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Computer navigation leads to more accurate glenoid targeting during total shoulder arthroplasty compared with 3-dimensional preoperative planning alone

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Background: Commercially available preoperative planning software is now widely available for shoulder arthroplasty. However, without the use of patient-specific guides or intraoperative visual guidance, surgeons have little in vivo feedback to ensure proper execution of the preoperative plan. The purpose of this study was to assess surgeons' ability to implement a preoperative plan in vivo during shoulder arthroplasty.

Methods: Fifty primary shoulder arthroplasties from a single institution were retrospectively reviewed. All surgical procedures were planned using a commercially available software package with both multiplanar 2-dimensional computed tomography and a 3-dimensional implant overlay. Following registration of intraoperative visual navigation trackers, the surgeons (1 attending and 1 fellow) were blinded to the computer navigation screen and attempted to implement the plan by simulating placement of a central-axis guide pin. Malposition was assessed (>4 mm of displacement or >10° error in version or inclination). Data were then blinded, measured, and evaluated.

Results: Mean displacement from the planned starting point was 3.2 ± 2.0 mm. The mean error in version was 6.4° ± 5.6°, and the mean error in inclination was 6.6° ± 4.9°. Malposition was observed in 48% of cases after preoperative planning. Malposition errors were more commonly made by fellow trainees vs. attending surgeons (58% vs. 38%, $P = .047$).

Conclusions: Despite preoperative planning, surgeons of various training levels were unable to reproducibly replicate the planned component position consistently. Following completion of fellowship training, significantly less malposition resulted. Even in expert hands, the orientation of the glenoid component would have been malpositioned in 38% of cases. This study further supports the benefit of guided surgery for accurate placement of glenoid components, regardless of fellowship training.

Level of evidence: Level III; Retrospective Cohort Comparison; Treatment Study

Keywords: Shoulder arthroplasty; guidance; navigation; accuracy; malposition; planning; computer guided

Glenoid component fixation is more reliable when placed closer to neutral version following anatomic total shoulder arthroplasty (TSA).[9] When implant retroversion exceeds 10°, the humeral head is more likely to subluxate

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posteriorly and cause increased cement mantle stresses, which can lead to component loosening.[4,10,11,15] Traditional glenoid preparation instruments for shoulder arthroplasty remain inaccurate, with surgeons most commonly placing the glenoid implant in excess retroversion.[2,18,19,24,27] Glenoid component positioning is a surgeon-modifiable risk factor affecting the longevity of anatomic shoulder arthroplasty, with higher rates of osteolysis reported in components with retroversion $> 15°$.[9]

Preoperative planning software has been widely introduced and used to select components and determine optimal implant position to ensure backside support and vault fixation. Preoperative planning improves the accuracy of glenoid component placement when used with standard instrumentation.[7,12,21,28] However, outliers in component placement continue to exist. Placement of the glenoid component close to neutral version remains a common target for shoulder surgeons when performing TSA. Although the effect of component version on reverse shoulder arthroplasty (RSA) remains debatable, baseplate inclination and inferior offset have both been associated with glenoid component notching.[6]

Without the use of patient-specific guides or intraoperative guidance, surgeons have no direct in vivo feedback to ensure proper execution of their preoperative plan. Visible landmarks of the scapula intraoperatively remain limited and play a role in the lack of reproducible component placement even within a single surgeon's practice.[25] Failure to accurately execute a preoperative plan may place a patient at risk of earlier component failure. In the case of TSA, glenoid component lucencies have been associated with worse patient-reported outcomes.[22] Similarly, notching following RSA has been associated with poorer clinical outcomes and can compromise glenoid baseplate stability.[17,20,23]

To improve component placement accuracy, numerous companies have introduced patient-specific instrumentation guides for shoulder arthroplasty. These are available in both disposable and reusable options and have been shown to improve the accuracy of glenoid component placement in vivo and in cadavers.[5,8] Despite availability, these guides have not been uniformly adopted by practicing surgeons because of the cost, availability, and perceived benefit. Without a patient-specific guide or image-guided instrumentation, surgeons do not have a reproducible manner in which to implement a preoperative plan.[1,3,16]

One alternative to patient-specific guides is the use of computer navigation.[18,27] This technology uses a line-of-sight camera and trackers affixed to both the scapula and surgical instruments to guide glenoid preparation and component implantation. Nashikkar et al[18] compared patients undergoing TSA prior to and following the introduction of intraoperative navigation. Compared with conventional instruments, this technology reduced the incidence of TSA glenoid components being placed $>5°$ from neutral version and inclination. However, preoperative planning software was not used for surgical procedures performed in the historical control group (January 2014 to July 2017). The primary purpose of this study was to assess surgeons' ability to implement a preoperative plan for shoulder arthroplasty glenoid component placement in vivo based on the central-axis guide pin.

Methods

We performed a retrospective review of all shoulders undergoing primary shoulder arthroplasty between September 2017 and April 2019 at a single institution. In 2017, 3-dimensional (3D) planning software and image-guided surgery (Equinoxe Planning App and ExactechGPS; Exactech, Gainesville, FL, USA) were introduced in our hospital. Using our institutional database, we identified all primary shoulder arthroplasties, including both anatomic shoulder arthroplasty (TSA) and RSA, that were performed using ExactechGPS guidance. After the introduction of this technology, performing surgeons began to identify and track their individual accuracy at executing their preoperative plans. For this study, 1 of 4 primary fellowship-trained surgeons, in conjunction with a fellowship trainee, used commercially available software to plan glenoid component placement. Intraoperatively, the participating surgeons individually blinded themselves to the intraoperative guidance screen and attempted to use standard techniques to replicate their preoperative plan. To be included in the study, a surgery had to include 2 individual data points. One data point was obtained from an attending-level surgeon with fellowship training in shoulder arthroplasty. The second data point was obtained from the fellow, with the exception of 2 cases in which 2 fellows participated (52 total data points). On the basis of the inclusion criteria, 50 shoulders were identified and their charts reviewed. Screenshots from the time of surgery indicating planned central-axis guide pin placement with blinded traditional techniques were evaluated (Fig. 1). Over the same study period, the participating attending surgeons performed 388 shoulder arthroplasties (range, 38-227 shoulder arthroplasties). The surgical volume for each attending surgeon in this series was as follows: B.S.S., 23 procedures; T.W.W., 21; K.W.F., 4; and J.J.K., 2.

Operative and study techniques

Prior to surgery, all participating surgeons reviewed 2-dimensional and 3D computed tomography (CT) scan reconstructions using commercially available planning software (Equinoxe Planning App). By use of the planning software, the appropriate anatomic shoulder arthroplasty or RSA was chosen and positioned into place on the face of the glenoid with both participating surgeons present. The final decision on implant placement was made by the attending surgeon in each case. The planned case was then saved and uploaded to the ExactechGPS unit for surgery (Fig. 2).

All surgical procedures were performed using a deltopectoral approach. The incision was extended 2 cm past the coracoid tip proximally to allow for appropriate exposure for placement of the coracoid tracker used for image guidance. A subscapularis peel was performed in the setting of RSA, and an osteotomy was performed for TSA. After an inferior capsular release was performed, the humeral head was dislocated. For TSA, the head was cut in its native retroversion, and for RSA, the head underwent

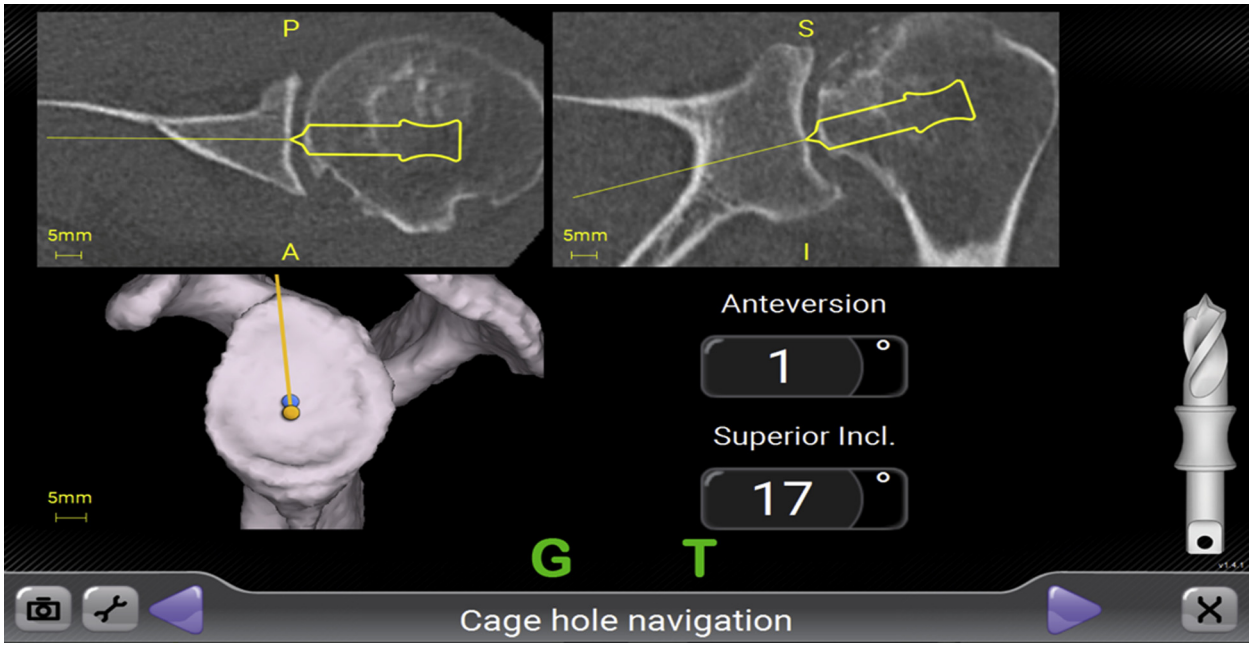

Figure 1 Example of ExactechGPS navigation screenshot showing 1° of anteversion error and 17° of superior tilt error in comparison with preoperatively planned component position. *P*, posterior; *A*, anterior; *S*, superior; *I*, inferior.

osteotomy in 20° of retroversion using an extramedullary guide. The glenoid was then exposed in routine fashion. The biceps stump and labral tissue were removed. If retained cartilage was present, it was removed using a Cobb elevator. The anterior neck of the glenoid was then débrided of soft tissue. Via electrocautery, a path toward the base of the coracoid and the undersurface of the coracoid arch was created to expose the bony anatomy. A Hohmann retractor was placed over the coracoacromial ligament, and the superior aspect of the coracoid was exposed. Via electrocautery, the superior surface of the coracoid was débrided of soft

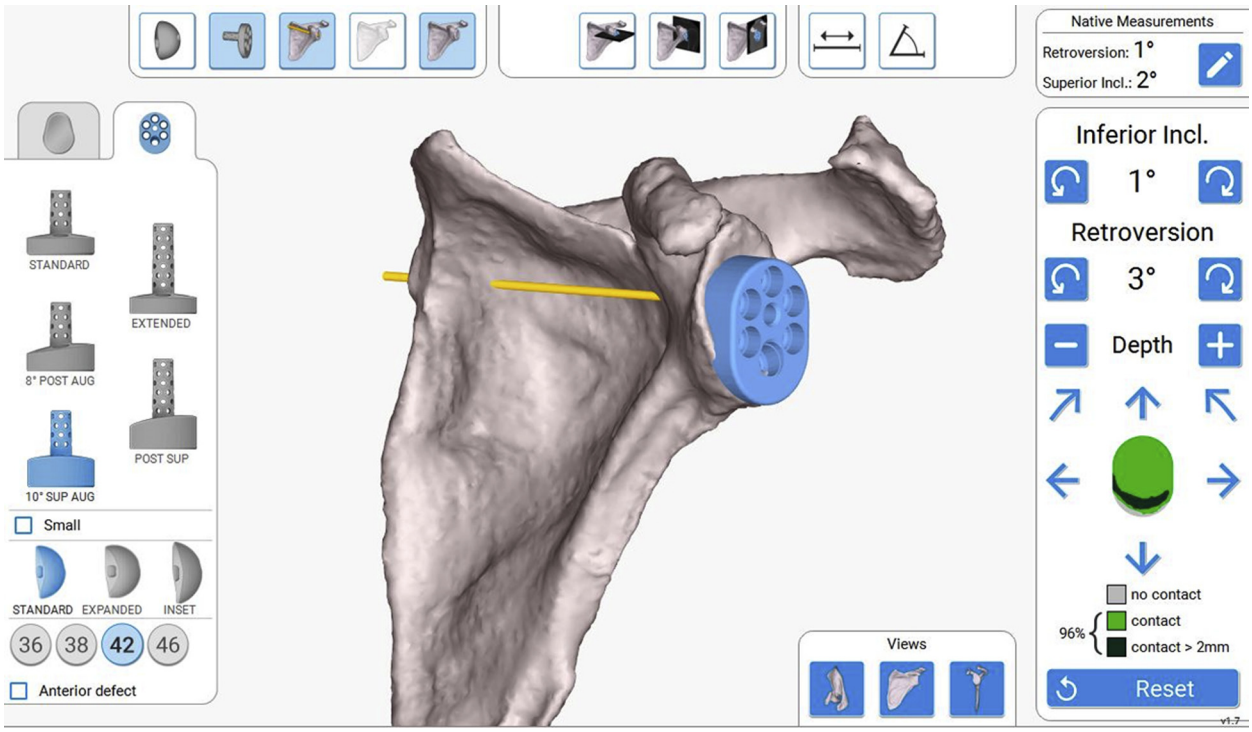

Figure 2 Example of Equinoxe Planning App for case shown in Figure 1. The component's central axis was planned in 3° of retroversion and 1° of inferior tilt. *Post*, posterior; *Aug*, augment; *Sup*, superior.

tissue. The tracker stand was then secured in place with 2 screws. The glenoid bony surface was registered according to the manufacturer's protocol. At this point, all surgeons were blinded to the navigation screen and were not allowed to review the reformatted CT images used to guide the surgical procedure. Using standard instruments and their memory of the preoperative plan, surgeons identified the planned starting point for the central cage of the implant, similarly to placement of the central-axis pin used by many shoulder arthroplasty systems. Each surgeon positioned the guided drill in what the surgeon believed to be the planned axis (version and inclination). Once the position was established, a screen capture was created for later comparison with the actual plan. Intraoperatively, each surgeon was blinded to the image capture and other surgeons' visual positioning. After each screen capture, surgeons continued with the case in routine fashion according to the preoperative plan.

Data analysis

Following identification of all eligible patients, all screenshots were collected and blinded. An orthopedic surgeon (E.H.) who did not participate in any cases reviewed all screenshots and recorded displacement from the planned starting point, version error (anteversion [positive] or retroversion [negative]), and inclination error (superior [positive] or inferior [negative]). Displacement was assessed using a validated computer screen measurement program (ImageJ; National Institutes of Health, Washington, DC, USA). Version error and inclination error were directly calculated from the computer guidance system. These measurements were then compared with the preoperative plan to calculate the difference in each. The mean and standard deviation for each measurement were calculated. The intraoperative execution of the plan was considered malpositioned if version or inclination errors exceeded 10° or if the starting point displacement exceeded 4 mm based on previous published research by Throckmorton et al.[25] Measurements were then divided based on the level of training (fellowship-trained attending vs. upper-extremity surgery fellow) and compared for each measurement. Comparisons were made by the Student t test (SPSS software, version 25; IBM, Armonk, NY, USA). The α value for statistical significance was set at .05.

Results

Fifty unique shoulder arthroplasty cases met the inclusion criteria and were evaluated. The mean age at surgery was 67 years (range, 38-90 years). Of the patients, 25 were men and 25 were women. Thirteen shoulders were treated with TSA, and 37 underwent RSA. Standard components were used in 3 TSA patients, with 10 requiring an 8° posteriorly augmented glenoid component. Among the shoulders treated with RSA, implants placed included standard implants (4), implants with posterior augmentation (4), implants with superior augmentation (9), and implants with posterosuperior augmentation (19). Glenoids were classified as Walch type A1 in 23 patients, type A2 in 6, type B1 in 5, type B2 in 13, and type B3 in 3. In patients treated with RSA, glenoids were classified as Favard type E0 in 22, type E1 in 9, and type E2 in 6.

Study cohort

Mean displacement from the planned starting point was 3.2 mm (range, 0.3-10.3 mm), with 18 measurements (18%) exceeding 4 mm. Absolute error in version averaged 6.4° (range, –24° to 24°). Of the cases, 49% exceeded 5° from the preoperative plan and 25% deviated beyond 10°. Errors resulting in excess retroversion were more common than those resulting in excess anteversion. The mean absolute error in inclination was 6.6° (range, –13° to 19°), with 50% of measurements exceeding the 5° error cutoff and 25% exceeding the 10° cutoff. Errors resulting in excess superior inclination were more common than those resulting in excess inferior tilt. When the malposition criteria (>4 mm of displacement or >10° error in version or inclination) were applied, 48% of intraoperatively executed plans would have deviated beyond the acceptable tolerances.[25]

Attendings vs. fellows

When fellowship-trained surgeons were compared with fellow trainees, mean displacement from the planned starting point was less in the attending group (3.0 mm vs. 3.4 mm, $P = .317$). The mean version error was also similar between groups, with attendings averaging 1° closer to re-creating the preoperative plan (5.9° vs. 6.9°, $P = .381$). Attending surgeons were able to more accurately replicate planned component inclination vs. trainees (5.1° vs. 8°, $P < .001$). Errors in excess of 10° were less common in the attending group for both version and inclination. Table I presents full details.

Most experienced vs. least experienced surgeon

Given the small discrepancies seen between the levels of training, a subgroup analysis was performed comparing the most experienced (T.W.W., 29 years) and least experienced (B.S.S., 3 years) attending surgeons. Mean displacement, version and inclination errors, and malposition were similar between surgeons. Table II presents full details.

Discussion

Traditional instruments remains the most commonly used tools for implanting shoulder arthroplasty components. Preoperative planning has been shown to improve implant orientation both in vivo and in cadaveric models, and new commercially available software has allowed for improved modeling and planning.[21] However, without PSI or intraoperative guidance, the ability to reliably place a glenoid component in the planned position appears to be imprecise.[12,14,19,25,26] On the basis of our results, 41% of cases were off by >10° of version and/or inclination and 49% of cases would have met the criteria for being malpositioned.

Table I Comparison of version and inclination errors between attending and fellow surgeons

	Attending surgeons (n = 50)	Upper-extremity fellows (n = 52)	*P* value
>5°			
Version, %	44	52	.56
Anteversion/retroversion, n	7/15	8/19	
Inclination, %	36	62	.018
Superior/inferior, n	14/4	26/6	
Version and/or inclination, %	66	83	.055
>10°			
Version, %	18	31	.21
Anteversion/retroversion, n	1/8	2/14	
Inclination, %	14	35	.057
Superior/inferior, n	6/1	16/2	
Version and/or inclination, %	30	52	.024
Malposition (>10° or >4 mm of displacement from planned starting point), n (%)	19 (38)	30 (58)	.047

Although significantly less common in surgeons who had completed fellowship training, errors exceeding 10° were still present in 38% of cases despite 3D preoperative planning with commercially available software.

In a study of 70 cadavers, Throckmorton et al[25] compared disposable patient-specific center-pin guides with traditional instrumentation. Patient-specific guides were found to improve the accuracy of glenoid component placement compared with traditional instruments, similarly to the findings of studies on visual navigation.[14,19,25,26] The mean error in version with traditional instrumentation was similar to that in this study (8° vs. 6.4°). The mean error in inclination with traditional instrumentation was also similar to that in this study (7° vs. 6.6°). When applying the criteria for component malposition (>4 mm of displacement or >10 error in version or inclination), Throckmorton et al reported 66% of cases performed with traditional instruments to be malpositioned. This is higher than the 48% of cases that would have resulted in a malpositioned component in our study. The difference in this rate may be the result of the use of 3D preoperative planning for all cases in this study, which has been shown to improve component alignment.[12]

Table II Comparison of errors by years of experience of attending surgeons

	T.W.W. (n = 21)	B.S.S. (n = 23)	*P* value
Mean displacement from planned starting point, mm	2.7 ± 1.6	3.3 ± 2.1	.26
Mean absolute version error, °	5.7 ± 4.7	6.6 ± 6.6	.60
Mean absolute inclination error, °	5.4 ± 3.8	4.9 ± 4.3	.71
>5°, %			
Version	48	48	.97
Inclination	43	30	.57
Version and/or inclination	67	70	.84
>10°, %			
Version	24	17	>.999
Inclination	14	13	>.999
Version and/or inclination	33	30	.84
Malposition (>10° or >4 mm of displacement from planned starting point), n (%)	10 (48)	8 (35)	.40

The rate of malposition after preoperative planning using commercial software is similar to the results of Jacqout et al.[13] In a study of 17 TSA cases performed after preoperative planning with commercially available software (Imascap, Plouzané, France), the authors reported a malpositioned component rate of 41% (7 of 17). This is similar to our rate of 48% for all surgeons. The higher rate in this study may be due to the inclusion of RSA as well as fellow trainees. It is possible that some patients may have had more significant bone loss and deformity that may have affected the accuracy of plan implementation. Jacqout et al compared their series with a previous study using the same software and patient-specific guides[5] and concluded that 3D preoperative planning was similar to patient-specific guides regarding mean version and inclination errors.

Our study differs from that of Jacqout et al.[13] in that each patient was able to serve as his or her own control. Rather than comparing with historical controls with different glenoid anatomy, we were able to use intraoperative visual tracking to identify how the preoperative plan would have been implemented without the need to subject patients to potential component malposition. The study was designed to replicate where the center pin for glenoid preparation would have been placed. As with multiple commercially available shoulder systems, once this pin is placed, the version and inclination are set as the glenoid is prepared. In addition, the guidance system used in this study (ExactechGPS) has previously been shown to accurately reproduce the intraoperative plan within 0.2° of planned inclination and 1.4° of planned version.[18] Given the high malposition rate in the hands of high-volume fellowship-trained surgeons shown in this study, shoulder surgeons should take caution in trusting their ability to implement a 3D preoperative plan in vivo using standard instruments and a central guide pin alone. Surgeons may need to consider other factors such as reaming depth and location, intraoperative fluoroscopy, patient-specific guides, and intraoperative navigation.[2,18,25]

This study is unique in that it evaluated the effect of fellowship training on the accuracy of implementing a preoperative plan using commercially available software. Compared with fellows, attending surgeons were

significantly less likely to implement a preoperative plan in a malpositioned orientation (38% vs. 58%, $P = .0470$). These effects were most prominent on inclination, for which errors averaged 5.1° for attendings compared with 8° for fellows. This finding is in contrast to that of Throckmorton et al,[25] who did not show a difference between high- and low-volume surgeons using cadavers. When comparing two high volume surgeons with differing years of experience, we did not demonstrate a difference in component malposition.

This study is the first study to assess the in vivo ability to implement a preoperative plan using traditional instruments via technology in which the patient can serve as his or her own control by use of optical navigation. However, there remain multiple limitations to this study. Measurements were taken prior to any bony preparation. However, the orientation of the captured image that represented plan implementation is similar to the center-pin guidance system used in other systems.[5,13,25] It is possible that surgeons may have made additional version or inclination corrections before completing reaming. However, in our experience, small errors in version are difficult to detect even with reaming owing to the lack of visual landmarks. Given our experience with guided surgery, we did not consider it desirable to modify the glenoid bone in an unguided manner without image guidance owing to the observed high rates of surgeon inaccuracy. This study is also limited by the fact that we were unable to assess final implant placement. Routine postoperative CT scans are also outside of the standard of care following shoulder arthroplasty and have historically not been approved by our institutional review board. However, previous studies have validated the accuracy of this technology.[18] Lastly, we remain unable to assess the clinical implications of guided vs. unguided surgery and its effect on component survival.

Conclusion

Surgeons, regardless of training, are unable to reliably execute placement of a glenoid component even after 3D preoperative planning using commercially available software. Even in a high-volume shoulder surgeon's hands, malpositioning occurred in 38% of cases. This study further supports the benefit of guided surgery for accurate placement of glenoid components in vivo, regardless of fellowship training.

Disclaimer

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Joseph J. King owns stock in Pacira Pharmaceuticals and is a paid consultant for Exactech.

Kevin W. Farmer is a paid consultant for Exactech and Arthrex.

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References

1. Allam Y, Silbermann J, Riese F, Greiner-Perth R. Computer tomography assessment of pedicle screw placement in thoracic spine: comparison between free hand and a generic 3D-based navigation techniques. Eur Spine J 2013;22:648-53. https://doi.org/10.1007/s00586-012-2505-7
2. Briem D, Ruecker AH, Neumann J, Gebauer M, Kendoff D, Gehrke T, et al. 3D fluoroscopic navigated reaming of the glenoid for total shoulder arthroplasty (TSA). Comput Aided Surg 2011;16:93-9. https://doi.org/10.3109/10929088.2010.546076
3. Domb BG, El Bitar YF, Sadik AY, Stake CE, Botser IB. Comparison of robotic-assisted and conventional acetabular cup placement in THA: a matched-pair controlled study. Clin Orthop Relat Res 2014;472:329-36. https://doi.org/10.1007/s11999-013-3253-7
4. Farron A, Terrier A, Büchler P. Risks of loosening of a prosthetic glenoid implanted in retroversion. J Shoulder Elbow Surg 2006;15:521-6. https://doi.org/10.1016/j.jse.2005.10.003
5. Gauci MO, Boileau P, Baba M, Chaoui J, Walch G. Patient-specific glenoid guides provide accuracy and reproducibility in total shoulder arthroplasty. Bone Joint J 2016;98-B:1080-5. https://doi.org/10.1302/0301-620X.98B8.37257
6. Gutiérrez S, Greiwe RM, Frankle MA, Siegal S, Lee WE. Biomechanical comparison of component position and hardware failure in the reverse shoulder prosthesis. J Shoulder Elbow Surg 2007;16(3 Suppl):S9-12. https://doi.org/10.1016/j.jse.2005.11.008
7. Hamilton MA, Polakovic S, Saadi P, Jones RB, Parsons IM, Cheung EV. Evaluation of preoperative implant placement in total shoulder arthroplasty. Bull Hosp Jt Dis (2013) 2015;73(Suppl 1):S47-51.
8. Heylen S, Van Haver A, Vuylsteke K, Declercq G, Verborgt O. Patient-specific instrument guidance of glenoid component implantation reduces inclination variability in total and reverse shoulder arthroplasty. J Shoulder Elbow Surg 2016;25:186-92. https://doi.org/10.1016/j.jse.2015.07.024
9. Ho JC, Sabesan VJ, Iannotti JP. Glenoid component retroversion is associated with osteolysis. J Bone Joint Surg Am 2013;95:e82. https://doi.org/10.2106/JBJS.L.00336
10. Hopkins AR, Hansen UN, Amis AA, Emery R. The effects of glenoid component alignment variations on cement mantle stresses in total shoulder arthroplasty. J Shoulder Elbow Surg 2004;13:668-75. https://doi.org/10.1016/s1058274604001399
11. Iannotti JP, Greeson C, Downing D, Sabesan V, Bryan JA. Effect of glenoid deformity on glenoid component placement in primary shoulder arthroplasty. J Shoulder Elbow Surg 2012;21:48-55. https://doi.org/10.1016/j.jse.2011.02.011
12. Iannotti JP, Weiner S, Rodriguez E, Subhas N, Patterson TE, Jun BJ, et al. Three-dimensional imaging and templating improve glenoid implant positioning. J Bone Joint Surg Am 2015;97:651-8. https://doi.org/10.2106/JBJS.N.00493

13. Jacquot A, Gauci M-O, Chaoui J, Baba M, Deransart P, Boileau P, et al. Proper benefit of a three dimensional pre-operative planning software for glenoid component positioning in total shoulder arthroplasty. Int. Orthop 2018;42:2897-906. https://doi.org/10.1007/s00264-018-4037-1
14. Kircher J, Wiedemann M, Magosch P, Lichtenberg S, Habermeyer P. Improved accuracy of glenoid positioning in total shoulder arthroplasty with intraoperative navigation: a prospective-randomized clinical study. J Shoulder Elbow Surg 2009;18:515-20. https://doi.org/10.1016/j.jse.2009.03.014
15. Mansat P, Briot J, Mansat M, Swider P. Evaluation of the glenoid implant survival using a biomechanical finite element analysis: influence of the implant design, bone properties, and loading location. J Shoulder Elbow Surg 2007;16(3 Suppl):S79-83. https://doi.org/10.1016/j.jse.2005.11.010
16. Miyasaka T, Kurosaka D, Saito M, Omori T, Ikeda R, Marumo K. Accuracy of computed tomography-based navigation-assisted total knee arthroplasty: outlier analysis. J Arthroplasty 2017;32:47-52. https://doi.org/10.1016/j.arth.2016.05.069
17. Mollon B, Mahure SA, Roche CP, Zuckerman JD. Impact of scapular notching on clinical outcomes after reverse total shoulder arthroplasty: an analysis of 476 shoulders. J Shoulder Elbow Surg 2017;26:1253-61. https://doi.org/10.1016/j.jse.2016.11.043
18. Nashikkar PS, Scholes CJ, Haber MD. Computer navigation re-creates planned glenoid placement and reduces correction variability in total shoulder arthroplasty: an in vivo case-control study. J Shoulder Elbow Surg 2019;28:e398-409. https://doi.org/10.1016/j.jse.2019.04.037
19. Nguyen D, Ferreira LM, Brownhill JR, King GJW, Drosdowech DS, Faber KJ, et al. Improved accuracy of computer assisted glenoid implantation in total shoulder arthroplasty: an in-vitro randomized controlled trial. J Shoulder Elbow Surg 2009;18:907-14. https://doi.org/10.1016/j.jse.2009.02.022
20. Roche CP, Stroud NJ, Martin BL, Steiler CA, Flurin P-H, Wright TW, et al. The impact of scapular notching on reverse shoulder glenoid fixation. J Shoulder Elbow Surg 2013;22:963-70. https://doi.org/10.1016/j.jse.2012.10.035
21. Scalise JJ, Codsi MJ, Bryan J, Brems JJ, Iannotti JP. The influence of three-dimensional computed tomography images of the shoulder in preoperative planning for total shoulder arthroplasty. J Bone Joint Surg Am 2008;90:2438-45. https://doi.org/10.2106/JBJS.G.01341
22. Schoch BS, Wright TW, Zuckerman JD, Bolch C, Flurin P-H, Roche C, et al. Glenoid component lucencies are associated with poorer patient-reported outcomes following anatomic shoulder arthroplasty. J Shoulder Elbow Surg 2019;28:1956-63. https://doi.org/10.1016/j.jse.2019.03.011
23. Simovitch RW, Zuckerman JD, Wright TW, Flurin P-H, Roche C. Impact of scapular notching on reverse total shoulder arthroplasty outcomes—5 year minimum follow-up. J Shoulder Elbow Surg 2019;28:e204-5. https://doi.org/10.1016/j.jse.2018.11.014
24. Stübig T, Petri M, Zeckey C, Hawi N, Krettek C, Citak M, et al. 3D navigated implantation of the glenoid component in reversed shoulder arthroplasty. Feasibility and results in an anatomic study. Int J Med Robot 2013;9:480-5. https://doi.org/10.1002/rcs.1519
25. Throckmorton TW, Gulotta LV, Bonnarens FO, Wright SA, Hartzell JL, Rozzi WB, et al. Patient-specific targeting guides compared with traditional instrumentation for glenoid component placement in shoulder arthroplasty: a multi-surgeon study in 70 arthritic cadaver specimens. J Shoulder Elbow Surg 2015;24:965-71. https://doi.org/10.1016/j.jse.2014.10.013
26. Venne G, Rasquinha BJ, Pichora D, Ellis RE, Bicknell R. Comparing conventional and computer-assisted surgery baseplate and screw placement in reverse shoulder arthroplasty. J Shoulder Elbow Surg 2015;24:1112-9. https://doi.org/10.1016/j.jse.2014.10.012
27. Verborgt O, De Smedt T, Vanhees M, Clockaerts S, Parizel PM, Van Glabbeek F. Accuracy of placement of the glenoid component in reversed shoulder arthroplasty with and without navigation. J Shoulder Elbow Surg 2011;20:21-6. https://doi.org/10.1016/j.jse.2010.07.014
28. Werner BS, Hudek R, Burkhart KJ, Gohlke F. The influence of three-dimensional planning on decision-making in total shoulder arthroplasty. J Shoulder Elbow Surg 2017;26:1477-83. https://doi.org/10.1016/j.jse.2017.01.006