in height-to-width ratio, anterior glenoid notch location, and depth between males and females[39]. The Matsumura method relies on the position of the medial vault apex; however, vault anatomy is slightly retroverted in both normal and arthritic shoulders, accounting for the greater retroversion calculated using this method[16]. The greater differences between the experimental and existing methods for B-type

TABLE V Concordance Between Methods by Glenoid Type*

Method Pairs	Non-OA	A2	B2	B3	C
SPBA vs. SPBA					
Experimental vs. Friedman	0.80 (0.64 to 0.89)	0.42 (0.12 to 0.65)	0.56 (0.2 to 0.78)	0.52 (−0.11 to 0.85)	0.58 (0.23 to 0.8)
Experimental vs. corrected Friedman	0.86 (0.75 to 0.93)	0.86 (0.72 to 0.93)	0.85 (0.67 to 0.93)	0.84 (0.48 to 0.96)	0.79 (0.52 to 0.92)
Friedman vs. corrected Friedman	0.77 (0.58 to 0.88)	0.46 (0.17 to 0.68)	0.71 (0.42 to 0.87)	0.81 (0.42 to 0.95)	0.75 (0.42 to 0.91)
SPBA vs. vault					
Experimental vs. Ganapathi-Iannotti	0.13 (−0.1 to 0.35)	0.36 (0.01 to 0.63)	−0.02 (−0.28 to 0.24)	0.05 (−0.12 to 0.21)	0.33 (0.01 to 0.59)
Experimental vs. Matsumura	0.1 (−0.05 to 0.25)	0.32 (0.12 to 0.49)	0.42 (0.15 to 0.63)	0.61 (0.12 to 0.86)	0.5 (0.21 to 0.71)
Friedman vs. Ganapathi-Iannotti	0.01 (−0.21 to 0.22)	0.17 (−0.15 to 0.46)	0.07 (−0.17 to 0.31)	0.08 (−0.11 to 0.27)	0.19 (−0.04 to 0.4)
Friedman vs. Matsumura	0.11 (−0.02 to 0.23)	0.37 (0.07 to 0.61)	0.19 (−0.14 to 0.49)	0.59 (0.14 to 0.83)	0.73 (0.37 to 0.9)
Corrected Friedman vs. Ganapathi-Iannotti	0.10 (−0.11 to 0.31)	0.32 (−0.03 to 0.6)	0.06 (−0.2 to 0.31)	0.09 (−0.1 to 0.28)	0.31 (0 to 0.56)
Corrected Friedman vs. Matsumura	0.17 (0.03 to 0.3)	0.31 (0.1 to 0.49)	0.51 (0.24 to 0.71)	0.74 (0.42 to 0.9)	0.76 (0.54 to 0.89)
Vault vs. vault					
Ganapathi-Iannotti vs. Matsumura	0.06 (−0.01 to 0.14)	0.16 (−0.05 to 0.36)	0.1 (−0.04 to 0.24)	0.07 (−0.05 to 0.18)	0.16 (−0.03 to 0.34)

*The values are given as the CCC with the 95% CI in parentheses. N = 34 for the non-OA group, 28 for the A2 glenoid group, 22 for the B2 group, 10 for the B3 group, and 14 for the C group.

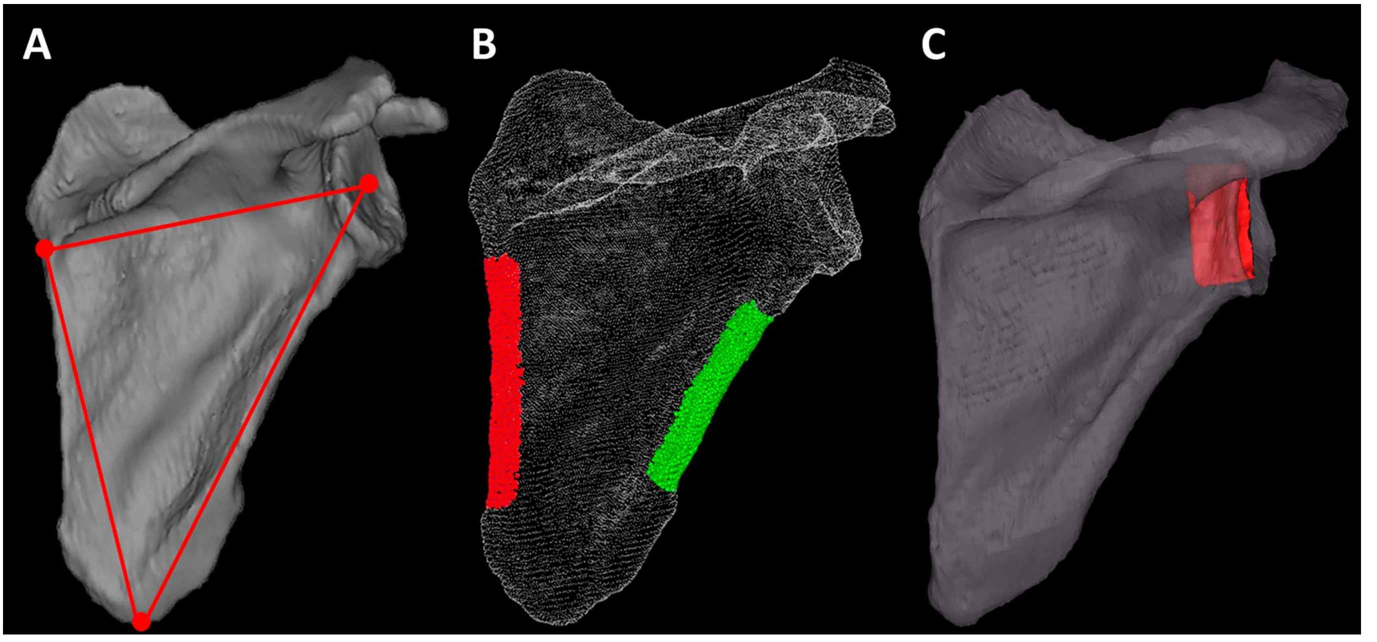

Fig. 6

Overview of selected reference systems. **Fig. 6-A** The corrected Friedman method is an SPBA that uses a 3-point reslice through a selection of points at the estimated glenoid center, scapula trigonum, and inferior pole to correct the CT orientation and define a scapular plane for version measurements. **Fig. 6-B** The experimental method is an SPBA that uses the medial and lateral borders to define a scapular plane for version measurements. **Fig. 6-C** The Ganapathi-Iannotti vault method uses a scaled and positioned 3D vault model for version measurements.

glenoids may be attributed to morphology. The experimental method utilizes the interior glenoid fossa, which will not contain osteophytes, whereas version measurements using existing methods may vary depending on the placement of the glenoid line if an osteophyte is present. These findings agree with research by Webb et al. that reference system differences and the presence of osteophytes contribute to measurement inconsistencies[25].

Moreover, the results of this study are consistent with previous findings that CT scan orientation impacts measurement inconsistency[9-15]. Version measurements using the Friedman method differed by 0.4° to 5.3° relative to other SPBAs in the individual groups. Table IV showed lower agreement between the Friedman method and the other 2 SPBAs (CCC = 0.86 to 0.90) than between the 2 SPBAs using the corrected orientation (CCC = 0.96), and this was also noted in the individual groups in Table V.

The third hypothesis, that inconsistency was greater in glenoids with OA than in non-OA glenoids, was largely confirmed. The presence of deformity increased measurement inconsistency for the experimental (by 0.2° to 3.8° compared with the glenoids without OA), Friedman (1.7° to 8.3°), corrected Friedman (1.8° to 6°), and Matsumura (6.3° to 7.3°) methods. The Ganapathi-Iannotti method demonstrated increased inconsistency (by 3.4°) for C glenoids but decreased inconsistencies for A2 (0.1°), B2 (1.7°), and B3 (5.5°) glenoids.

Additionally, agreement among the SPBAs with corrected orientation remained consistent even in the glenoids with the most eccentric bone loss, rather than increasing with increasing bone loss. However, the version measurements for each vault method were inconsistent with the other methods, and the discordance increased with increasing eccentric bone loss.

A clinical implication of this study is that surgical planning software must be used judiciously for the surgical management of glenohumeral arthritis because of the existence of variations between these tools as well as in the surgeon interpretation of the images that are being analyzed.

This study had certain limitations. The retrospective nature of the study resulted in small sample sizes for the B2, B3, and C glenoid subgroups. Use of a multicenter database for future work may help to mitigate this limitation. In addition, there was variability in selection of the images used for the measurements, in selection of the points used for correction of CT scan orientation, and in placement of the glenoid and reference lines (particularly among highly retroverted glenoid subgroups) between observers. In the experimental method, the point cloud extractions used to identify the medial and lateral borders and the glenoid fossa represent a potential additional source of bias, but it is expected to be minor. The third limitation is the use of custom-written software for the point cloud extractions in the experimental method. However, thresholding and segmentation techniques in existing surgical planning software would be feasible alternatives for identifying the borders during clinical use of the experimental method.

In conclusion, use of a novel 3D method based on the medial and lateral borders of the glenoid may improve the accuracy of glenoid version measurements and understanding of the morphology of the native glenoid. This experimental method was able to reliably define the version of the pathological glenoid in 3 dimensions, and the resulting measurements were highly comparable with those obtained with the corrected Friedman method. This study also compared numerous methods and found that the measurement inconsistencies among them could be attributed to differences in reference systems and CT orientation and could depend on the extent of glenoid deformity. It demonstrated that the most consistent version measurements were provided by the methods based on the scapular plane, such as the study's experimental method and the corrected Friedman method. Thus, accurate depiction of morphology for surgical planning may be achieved using any of those methods. ■

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