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Does commercially available shoulder arthroplasty preoperative planning software agree with surgeon measurements of version, inclination, and subluxation?

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Background: Preoperative planning with commercially available imaging software in shoulder arthroplasty may allow for improved decision-making and more accurate placement of the glenoid component.
Methods: A total of 81 consecutive shoulder computed tomography scans obtained for preoperative planning purposes for shoulder arthroplasty were analyzed by commercially available software from 4 companies (Blueprint: Wright Medical, Memphis, TN, USA; GPS: Exactech, Gainesville, FL, USA; Materialise: DJO, Vista, CA, USA; and VIP: Arthrex, Naples, FL, USA) and by 5 fellowship-trained sports medicine/shoulder surgeons. Inclination, version, and subluxation of the humerus were measured in a blinded fashion on axial and coronal sequences at the mid-glenoid. Surgeon measurements were analyzed for agreement and were compared with the 4 commercial programs.
Results: Surgeon reliability was acceptable for version (intraclass correlation coefficient [ICC]: 0.876), inclination (ICC: 0.84), and subluxation (ICC: 0.523). Significant differences were found between surgeon and commercial software measurements in version ($P = .03$), inclination ($P = .023$), and subluxation ($P < .001$). Software measurements tended to be more superiorly inclined (average $-2°$ to $2°$ greater), more retroverted (average $2°$-$5°$ greater), and more posteriorly subluxed (average $7°$-$10°$ greater) than surgeon measurements. In comparing imaging software measurements, only Blueprint was found to produce significantly different version measurements than surgeon measurements ($P = .02$).
Conclusion: Preoperative planning software for shoulder arthroplasty has limited agreement in measures of version, inclination, and subluxation measurements, whereas surgeons have high inter-reliability. Surgeons should be cautious when using commercial software planning systems and when comparing publications that use different planning systems to determine preoperative glenoid deformity measurements.
Level of evidence: Basic Science Study; Validation of Computer Modeling

Keywords: Shoulder arthroplasty; preoperative planning software; version; inclination; subluxation; accuracy

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This study was deemed exempt from institutional review board approval (OHR-19).

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Anatomic and reverse shoulder arthroplasty are effective treatment options for many shoulder conditions including glenohumeral arthritis, rotator cuff tear arthropathy, and others.[7,11,18,21] Although results after total shoulder arthroplasty (TSA) and reverse total shoulder arthroplasty (RTSA) have generally been good, there is still significant room for improvement. One recent trend that has emerged in an effort to improve implant positioning and, therefore, potentially clinical outcomes is preoperative planning. The use of this technology allows for treating surgeons to better appreciate variations in glenoid morphology and also produces the opportunity for patient-specific instrumentation (PSI) that provides a more precise method to achieve the goals established with the preoperative plan.[9,15,23,24]

Previous studies have demonstrated reasonable reproducibility of PSI where the final glenoid component is often within 2°-3° of the templated version and inclination.[8,14] In theory, if the preoperative plan is consistent with current evidence-based criteria for ideal glenoid component implantation, the implant should be placed in proper position that correlates to longer-term implant success. However, if the templated preoperative plan is inaccurate, the glenoid component can be placed in inappropriate alignment, or, the actual glenoid procedure may be altered or deviate from current best-practice recommendations. Although surgeon input is necessary to create the final preoperative plan in these various software platforms, many surgeons attempt to follow the templated plan without adjusting intraoperatively. If the software is underestimating or overestimating version, inclination, or subluxation, it is possible to direct the surgeon into improper component placement. Even more concerning is that some surgeons may use these measurements to decide between anatomic and reverse arthroplasty, and thus software that provides accurate measurements is clinically important in determining that patients are getting the proper implant based on current recommendations.

The purpose of this study was to compare measurements of glenoid version and inclination along with humeral head subluxation between fellowship-trained sports and shoulder surgeons and 4 commercially available preoperative planning software programs. The authors hypothesized that based on their own experience, there would be acceptable agreement between surgeon measurements in all parameters, whereas preoperative planning software would overestimate glenoid version and inclination as well as humeral head subluxation.

Methods

Consecutive shoulder computed tomography (CT) scans that were obtained for preoperative planning purposes for primary TSA or RTSA from May 2017 to October 2019 from 3 authors (AAR, EL, MTP) were deidentified and used for this project. A total of 90 preoperative CT scans for TSA and RTSA were deidentified and available for review. Acceptable criteria for the CT scans included a minimum slice thickness of 1 mm, inclusion of the entire scapula, absence of metal in the proximal humerus or glenoid, and acceptance by all planning systems. There were 9 scans that were excluded as they either could not be analyzed by Blueprint (6 scans) or were duplicates (3 scans). This provided a total sample size of 81 scans.

All scans were analyzed using the following software platforms: VIP (Arthrex, Naples, FL, USA), Blueprint (Wright, Memphis, TN, USA), Materialise (DJO, Vista, CA, USA), and GPS (Exactech, Gainesville, FL, USA). All software platforms measured glenoid version and inclination. Only Blueprint and Materialise measure humeral head posterior subluxation with respect to the central axis of the glenoid on an axial view of the glenohumeral joint.

In addition, the 2D corrected CT scans were also measured by 5 fellowship-trained sports medicine/shoulder and elbow surgeons (BJE, PNC, GH, BCW, EL) All measures were based on axial and coronal at the mid-glenoid with images oriented into the plane of the scapula. This technique was previously described by Chalmers et al.[5] One author (BJE) used a 3D reconstruction to orient all CT scans into the plane of the scapula, identified the precise boundaries of the face of the glenoid, and then determined the mid-glenoid slice on both the axial and coronal images (Horos, Geneva, Switzerland). These images were saved and then sent out to all surgeons making measurements. All surgeons used these 2 slices to measure version, inclination, and humeral head subluxation. Glenoid version was measured using the technique described by Friedman, whereas inclination was measured as previously described by Chalmers (Fig. 1).[5,13] Retroversion was recorded as a negative number (eg, 10° of retroversion was recorded as −10°), and superior inclination was recorded as a positive number (eg, 5° of superior inclination was recorded at 5°) (Fig. 2). Humeral head subluxation was calculated as the percentage of the humeral head posterior to Friedman's line, with >50% representing posterior subluxation (Fig. 3).[16] All examiners were blinded to software measurements and the measurements of the other surgeons, and all industry-based software measurements were blinded to surgeon measurements and the measurements from the other commercial software programs.

Measurements from all 5 examiners were compared to determine intraclass correlation coefficients for agreement among surgeons on version and inclination. The measurements for all 5 surgeons were then averaged together, and the mean was compared with the VIP, Blueprint, Materialise, and GPS measurements, respectively. This was performed for glenoid version, inclination, and humeral head subluxation. All of the software programs used in this study provide a calculation for glenoid version and inclination; however, only Blueprint and Materialize provide a subluxation measurement.

Statistics and power analysis

To determine interobserver reliability, we compared between-surgeon measurements using intraclass correlation coefficients with 0.5 selected a priori as the lower limit of acceptability. Descriptive statistics were calculated, and measurements made between methods were compared using both an analysis of variance to examine for significant differences between all groups and

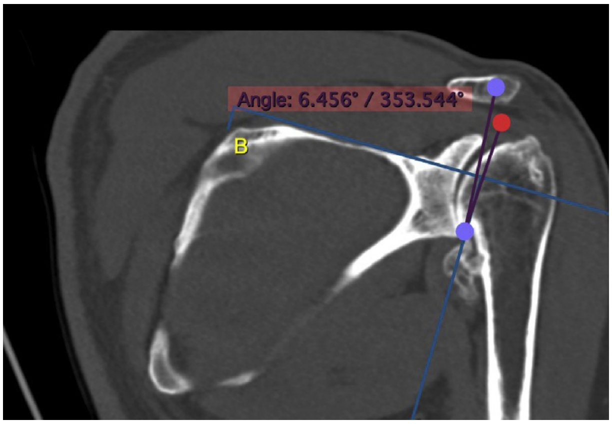

Figure 1 Representative shoulder coronal computed tomography slice oriented in the plane of the scapula used for measurement of glenoid inclination. A line along the supraspinatus fossa was used, and the angle between the perpendicular line to the supraspinatus fossa and a line connecting the superior and inferior portion of the glenoid produced the glenoid inclination measurement.

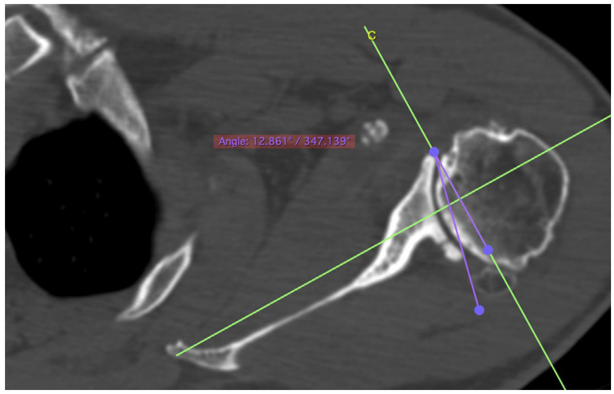

Figure 2 Representative shoulder axial computed tomography slice oriented in the plane of the scapula used for measurement of glenoid version. A line connecting the medial border of the scapula and the mid portion of the glenoid was used, and the angle between a perpendicular line to this glenoid line and a line connecting the anterior and posterior aspects of the glenoid produced the glenoid version measurement.

Tukey's testing to examine for significant differences between each group pairing. All analyses were conducted using Excel 16 (Microsoft, Redmond, WA, USA) and SPSS 25 (IBM, Armonk, NY, USA). An a priori power analysis was conducted and determined that 81 scans would be necessary to have the power to detect a 2° difference in version between groups, should one exist with alpha set at 0.05, assuming a nonnormal distribution of data and using variances from a prior comparative study between measurement methods.[4,5]

Results

Surgeon reliability was found to be acceptable for version, inclination, and subluxation (Table I), suggesting that between-surgeon agreement on the scapula landmarks and technique to calculate the measurement was acceptable.

No significant differences were found between surgeon and computer measurement methods in version ($P = .057$). However, in post hoc testing, there were significant differences between Blueprint and surgeon measurements ($P = .030$) with no significant differences in post hoc testing between VIP and surgeon measurements ($P = .162$), Materialise and surgeon measurements ($P = .264$), or GPS and surgeon measurements ($P = .641$). Generally, software methods produced more retroverted measurements than surgeon measurements (Table II). Differences between average surgeon version measurements and software program measurements are shown in Table III.

Significant differences were found between surgeon and computer measurement methods in inclination ($P < .001$). However, there were no differences between surgeon measurements and any of the individual software groups, with all of the differences being driven between software groups in post hoc testing (Table IV). VIP and Blueprint tended to overestimate inclination by an average of 2° from surgeon measurements, GPS tended to underestimate inclination by 2° from surgeon measurements, and Materialise was almost exactly accurate with surgeon measurements. However, none of these differences reached statistical significance. Differences between average surgeon inclination measurements and software program measurements are shown in Table V.

Significant differences were found between surgeon and computer measurement methods in subluxation ($P < .001$), with significant differences in post hoc testing between each automated measurement method and surgeon measurements (Blueprint vs. Surgeon $P < .001$, Materialise vs. Surgeon $P < .001$). Both automated methods produced more posterior subluxated measurements than surgeon measurements (Table VI).

Discussion

Preoperative planning software for shoulder arthroplasty has become increasingly common among surgeons in an effort to improve an understanding of anatomy and subsequent placement of components during surgery. However, the practice of consistently working through a preoperative plan with a specialized CT scan and commercially available software represents a small minority of shoulder arthroplasty surgeons. When experienced shoulder arthroplasty surgeons have compared the results of their calculations with software programs, or less commonly compared the results of more than 1 software program for the same set of calculations, there has been concern that the results are not exactly the same. The hypotheses of this study were

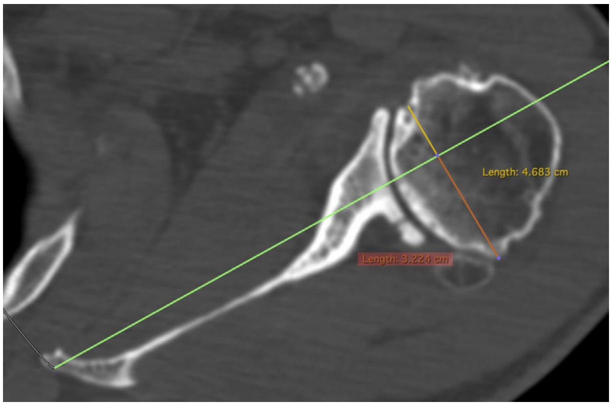

Figure 3 Representative shoulder axial computed tomography slice oriented in the plane of the scapula used for measurement of humeral head subluxation. The diameter (D) of the humeral head was measured, and the distance from the mid portion of the glenoid to the posterior aspect of the humeral head was measured (*d*). These numbers were then divided (*d/D*) and produced the percentage of posterior humeral head subluxation, with 50% noted to be a well-centered head with no significant posterior subluxation.

Table I Between-surgeon reliability statistics

Variable	ICC [95% CI]
Version	0.876 [0.834-0.912]
Inclination	0.84 [0.788-0.885]
Subluxation	0.523 [0.428-0.622]

ICC, intraclass correlation coefficient; *CI*, confidence interval.

confirmed as between-surgeon measurements for version, inclination, and subluxation demonstrated acceptable agreement, whereas preoperative planning software tended to overestimate glenoid version, inclination, and humeral head subluxation.

As the number of shoulder arthroplasties continues to increase, there has been an emphasis on maximizing patient satisfaction and clinical outcomes while minimizing complications.[10,11] The most common site for failure in a TSA and RTSA is the glenoid component.[2,12,20,22] Hence, if complications with the glenoid implant and fixation could be minimized, the long-term survivorship of shoulder arthroplasty procedures would be significantly improved. Preoperative planning for glenoid placement based on a patient's 3D anatomy provides the benefit of potentially improving glenoid placement in TSA and RTSA, more accurately and precisely implanting and fixing the glenoid component in a position that is associated with evidence-based recommendations.[1,19] Currently, 3D CT scans are the gold standard for determining a patient's glenoid anatomy as Kwon et al[17] demonstrated that glenoid measurements made from a 3D CT scan were no different than those made from the cadaver scapula that was scanned with the 3D technology. Chalmers et al[6] found that glenoid inclination could not be accurately measured on radiographs as these tended to underestimate glenoid inclination by an average of 5°. As the preoperative planning technology for shoulder arthroplasty procedures is still relatively new, no studies have definitively shown improved survivorship using a software-derived preoperative plan and subsequent implantation with PSI. Similarly, there is little information regarding the accuracy of various 3D planning software programs in terms of providing measurements that correlate directly to actual scapulae, the algorithms used to produce the calculations, or the correlations to the accepted standard hand measurements by a surgeon.

Denard et al[9] recently evaluated whether glenoid version and inclination obtained from preoperative 3D planning software differed between programs. The authors compared the version and inclination between VIP and Blueprint for 63 consecutive patients undergoing primary shoulder arthroplasty. They found that the average glenoid version using Blueprint was 10.9° compared with 9.3° for VIP ($P = .04$) and that the average glenoid inclination was 9.0° for Blueprint compared with 9.7° for VIP ($P = .463$). Interestingly, when evaluating differences in version, the difference between Blueprint and VIP was less than 5° in 44 patients (69.8%), 5°-10° in 12 patients (19.0%), and greater than 10° in 7 patients (11.1%). With inclination measurements, the difference between Blueprint and VIP was less than 5° in 34 patients (54.0%), 5°-10° in 17 patients (27.0%), and greater than 10° in 12 patients (19.0%). These results were similar to the results in the current study as Blueprint version measurements were significantly greater than the other systems, whereas inclination measurements did not differ significantly between systems.

All systems, however, overestimated version and subluxation when compared with the gold-standard manual measurements. In the current study, when magnitude of difference in measurements between software and surgeons was evaluated, GPS had the most measurements within 5° of surgeon measurements for version (85%) and inclination (79%), whereas Blueprint had the fewest measurements within 5° of surgeon measurements for version (56%) and inclination (65%). The lower agreement between Blueprint and surgeon measurements may be due to differences in the geometrical algorithm and mathematical calculations. VIP, GPS, and Materialise all use anatomic landmarks to determine the plane of the scapula, whereas Blueprint uses an average scapula plane and best-fit sphere. However, it is currently unknown which method better approximates true anatomy and provides potentially a more valuable guide for the best practice of glenoid implantation, both in regard to position of the implant and the selection of the actual implant itself (eg, anatomic vs. reverse). It is unclear if different measurement tools are needed to improve implant selection and alignment. For example, many surgeons believe that correcting glenoid deformity to within −10° of retroversion or less is likely to provide a better long-term

Table II Version measurements

Variable	VIP	Blueprint	Materialise	Exactech	Surgeon
Mean version ± SD (°)	−17 ± 11	−19 ± 12	−17 ± 11	−16 ± 11	−14 ± 10
P value	.23	.03	.36	.641	NA
Mean difference [95% CI] (°)	4 [−1 to 8]	5 [0 to 10]	3 [−2 to 8]	2 [−2 to 7]	NA
Max difference (°)	19	14	11	18	NA

SD, standard deviation; *CI*, confidence interval; *NA*, not applicable; *ANOVA*, analysis of variance.
P values are results from post hoc Tukey's testing with surgeon measurements, overall ANOVA $P = .030$.

Table III Number of studies from each software program that differed from average surgeon version measurement broken down by degree difference in version

Version	VIP	Blueprint	Materialise	GPS
	N (%)	N (%)	N (%)	N (%)
Within 5° of surgeon measurement	49 (61)	45 (56)	61 (75)	69 (85)
Between 5° and 10° of surgeon measurement	26 (32)	23 (28)	15 (19)	10 (12)
Greater than 10° difference from surgeon measurement	6 (7)	13 (16)	5 (6)	2 (3)

outcome. If 1 system overestimates version, especially when the difference is more than 5°-10° in 30% of the cases, this may lead some surgeons to change from an anatomic shoulder replacement to a reverse shoulder replacement. Furthermore, it may lead to decisions regarding augmentation of the glenoid reconstruction either with bone or implant material, complicating the execution of the procedure.

Boileau et al[3] recently performed a study to compare automated 3D glenoid version and inclination measurements (Glenosys; Imascap, Plouzané, France) in 60 osteoarthritic shoulders with several previously described manual and semiautomated glenoid inclination and version methods. The authors used several techniques for measurements including the Friedman version angle on 2D CTs, the Friedman method on 3D multiplanar reconstructions (corrected Friedman method), the Ganapathi-Iannotti and Lewis-Armstrong methods on 3D volumetric reconstructions (for glenoid version), and the Maurer method (for glenoid inclination). Similar to our study, the authors reported excellent intraobserver and interobserver reliability between surgeons who performed these measurements. They found no difference between automated and previously described glenoid version/inclination measurements and concluded that fully automated software for the 3D measurement of glenoid version and inclination in arthritic shoulders was reliable and accurate. These results are remarkably different from the present study as well as other previously published studies where most preoperative planning software tended to overestimate glenoid version and inclination.[5]

Previous studies have assessed the surgeon's ability to translate the preoperative plan to the operating room. Dallalana et al[7] evaluated 20 patients who underwent shoulder arthroplasty (10 TSA and 10 RTSA) using a CT-based PSI system. Patients in the study underwent postoperative CT scans to compare final implanted component position with the preoperatively planned position. The authors found that the PSI reliably placed the glenoid in an appropriate position with an average deviation in glenoid version from the preoperatively planned version of 1.8° (range, 0.1°-7.3°) and average deviation in glenoid inclination from the preoperatively planned inclination of 1.3° (range, 0.2°-4.5°). Similarly, Verborgt et al[23] used postoperative CT to compare final glenoid component version and inclination after RTSA with preoperative templated position in 32 patients who underwent RTSA. The authors found a slightly higher difference in implanted glenoid version and inclination than the previous studies with the mean deviation in baseplate version from the preoperative plan of 4.4° (range, 0.3°-13.7°) and in baseplate inclination of 5.0° (range, 0.1°-14.5°). This is the first study to date to compare surgeon measurements of glenoid version and inclination as well as humeral head subluxation to several preoperative planning software programs.

Although this study found that preoperative planning software tended to overestimate version, inclination, and subluxation, the clinical significance of this finding is unclear. A small amount of variation at the time of surgery in glenoid placement is expected, and the difference in preoperative measurements may or may not be clinically relevant. Future studies evaluating differences in outcomes for patients who underwent shoulder arthroplasty with different preoperative planning software are needed to better answer this question.

Of note, all CT scans measured by the surgeons in this study were oriented in the plane of the scapula before measurements were made. Chalmers et al[4] recently

Table IV Inclination measurements

Variable	VIP	Blueprint	Materialise	Exactech	Surgeon
Mean inclination ± SD (°)	9 ± 5	9 ± 7	7 ± 6	5 ± 5	7 ± 6
P value	.432	.446	.89	.086	NA
Mean difference [95% CI] (°)	−2 [−4 to 1]	−2 [−4 to 1]	1 [−2 to 3]	2 [0 to 5]	NA
Max difference (°)	17	19	21	19	NA

SD, standard deviation; *CI*, confidence interval; *NA*, not applicable; *ANOVA*, analysis of variance.
P values are results from post hoc Tukey's testing with surgeon measurements, overall ANOVA $P = .023$.

Table V Number of studies from each software program that differed from average surgeon inclination measurement broken down by degree difference in inclination

Inclination	VIP	Blueprint	Materialise	GPS
	N (%)	N (%)	N (%)	N (%)
Within 5° of surgeon measurement	59 (73)	53 (65)	62 (76)	64 (79)
Between 5° 10° of surgeon measurement	18 (22)	22 (27)	16 (20)	13 (16)
Greater than 10° difference from surgeon measurement	4 (5)	6 (8)	3 (4)	4 (5)

Table VI Subluxation measurements

Variable	Blueprint	Materialise	Surgeon
Mean subluxation ± SD (%)	73 ± 14	70 ± 12	63 ± 9
P value	<.001	<.001	NA
Mean difference [95% CI] (%)	−10 [−15 to −6]	−7 [−12 to −3]	NA
Max difference (%)	24	20	NA

SD, standard deviation; *CI*, confidence interval; *NA*, not applicable; *ANOVA*, analysis of variance.
P values are results from post hoc Tukey's testing with surgeon measurements, overall ANOVA $P < .001$.

evaluated 31 preoperative CT scans on patients undergoing shoulder arthroplasty. The authors measured glenoid version, inclination, and depth and humeral subluxation on 2D CT images in the plane of the body as well as on 2D images in the plane of the scapula. The authors found that when CT images were not reoriented into the plane of the scapula, version and inclination were significantly overestimated. Hence, the images in this study were carefully oriented in the plane of the scapula before measurements were made to prevent overestimation of version and inclination. The reasons behind the differences in planning software between various companies are unclear; however, a better understanding of the variables may allow improved templating with subsequent improved accurate implant placement. Finally, the variability of these results suggests that surgeons should use these tools to better understand the deformity and the expected technical challenges that will be present at the time of glenoid reconstruction, but final decisions should be predicated on multiple factors including intraoperative findings, preoperative plan, quality of patient tissue, surgeon experience, and evolving evidence-based outcomes associated with implant longevity and patient function.

Limitations

All CT scans were oriented in the plane of the scapula by 1 author, and all surgeon measurements were made off of the same axial and coronal slice. Although measurements were made independently with all surgeons blinded to the other surgeons' measurements as well as the software measurements, using the same axial and coronal slice could have improved accuracy and correlation between surgeon measurements. This study did not include all commercially available preoperative planning systems and so we cannot comment on those programs that were not analyzed. This study also only assessed preoperative planning and did not evaluate translatability in the operating room (OR). Finally, this study did not control for specific glenoid deformity, and it is unclear if certain deformity patterns are more likely to result in computer-generated version/inclination variability. Further study is needed to compare the clinical and radiographic long-term outcomes after preoperative planning with these various programs to confirm the value of this process in the care of patients with shoulder arthritis.

Conclusion

Preoperative planning software for shoulder arthroplasty has limited agreement in measures of version, inclination, and subluxation measurements, whereas surgeons have high inter-reliability. Surgeons should be cautious when using commercial software planning systems and when comparing publications that use different planning systems to determine preoperative glenoid deformity measurements.

Disclaimer

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