Emerging Technologies in Shoulder Arthroplasty

Navigation, Mixed Reality, and Preoperative Planning

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KEYWORDS

• Shoulder arthroplasty • Navigation • Augmented reality • Mixed reality • Computer-assisted surgery • Patient-specific instrumentation • Preoperative planning

KEY POINTS

- Accurate and precise placement of shoulder arthroplasty components is thought to maximize postoperative function and increase long-term implant survival.
- Preoperative planning with 3-dimensional computed tomography scapula reconstructions adds critical information for understanding complex glenoid deformities and being adequately prepared for intraoperative success.
- Patient-specific instrumentation, intraoperative navigation, and mixed reality increase a surgeon's ability to replicate preoperative plans, minimize component malposition, and maximize fixation during shoulder arthroplasty.

INTRODUCTION

With an advancing population age, anatomic and reverse shoulder arthroplasty (aTSA and rTSA, respectively) have a well-established track record in decreasing pain, enhancing patient function, and improving quality of life for the management of end-stage osteoarthritis, irreparable rotator cuff tears, proximal humerus fractures, and rotator cuff arthropathy.[1–3] Both implants have shown excellent long-term survivorship, with 10-year primary aTSA survival rate of 96%[4] and primary rTSA survival rate of 91%[5]; however, complications occur in roughly 11% of aTSA[6] and 16.5% of rTSA procedures.[5] Instability and component loosening, especially the glenoid component, are common complications and causes for revision surgery, with glenoid loosening occurring in 1.2% of rTSAs (7.2% of all rTSA complications) and 3.9% of aTSAs (37.7% of all aTSA complications).[6–9] Glenoid malpositioning represents a factor for these complications.[10–12]

Although the ideal positions for both the humeral and glenoid components are unknown and remain a topic for debate, glenoid positioning in more than 10° to 15° of retroversion leads to more micromotion at the bone-cement surface for aTSA, increased glenoid contact pressures, and significantly increased osteolysis around the central peg in aTSA.[10–12] With regards to rTSA, glenoid fixation is enhanced by maximizing the bone-metal interface, maximizing screw length, and minimizing cortical perforations.[13,14] Guide-pin placement after glenoid exposure remains a critical step for establishing version and inclination, while placing the component on an axis to achieve strong screw purchase in the scapular pillars.[15,16] Re-establishing neutral inclination has been a focus

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for placement of the rTSA baseplate given the increase in stress seen at the bone implant interface in biomechanical testing.[17]

Additionally, erroneous screw trajectories in rTSA glenoid baseplate fixation may increase micromotion at the baseplate-bone interface, decreasing bone in-growth, and predisposing to aseptic baseplate loosening,[18] while screw perforation of the glenoid vault is associated with injury to periscapular neurovascular structures and scapular spine fractures.[19–23] To limit baseplate micromotion, biomechanical studies emphasize the importance of accurate screw trajectory,[24] maximizing screw length, especially in the anterior and inferior baseplate screw holes,[25] and using enough screws (between two and four) to achieve stable fixation without decreasing the quality of bone for possible future revisions or increasing the risk of cortical violation.[25,26]

With more than 70% of all shoulder arthroplasty procedures in the United States being completed by surgeons performing fewer than 10 per year, this lower surgical volume and experience could alter component position accuracy and reduce outcomes.[27,28] Additionally, higher degrees of preoperative glenoid deformity and an intraoperative inability to visualize the scapular plane to correctly judge glenoid orientation likely also contribute to the variability and malpositioning of the glenoid components and baseplate screws.[29,30]

The field of shoulder arthroplasty has been investigating various methods to help the surgeon better understand the preoperative deformity, plan for component placement, and execute the surgical plan accurately. The most critical advances so far include preoperative planning with 3-dimensional computed tomography (CT) scapular reconstructions, patient-specific instrumentation (PSI), intraoperative navigation, and intraoperative mixed reality (MR) devices. Debate exists which of these technologies will emerge as the gold standard, and it is prudent for shoulder surgeons to be knowledgeable with all existing technology. The following sections highlight the key features and relevant literature related to these advancements in shoulder arthroplasty.

PREOPERATIVE PLANNING

Background

Preoperative planning is becoming an increasingly studied and utilized trend in order to better understand glenohumeral parameters and accurately execute a shoulder arthroplasty. Although this trend is relatively new in shoulder arthroplasty, the concepts of preoperative planning and implant templating are well established for other orthopedic procedures, especially total knee and hip arthroplasties.[31–33] These plans can help the surgeon better understand patient anatomical considerations and have appropriate implants ready for use; additionally, they may lead to improved surgical outcomes. With this in mind, preoperative planning can play an integral role in achieving better results and implant positioning within shoulder arthroplasties.

Preoperative Imaging–Radiographic to 3-Dimensional

Overview of imaging options

Shoulder arthroplasty preoperative imaging begins with standard shoulder radiographs (ie, Grashey view true-AP, scapular Y, and axillary lateral). The axillary lateral view can provide a general sense of the patient's glenoid version, as well as his or her anteroposterior wear and subluxation patterns, which are critical to evaluate for possible intraoperative correction or augmentation during shoulder arthroplasty. True-AP radiographs can provide knowledge regarding inclination and superior wear typical in later stages of rotator cuff tear arthropathy. Advanced imaging, including MRI and/or 2-dimensional CT, are ordered at the prerogative of the surgeon depending on the concern for rotator cuff pathology or better evaluation of glenoid version, deformity, and available bone stock. Lowe and colleagues[34] investigated glenoid version measurement, Walch classification, and interobserver agreement between CT and MRI, finding MRI and CT have excellent interobserver agreement in calculating the glenoid version and Walch classification for less severe glenoid deformity, but CT may be more suitable to distinguish between type B2 and C glenoids.

With more advanced software and computing capabilities, 3-dimensional CT reconstructions of the scapula and humerus allow for finer-detail analysis of the boney architecture prior to surgery. Several companies have software that can reconstruct 2-dimensional CT into 3-dimensional images along the scapular plane identified by the inferior scapular angle, the scapular trigonum, and the center of the glenoid. Table 1 illustrates commercially available 3-dimensional planning and patient-specific instrumentation systems. From these 3-dimensional CT scans, the glenoid vault model could be used to estimate a patient's normal, premorbid glenoid for use in calculating version and inclination.[35] Fig. 1 shows representative images of the preoperative planning process using Arthrex VIP planning software before rTSA.

Table 1
Available 3-dimensional glenoid planning software and patient-specific instrumentation

Company	System	Reusable PSI?	Description
DJO Global	Match Point System	No	Preoperative 3-dimensional planning system allows for surgeon input on glenoid position. The PSI 3-dimensional guide is manufactured by Materalise for guide pin placement.
Depuy Synthes	TRUMATCH	No	Preoperative 3-dimensional planning system allows for surgeon input on glenoid position. The PSI 3-dimensional guide is manufactured by Materalise for guide pin placement
Zimmer Biomet	Signature ONE	No	Preoperative 3-dimensional planning system allows for surgeon input on glenoid position. Multiple 3-dimensional guides are manufactured for guide pin placement, reaming depth, baseplate impacting, and baseplate screw guide.
Arthrex	OrthoVis and VIP	Yes	Preoperative 3-dimensional planning system allows for surgeon input on glenoid position. Intraoperatively the Arthrex 5-dimensional targeter legs are adjusted to fit the glenoid for planned guide pin trajectory. This is a reusable PSI.
Stryker	Blueprint	No	Preoperative 3-dimensional planning system allows for surgeon input on glenoid position. The PSI 3-dimensional guide is manufactured by Materalise for guide pin placement. Blueprint originally created by Tornier and utilized Glenosys planning software (Imascap). This product was later acquired by Wright Medical and subsequently by Stryker.
Exactech	Equinoxe Planning App	N/A	Preoperative 3-dimensional planning system allows for surgeon input on glenoid position. There is no PSI available, but planning can be used with ExactechGPS navigation system.
Medacta	MyShoulder	No	Preoperative 3-dimensional planning system allows for surgeon input on glenoid position. In-house manufacturing of PSI for guide pin placement and humeral neck cut.

Comparison of 2-dimensional and 3-dimensional computed tomography imaging for glenoid pathology

Axial 2-dimensional CT images are typically used to assess glenoid wear patterns, Walch classification,[16] and version via the method proposed by Friedman and colleagues,[36] while coronal images can assess inclination.[37] However, these measurements made on 2-dimensional imaging are imprecise to accurately depict glenoid deformity. Scalise and colleagues[38] investigated the interobserver reliability for accurate glenoid version, inclination, and area of bone loss between 2-dimensional and 3-dimensional images analyzed by 4 surgeons, finding that 3-dimensional reconstructions allowed for more accurate understanding and better agreement on areas of bone loss that directly affected their proposed implant placement. Kwon and colleagues[39] measured glenoid morphology on 3-dimensional images of cadaveric shoulders, finding a high degree of accuracy compared with their true anatomic measurements. The difference between 2-dimensional and 3-dimensional measurements relates to the plane of image acquisition (gantry angle) for CT scans and the resting scapular rotation, which can vary between patients. Two separate studies showed that small variations in the scapular rotation resulted in significant alterations in version and inclination measurements on 2-dimensional CT scans that are not reformatted in the scapular plane.[40,41] Thus, 3-dimensional reconstructions reduce the variability between CT scanners and

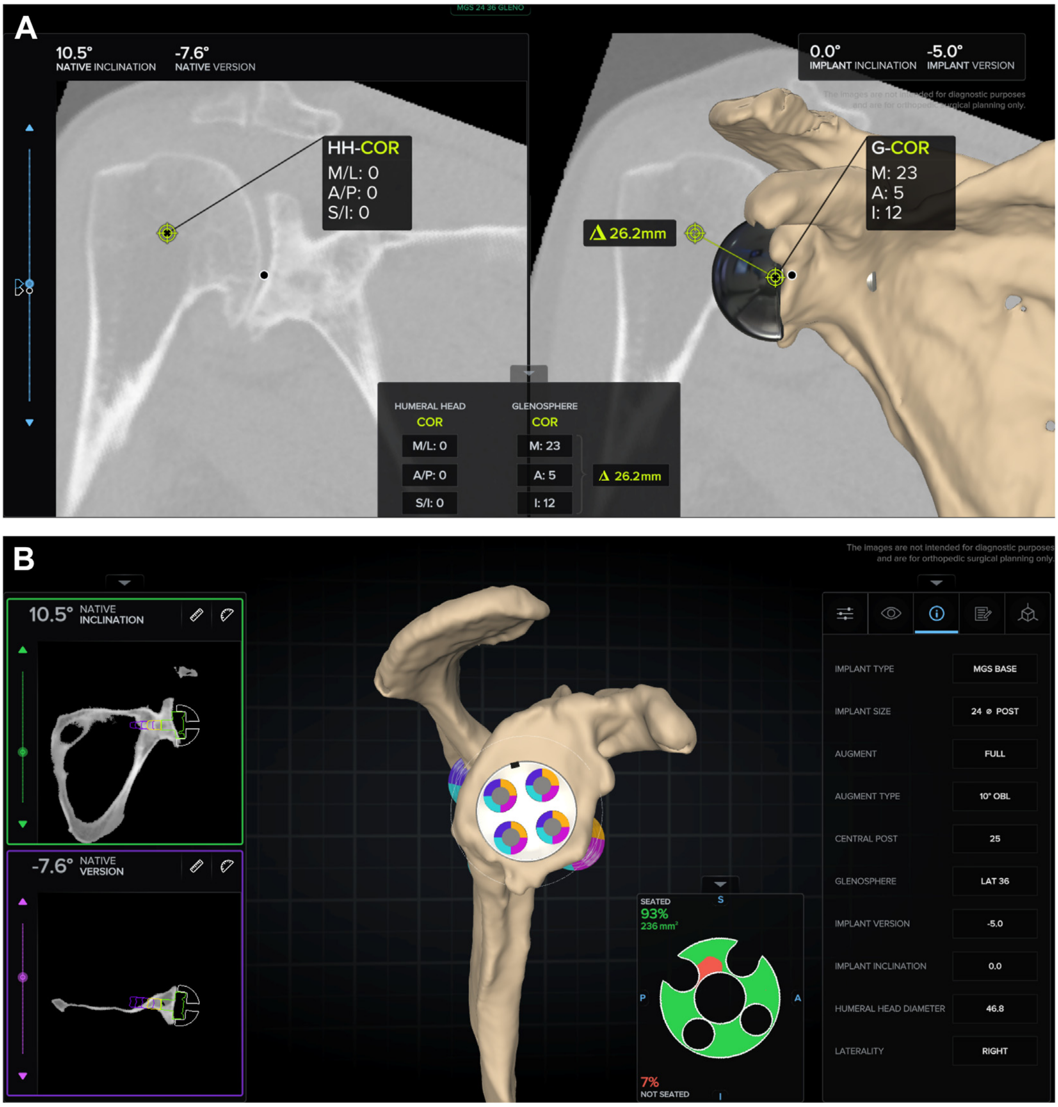

Fig. 1. Representative images of the Arthrex VIP preoperative planning system for rTSA. Part A (*upper*) shows the change in center of rotation between the native humeral head and the proposed placement of the glenosphere. Part B (*lower*) depicts proposed baseplate position on the glenoid indicating native and implant parameters regarding version and inclination.

technicians, which could directly affect glenoid measurements.

As discussed earlier, there are multiple commercially available 3-dimensional planning software systems that calculate glenoid version, inclination, and humeral head subluxation. Various studies have investigated the measurement agreement between these systems and with surgeon measurements, as the systems vary in their method for calculating the previously mentioned values. For instance, Bluprint (Stryker) utilizes an automated process via a best-fit sphere, while several other companies use a manual-input landmark system for calculation (VIP [Arthrex], Materialise [DJO], and GPS [Exactech]). Denard and colleagues[42] compared glenoid version and inclination measured on 63 patients calculated with Blueprint (Stryker) and VIP (Arthrex) 3-dimensional software. With regards to version and inclination, Blueprint and VIP had agreement within 5° in 69.8% and 54.0% of shoulders, respectively, while more than 10° of variation was seen in 11.1% and 19.0% of shoulders, respectively.[42] This considerable variability was further investigated by Erickson and colleagues,[43] comparing surgeon-calculated 2-dimensional preoperative measurements and those calculated with 4 commonly available 3-dimensional planning systems (Blueprint, VIP, Materialise, and GPS). With surgeon measurements as the reference, Blueprint had less agreement within 5° for version and inclination and more measurements with a greater than 10° difference compared with VIP, Materialise, and GPS. The authors noted that the difference in agreement likely relates to the automated system utilized with Blueprint and the manual method with the other 3 software systems.[43]

3-dimensional reconstructions and their effect on glenoid surgical plans

Glenoid wear patterns can be corrected via 3 main methods: eccentric reaming, bone grafting, or glenoid augmentation. Eccentric reaming remains a viable option for less severe version correction, with eccentric reaming to correct more than 15° of retroversion to neutral is associated with a higher risk of glenoid vault violation.[44,45] Bone grafting larger defects is an effective solution for both aTSA and rTSA, but has a risk for nonunion and resorption that can be alleviated by the use of posterior augmentation to replace grafting.[46,47]

Beyond the more accurate representation of glenoid pathology with 3-dimensional CT scans, these images can be utilized to affect intraoperative decisions. Rosenthal and colleagues[48] investigated how preoperative planning with 2-dimensional versus 3-dimensional imaging affected glenoid version correction methods in patients undergoing a shoulder arthroplasty, finding that surgeons who preoperatively planned with 3-dimensional images chose to use augmented glenoids for version correction in 54% of cases compared with just 15% of cases utilizing 2-dimensional preoperative planning, with the remainder of patients undergoing eccentric reaming for version correction.

Intraoperative glenoid guide-pin placement utilizing 3-dimensional preoperative planning

As previously discussed, accurate glenoid guide-pin placement is a critical step in determining the version, inclination, and final placement of the glenoid component. Free-hand guide-pin placement based on 2-dimensional preoperative imaging can result in high variability in final component position. Jacquot and colleagues[49] utilized the Glenosys 3-dimensional preoperative planning system to find an optimal guide-pin location while utilizing a free-hand technique to place the guide pin. They showed that preoperative planning with 3-dimensional software resulted in high accuracy between preoperative plans and postoperative guide pin location with mean errors of less than 5° for version and inclination, while having high precision and eliminating outliers causing malposition of the implant based on Throckmorton and colleagues'[50] criteria. Jacquot's group did notice that the freehand technique resulted in the mean guide pin start point being 3 mm from the preoperative plan, with 41% of cases being malpositioned greater than 4 mm, which could lead to baseplate overhang or impingement, an error that was eliminated by the use of patient-specific instrumentation. The high accuracy obtained for guide-pin and glenoid component position utilizing 3-dimensional preoperative planning was further supported by Berhout and colleagues.[51,52]

Preoperative templating

Preoperative templating for component size and position is a critical portion of total joint procedures that has not translated as widely into shoulder arthroplasty. With hip and knee arthroplasties, templating relies on radiographs, with limited use of CT images to assist in the planning process. The converse is likely the case for shoulder arthroplasty. Lee and colleagues[53] utilized calibrated Grashey-view radiographs to template their Tornier Aequalis humerus implant. This group found low inter-rater agreement on templated implant size except for humeral head size, and only 62% of patients received humerus head sizes within 1 size of the preoperative template, with inter-rater preoperative templating agreement and actual implant used even lower for neck angle and stem size. The group remarked that templating from an anteroposterior (AP) radiograph alone is not helpful, as the sagittal plane of the humerus is typically narrower and can greatly affect implant size used in surgery. As an alternative to radiographs, Freehill and colleagues[54] utilized 3-dimensional CT images of the humerus and scapula for templating. They found that final glenoid selection matched preoperative planning perfectly for 89% of cases and within 1 glenoid size for 99% of cases, while a similar agreement was found for both stemmed and stemless humeral components. Freehill concluded that 3-dimensional CT images were a viable imaging option for preoperative templating.

Advances in proximal humerus preoperative planning

Accurate anatomic neck osteotomies in shoulder arthroplasty are necessary for establishing humeral head inclination and retroversion. Understanding the patient's premorbid proximal humerus anatomy is critical, especially in cases of severe osteoarthritis or proximal humerus fractures that make it difficult to determine humeral head height, neck angle, and retroversion. Poltaretskyi and colleagues[55] created and validated a statistical shape model (SSM) that is able to accurately recreate premorbid proximal humerus anatomy for osteoarthritis and proximal humerus fractures with varying diaphyseal extension. Although literature regarding humerus neck cuts is limited, Poltaretskyi's group envisions this SSM being applied to preoperatively plan a neck cut in 3 dimensions and create a patient-specific guide or project the premorbid anatomy onto the patient intraoperatively using augmented reality.

Patient-Specific Instrumentation

Background

Patient-specific instrumentation (PSI) is not a novel technique within orthopedics and has been utilized in other fields including total hip and knee arthroplasties.[56] Within the field of shoulder arthroplasty, PSI refers to sterilizable instruments that have been created based on preoperative 3-dimensional planning to better facilitate correct positioning of the components, most commonly the guide pin placement in the glenoid. PSI is an alternative to intraoperative navigation systems, which are expensive, not readily available to most surgeons performing shoulder arthroplasties,[27] have a higher learning curve, and can be cumbersome to use. PSI may provide similar levels of accuracy as navigation, while reducing the surgical cost and steps associated with navigation.

Importantly, PSI relies on 3-dimensional CT images and requires user input for the creation of the ideal guide pin trajectory, applying much of the same principles and outcomes discussed previously in preoperative imaging. Most commercial shoulder arthroplasty companies offer 3-dimensional planning software that is integrated with a manufacturing side to create these instruments with a typical turnaround of 3 to 6 weeks. The glenoid guide is typically 3-dimensionally printed using sterilizable resin that will sit on the patient's glenoid intraoperatively with a drill hole aligning the preplanned trajectory.[57,58] Some companies allow for the use of reusable glenoid targeting guides that can minimize the cost associated with PSI implementation (eg, the Arthrex 5D glenoid targeter guide).

Application and outcomes for patient-specific instrumentation

Several studies have showed greatly increased accuracy with PSI based on 3-dimensional preoperative planning. Hendel and colleagues[59] performed a prospective randomized controlled trial investigating the accuracy of 3-dimensional planning with the PSI method or 2-dimensional planning with a free-hand guide-pin placement intraoperatively to place a glenoid in neutral version and inclination. This group showed the use of 3-dimensional imaging and PSI is more accurate and precise, especially with regards to inclination and preoperative retroversion greater than 16° as the mean deviation from neutral version was retroverted 1.2° with PSI and retroverted 10° with conventional planning and instrumentation.[59] This was similarly supported by Throckmorton and colleagues,[50] who compared PSI and traditional instrumentation for aTSA and rTSA glenoid components, finding PSI guides to be more accurate and greatly reduce the amount of significant malpositioned components. Considered a landmark study applying 3-dimensional planning and PSI, Iannotti and colleagues[60] investigated glenoid guide-pin accuracy with standard instrumentation using 2-dimensional CT planning, 3-dimensional CT planning alone, and 3-dimensional CT planning with PSI. In this study, OrthoVis 3-dimensional software was used for glenoid component planning (neutral version and inclination) and to create a printed 3-dimensional model of the glenoid architecture with planned guide-pin placement for the PSI group. Intraoperatively, the Glenoid Intelligent Reusable Instrument System (Custom Orthopedic Solutions; now the Arthrex 5-dimensional glenoid targeter guide) was placed over the sterilized model's guide pin, and the guide's tines were adjusted to fit over the model's rim, customizing the PSI to the patient's anatomy for guide-pin placement. The authors found no significant difference in version, inclination, or entry point for 3-dimensional planned glenoid with or without the PSI, but did find that either 3-dimensional system (with or without the PSI) resulted in significant improvements in accuracy compared to 2-dimensional planning with standard instrumentation for guide-pin placement.[60] Fig. 2 shows intraoperative use of the Arthrex 5-dimensional targeter guide for guide-pin placement.

A systematic review and meta-analysis on PSI versus standard instrumentation published by Cabarcas and colleagues[61] found that standard instrumentation resulted in mean errors of 7.1° (range 3.5°–11.2°) for version, 8.45° (range 2.8°–11.65°) for inclination, and 2.6 mm (range 1.7–3.4 mm) for entry point offset. With the use of PSI, the average mean errors were reduced

Fig. 2. Intraoperative use of the Arthrex 5-dimensional targeter guide for glenoid guide-pin placement.

to 3.47° (range 0.5°–4.49°) for version, 2.36° (range 0.1°–4°) for inclination, and 1.67 mm (range 1.09–2.4 mm) for entry point offset.[61]

Villatte and colleagues[62] published a meta-analysis including 7 clinical and 5 cadaveric studies comparing 3-dimensional planned PSI with standard instrumentation, finding that while PSI provided higher accuracy, the mean difference between PSI (version: 2.73° ± 0.48; inclination: 1.88° ± 0.41; entry point 1.06 mm ± 0.2) and standard instrumentation (version: 5.88° ± 1.10; inclination: 5.78° ± 0.98; entry point 2.04 mm ± 0.4) was small and likely not clinically relevant. However, the percentage of components classified as outliers or significantly malpositioned was 68.6% using standard instruments and 15.3% using PSI, going further to state that PSI was much more accurate and precise, with higher degrees of preoperative retroversion or more complex glenoid deformity.[62] Thus, PSI may be more useful in complex deformity correction or for low-volume surgeons where inexperience may lead to higher malpositioned components.

Manufacturing time for PSI can be between 3 and 6 weeks, and costs can be significant, ranging from $500 to 1200.[58] For this reason, Darwood and colleagues[63] developed and published a novel method to create PSI intraoperatively in a sterile manner in under 4 minutes. Preoperatively, the group performed standard 3-dimensional planning and uploaded their guide pin planned trajectory into a robot fitted with sterile drapes and a drill in the operating room. After the glenoid is exposed, an elastic membrane blank is filled with a sterile moldable polymer. Once filled, the mold is pressed into the patient's glenoid and allowed to harden, creating a 3-dimensional replica of the surface of the glenoid. This hardened mold is placed on the robot, which utilizes the preoperative 3-dimensional plans to drill a guide for the glenoid pin. Once finished, the patient-specific instrument is ready for use. This group trialed this method on 24 cadaver shoulders and found exceptionally high accuracy with mean variations of guide-pin placement within 2° degrees of preoperatively planned version and inclination.[63] This method or reusable glenoid guide system (Arthrex 5-dimensional targeter) offers a promising solution to manufacturing time and costly commercial PSI.

Limitations

Further limitations do exist with the application of PSI. Gomes and Hendel and colleagues[57,59] both note that the software performing the 3-dimensional reconstruction and PSI creation may or may not remove calcified labrum or osteophytes; thus the PSI would require the surgeon to leave these structures in place until the guide pin is drilled or the PSI will not fit accurately. As adequate exposure of the glenoid can be difficult in patients, PSI use requires perfect exposure of the glenoid to clean off soft tissues that may prevent the guide from seating well. Additionally, most PSI utilizes a single guide-pin placement, which can predispose to off-axis reaming.[59,64] Finally, there are few data relating high accuracy of the guide-pin placement and glenoid component position to clinical outcomes. Also, reaming depth is not typically incorporated into PSI guides, which affects overall medialization of the joint line and is difficult to assess intraoperatively.

Summary Regarding the Use of Preoperative Planning

Preoperative planning with 3-dimensional CT images and the use of patient-specific instrumentation have been shown to improve the accuracy between the individual surgeon's preoperative ideal glenoid or humeral position and the final implanted position. Furthermore, the use of 2-dimensional imaging systems for measuring preoperative inclination and version may be inaccurate, compared with

3-dimensional imaging.[65] There are few data yet that clinically correlate this to improved patient outcomes, namely because of a lack of data that support what the correct glenoid version or inclination should be.[52] Some argue that the glenoid should be placed ideally at neutral version avoiding more than 15° degrees of retroversion and 0°-10° of inferior inclination to decrease stress on the rotator cuff and at the bone-implant surface.[10–12,66] Another school of thought supports recreation of the patient's pre-morbid version and inclination. Additionally, other factors such as glenoid guide pin entry point and reaming depth may also be critical for correct glenoid placement.[52] Future investigations are needed to elucidate what the ideal glenoid position should be, as preoperative 3-dimensional planning and patient-specific instrumentation can help achieve this accurately.

NAVIGATION

Background

Intraoperative navigation is a familiar concept within orthopedic surgery, especially within the fields of hip and knee arthroplasty, where its utilization has become more common.[67–69] Evidence within these fields has shown that navigation can improve accurate placement of components, while reducing outliers leading to malpositioning.[69,70] Similarly, navigation could offer great benefits in shoulder arthroplasty, especially with regards to accuracy of the humeral head cut, glenoid component position, and stable fixation of glenoid baseplate for rTSA; however, navigation has not become as utilized for shoulder arthroplasty as it has for knee and hip arthroplasty. As stated previously, proper glenoid position can potentially decrease glenoid loosening and decrease need for revisions, offering advantages similar to patient-specific instrumentation, MR, and 3-dimensional CT preoperative planning. Specific advantages related to navigation include the ability to detect glenoid reaming depth, improve reverse arthroplasty baseplate screw trajectory to maximize length, and offer dynamic real-time feedback. An important utility of navigation is the real-time feedback for ideal trajectory and screw length with glenoid baseplate fixation. As discussed previously, accurate trajectory of baseplate screws is critical to minimize complications and maximize screw purchase to decrease micromotion and aseptic loosening.[18–26]

Many commercial and noncommercial investigational navigation systems exist and are reported in the literature. The typical process for navigation involves preoperative and intraoperative steps that can increase planning and surgical times.[71,72] Preoperatively, either 2-dimensional or 3-dimensional CT scans are uploaded to planning software where the surgeon plans preferred humeral cuts, glenoid component position with or without use of augmentation or grafting, and baseplate screw trajectory for rTSA. After glenoid exposure intraoperatively, a registration process occurs to allow the navigation system to orient the preoperative plan with the patient's anatomy. Registration typically occurs with a fixed optical sensor on the coracoid and manual pinpoint registration of unique points along the acromion, coracoid, and glenoid face. Following registration, most commercial systems utilize optical tracking devices on the drills and saws to achieve correct orientation with planned measurements. The following section reviews important literature regarding the validity, accuracy, and limitations of navigation for shoulder arthroplasty. An overview of the commercially available navigation systems can be found in Table 2.

Intraoperative Navigation for Shoulder Arthroplasty

In one of the earliest studies regarding shoulder arthroplasty navigation, Edwards and colleagues[73] published a validation study for intraoperative navigation, confirming a high degree of agreement between intraoperative measurements made with navigation and postoperative CT measurements. Aminov and colleagues[74] utilized a dental navigation system (Navigate Surgical Technologies) to trial navigation on 3-dimensional printed scapula models to assist with glenoid guide-pin placement with planned neutral version and inclination, finding high accuracy with near-perfect placement of the guide pin. The authors of this study noted the cheap, low-profile, and already wide availability of this navigation system. Nguyen and colleagues[75] compared glenoid implant position in anatomic shoulder replacement using standard instrumentation with navigation using 3-dimensional models of 16 cadaver shoulders with preprocedure 3-dimensional CT planning for neutral glenoid version and inclination. Navigation was significantly more accurate than standard instrumentation for final implant version (1.5° ± 1.9° and 7.4° ± 3.8, respectively), with no significance found for final inclination, but navigation was more accurate. The authors measured version at all steps for glenoid component placement–guide pin, reaming, and final implantation after cementing–finding significant alterations and increased variability in version and inclination

Table 2
Intraoperative shoulder arthroplasty navigation systems

Company	System	Description
Exactech	ExactechGPS	Utilizes a fixed tracker placed into the coracoid, as well as landmark registration. Instruments are tracked during all steps of glenoid component placement: guide pin placement, reaming, baseplate and glenosphere placement, and baseplate screw depth/trajectory. Used with the Exactech Equinoxe shoulder system.
Kinamed	NaviPro Shoulder	Navigation system that can be universally used with all shoulder systems – reverse or anatomic. Tacking system used for glenoid component placement, as well as humeral cut version and inclination measurement.

during the reaming and cementation steps for standard and navigated processed. They noted while guide-pin placement is a critical step for final position, off-axis reaming and nonsymmetric seating during cementation may be other sources of component placement error that would benefit from the navigation process.[76]

Several cadaveric studies using navigation for glenoid guide-pin placement have been published, finding that navigation resulted in high accuracy. Using the ExactechGPS system, Colasanti and colleagues[77] had an average mean guide-pin placement of 3.1° plus or minus 2° in anteversion and inferior inclination of 5.4° when planning for neutral version and 10° of inferior tilt. Verborgt and colleagues[78] performed a cadaveric study on 14 shoulders using 2-dimensional CT planning (neutral version and 10° inferior tilt) to compare glenoid component and baseplate screw placement with and without navigation. Navigation resulted in significantly more accurate component placement than without navigation in both version (3.1° vs 8.7° anteversion, respectively) and inclination (−5.4° vs +0.9°, respectively), with postprocedure dissection finding less glenoid vault screw violation with navigation (2 screws with navigation and 5 without).[78]

Similar to cadaveric studies, multiple studies investigating navigated shoulder arthroplasty in patients have been published. Kircher and colleagues[79] reported on increased surgical time needed for 2-dimensional CT-planned navigation in a small cohort of patients. Because of significant issues and errors with the intraoperative registration process, navigation was aborted in 6 cases, but of those completed, navigation increased surgical time by 31 minutes (169.5 minutes with navigation vs 138 minutes without navigation), which could be explained by a higher learning curve needed with navigation to become efficient, as this study only included 10 patients in the navigation arm.[79] The possible learning curve associated with navigation was investigated by Wang and colleagues[80] utilizing the ExactechGPS system in 24 reverse arthroplasties. Compared with Kircher and colleagues,[80] Wang's study found little difference in surgical time utilizing navigation (77.3 minutes ± 11.8 with navigation and 78.5 minutes ± 18.1 without navigation), and found that surgical time seemed to decrease and plateau after the first 8 cases of a surgeon utilizing navigation for reverse shoulder arthroplasty. Finally, Schoch and colleagues[81] reported on glenoid component position accuracy with navigation, comparing high-volume attending surgeons with lower-volume orthopedic surgery fellows. Using the ExactechGPS system, the mean errors compared with preoperative plans were reported. The mean version error was 6.4° anteverted, with 49% of shoulders exceeding 5° of error and 25% exceeding 10°. Similarly, the mean inclination error was 6.6° of superior tilt (50% exceeded 5° of error and 25% exceeding 10°), and the mean guide pin entry point error was 3.2 mm, with 18% exceeding 4 mm.[81] With these measurements, navigation resulted in 48% of components being malpositioned based on the criteria from Throckmorton and colleagues.[50] While this is considerable, the authors note that their malpositioning was less with navigation than those with standard instrumentation without navigation seen in Throckmorton's study, recommending the use of navigation or patient-specific instrumentation for lower-volume surgeons.[81]

Sadoghi and colleagues[82] published a systematic review of 5 studies including 117 navigated and 114 non-navigated shoulder anatomic and reverse arthroplasties investigating glenoid component placement accuracy, with the included studies planning for neutral version and 0° tilt of the component. They found navigation resulted in significantly improved accuracy utilizing navigation for version (4.4° ± 0.41 with navigation and 10.6° ± 0.67 without navigation).[82] Similarly, Burns and colleagues[83] performed a review of 9 studies comparing glenoid component placement utilizing PSI or navigation with standard instrumentation. When analyzing studies with control groups (standard instrumentation), both PSI and navigation resulted in significant improvements in accuracy of guide-pin placement compared with standard instrumentation resulting in a higher amount of malpositioned implants.[83] With these results in mind, the authors recommended the use of either PSI or navigation to improve the inaccuracy that occurs with standard instrumentation.

Because of the previously mentioned importance of glenoid baseplate screw fixation, several studies also investigated the effect navigation has on baseplate fixation in rTSA. Moreschini and colleagues[84] compared baseplate screw number to achieve solid fixation and mean length of baseplate screw implanted with ExactechGPS navigation compared to preoperative planning with just 2-dimensional CT imaging. They found that navigation required only 11 more minutes of surgical time and resulted in a mean screw length of 35.5 mm with navigation versus 29.2 mm without navigation, also noting that more than 2 screws were needed for stable fixation in only 40.9% of patients with navigation but 85% of patients without navigation. Similarly, Hones and colleagues[85] performed a similar study with 200 patients divided equally between baseplate screw placement with and without navigation, finding a significant increase in average screw lengths with navigation (35 mm with navigation and 32.6 mm without navigation). Finally, Sprowls and colleagues[86] found that navigation resulted in longer mean screw length (36.7 mm with navigation and 30 mm without navigation), longer composite screw length (84 mm with navigation and 76 mm without navigation), and more baseplates achieving solid fixation with just 2 screws (68.6% with navigation and 50.8% without navigation). This group also noted navigation increased operative times by roughly 13 minutes and significantly improved accuracy of component version.

Although much of the literature regarding navigation in shoulder arthroplasty revolves around the glenoid, there are a few studies looking at navigation for the humeral component. Humeral head osteotomy can dictate the component height, version, and neck-shaft angle (NSA), and alterations in these values can predispose to early failure or complications. For instance, a humeral cut too low can damage the cuff insertion and tuberosities, or increase instability, while a cut too high can potentially overstuff the joint leading to early failure.[1,87,88] To investigate the use of navigation during the humeral neck osteotomy, Cavanagh and colleagues[89] utilized 3-dimensional printed shoulders from cadaver models to compare the use of a PSI with navigation based on preplanned values for the humeral height, version, and NSA. They found that there was no significant or clinically relevant difference between using a PSI jig or navigation for the osteotomy in either arthritic or nonarthritic shoulders.

Summary Regarding Navigated Shoulder Arthroplasty

As in knee and hip arthroplasty, navigation in shoulder arthroplasty can have great benefits on improving the accuracy of the glenoid component position, maximizing baseplate fixation, and decreasing the occurrence of malpositioned implants or baseplate screws. Additionally, similar to PSI, navigation may be more beneficial for lower-volume surgeons to limit implant malpositioning.[81] However, there are a number of limitations, including the added surgical time supported by most studies,[79,84,86] high cost, intraoperative navigation malfunctioning,[79] and lack of easy portability. Compared with PSI, navigation can be used for baseplate screw placement, but the accuracy for glenoid guide-pin placement or humeral neck osteotomy is not significantly different with navigation. More studies are needed to justify the utility of navigation over PSI for use in shoulder arthroplasty, especially in anatomic TSA when baseplate screw fixation is not of concern.

MIXED REALITY

Background

As has been discussed, 3-dimensional preoperative planning, patient-specific instrumentation, and intraoperative navigation can greatly improve surgical plans, produce fewer malpositioned implants, and increase the overall accuracy for glenoid positioning. Despite this, PSI and navigation are expensive. Additionally, PSI product turnaround is slow, navigation can be cumbersome to utilize in the operating room, and both increase surgical or preoperative planning time.[62,82] An alternative or adjunct to the previously mentioned methods of accurate glenoid component placement revolves around the cutting-edge technology of MR (or augmented reality [AR]) devices. MR devices are being introduced into the literature and fields of neurosurgery and vascular surgery, with orthopedic surgery following suit. Within orthopedic surgery, MR has been investigated for the use in education, spine instrumentation, trauma involving pelvic and femur fractures, osteotomies, and hip and knee arthroplasty.[90] An overview of available MR systems in shoulder arthroplasty can be found in Table 3.

Application of Mixed Reality in Shoulder Arthroplasty

Thus far, MR has been mainly limited to 3-dimensional models, cadavers, and in patients to a limited extent, but there is great promise for more widespread application. This is especially true for shoulder arthroplasty for similar reasons to the use of navigation and PSI: glenoid component positioning and better understanding of patient anatomy intraoperatively.

One of the earlier applications of MR technology was published in 2019 by Berhouet and colleagues[91], who utilized a novel method to approximate a patient's premorbid glenoid anatomy and project this onto the surgical field to aid in glenoid component placement. In this study, Berhouet's team created a 3-dimensional CT library of healthy, generic scapula models and devised a method to create a crude premorbid 3-dimensional image of a patient's glenoid and scapula. This crude model was morphed with a similar generic scapula out of their library to create a refined glenoid/scapula model that best approximated the patient's premorbid state. This 3-dimensional reconstruction was uploaded to Epson Moverio BT-200 smart glasses (Seiko Epson Corporation, Nagano, Suwa, Japan), which would be worn by the surgeon to project the premorbid scapula onto the patient's shoulder intraoperatively. This ideally would allow the surgeon to better understand premorbid anatomy for correct glenoid guide-pin placement.[91]

Following this, Kriechling and colleagues[92,93] investigated the use of MR technology on glenoid guide-pin placement in a 3-dimensional printed scapula model, followed by a cadaveric study. This group utilized 3-dimensional CT for preoperative planning of guide-pin placement for rTSA, aiming for 0° version and inclination with an inferiorly oriented entry point for an inferiorly placed baseplate. The plan was uploaded to Microsoft cloud and the Microsoft HoloLens1 (Microsoft Corporation, Redmond, Washington). Kriechling created a custom registration device to pinpoint the acromion, coracoid, and glenoid to match the intraoperative surface with the 3-dimensional CT. After registration, the 3-dimensional scapula image and planned guide pin trajectory are holographically projected onto the surgeon's field of view through the glasses. High accuracy of the guide pin trajectory on postoperative CT was found utilizing the above MR method. The 3-dimensional model method resulted in a mean trajectory error (encompassing version and inclination) of 2.7° plus or minus 1.3 and entry point error of 2.3 mm plus or minus 1.1, while cadaveric use resulted in similarly accurate placement with mean trajectory error of 3.8 plus or minus 1.7 and entry point error of 3.5 mm plus or minus 1.7.[94,95]

In similar studies, Schlueter-Brust and colleagues and Gregory and colleagues utilized Microsoft's HoloLens2 technology without the use of an intraoperative registration

Table 3
Mixed reality systems in shoulder arthroplasty

Company	System	Description
Stryker	Blueprint Mixed Reality	Preoperative 3-dimensional planning with Blueprint. Headset worn intraoperatively shows 3-dimensional image of preoperative humeral and glenoid plans.
Microsoft	HoloLens	Preoperative 3-dimensional planning is uploaded to the HoloLens worn intraoperatively. The HoloLens overlays a holographic image of the preoperative plan. Used in several studies with and without a registration process. Registration process can help the holographic image overlay to remain fixed on the patient's anatomy intraoperatively.
Medacta	NextAR	Preoperative 3-dimensional planning with MyShoulder. Intraoperative hybrid navigation and MR system that utilizes a fixed tracker on the coracoid and instrument trackers for all steps of glenoid component placement. NextAR Smart Glasses worn intraoperatively displays the real-time feedback from the navigated system with the preoperative plan.

process.[94,95] Schlueter-Brust's team performed a cadaveric study investigating the accuracy of glenoid guide-pin placement with a preoperatively planned 3-dimensional scapular image overlayed via the MR device without a registration process. Their results showed a mean trajectory error (again accounting for combined inclination and version) of 3.9 plus or minus 2.4 and entry point error of 2.4 mm plus or minus 0.7.[96] Gregory and colleagues[95] performed a reverse shoulder arthroplasty utilizing the HoloLens2 on the patient. Intraoperatively, the HoloLens2 projected the preoperative plan on the patient's unregistered glenoid, while the HoloLens2 was connected to a video conference with 4 other surgeons in different countries who could offer real-time advice and adjust the heads-up display (HUD). Although actual measurements of the glenoid component position were not measured, the authors noted adequate position of the component with a surgical duration of 90 minutes.

In the most recent and advanced use of MR technology, Rojas and colleagues[96] described a procedure to use a combination of MR technology and intraoperative navigation on a patient undergoing rTSA. The 3-dimensional preoperative plans were uploaded to a navigated MR system NextAR (Medacta International), which utilizes an intraoperative control-unit (CU) with video display, a fixed tracking device implanted into the coracoid via K-wire, camera tracker that is attachable to all surgical instruments, and glasses to provide a HUD for the surgeon. Registration begins with the 4 borders of the glenoid and then incorporates 15 unique points on the coracoid and glenoid to overlay the 3-dimensional plan onto both the CU and the surgeon's HUD. During all steps of glenoid component placement (utilizing the variably applied camera tracker), the surgeon is provided with real-time versus planned trajectory information, including version, inclination, entry-point position, reaming depth, baseplate placement, and ideal baseplate screw trajectory to maximize length.[96]

Advantages and Limitations of Mixed Reality Technology

These prior studies each show the various advantages and limitations for the application of MR technology in shoulder arthroplasty. Overall, the accuracy of guide-pin placement using MR technology is better compared to free-hand placement, lending to its great prospect in helping maximize accuracy and decrease malpositioning, especially for lower-volume surgeons.[61,92–94] MR technology provides real-time information of glenoid component placement similar to navigation as opposed to PSI with delayed post-operative feedback. The display of information on the HUD allows the surgeon to stay focused on the surgical field compared with pure navigation strategies, and the tracker registration process is simple to use.[96] Registration simplifies and streamlines the HUD overlay process. Schlueter-Brust and colleagues and Gregory and colleagues note the need to virtually drag, rotate, and resize the overlayed scapular hologram while holding the surgeon's head still to keep the scapula hologram from moving, while registration establishes and maintains the virtual position of the scapular hologram on the patient.[92–96]

Limitations are related to the typical availability of these MR head-sets, preoperative 3-dimensional planning software, cost, and possibility for coracoid fracture if a combined MR-navigation strategy is used.[96] The Microsoft HoloLens2 retails for $3500, which is more expensive than PSI but is reusable and vastly cheaper than navigation systems. Additionally, most available MR wearable devices are designed for entertainment and multimedia viewing, which may hinder the accuracy and precision.[91–95]

Summary and Future Ventures for Mixed Reality in Shoulder Arthroplasty

Mixed or augmented-reality provides an exciting application to the field of shoulder arthroplasty that improves on the possible disadvantages of 3-dimensional planning alone, PSI, and sole use of intraoperative navigation, while outperforming standard instrument free-hand glenoid guide-pin placement. Literature is limited on the use of this technology in shoulder arthroplasty, and future studies could investigate the use on patients to correlate with clinical outcomes. MR technology is being utilized in medical education, and this technology can similarly be applied to resident training within shoulder arthroplasty, intraoperative telementoring or teleconferencing for difficult glenoid deformities or surgeons early into practice, and postoperative performance evaluation and critiquing.[95,97]

SUMMARY

Although the ideal component positions to optimize patient outcomes following shoulder arthroplasty remain unknown, accurate placement of the glenoid and humeral components is critical for long-term survival. Preoperative planning with 3-dimensional CT is becoming a commonly utilized strategy to better understand patient anatomy for operative success. Further research is needed and warranted to find the role of other intraoperative assistive devices in shoulder arthroplasty, including patient-specific instrumentation, navigation, and MR; however, this field is already showing great promise towards achieving this goal and likely represents the future of shoulder arthroplasty.

CLINICS CARE POINTS

- Accurate and precise placement of shoulder arthroplasty components is thought to maximize postoperative function and increase long-term implant survival.
- Preoperative planning with 3-dimensional CT scapula reconstructions adds critical information for understanding complex glenoid deformities and being adequately prepared for intraoperative success.
- Patient-specific instrumentation, intraoperative navigation, and MR increase a surgeon's ability to replicate preoperative plans, minimize component malposition, and maximize fixation during shoulder arthroplasty.

DISCLOSURE

The authors have nothing to disclose.

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