



Research Article

Development of a 3D Printing and Virtual Reality Workflow for Glenoid Fracture Preoperative Planning: A Scoping Review and Preliminary Survey of Surgeons

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Abstract

Glenoid fractures pose a significant challenge for preoperative planning because their complex, comminuted three-dimensional anatomy is incompletely represented by conventional two-dimensional computed tomography (CT). This study aimed to (i) map the evidence on three-dimensional (3D) printing and virtual/augmented reality (VR/AR) for glenoid fracture and related shoulder surgical planning, (ii) assess the technical feasibility of an institutional CT-to-3D-print and CT-to-VR workflow, and (iii) explore preliminary surgeon perceptions. A scoping review was conducted using Joanna Briggs Institute methodology and reported according to PRISMA-ScR. PubMed, Scopus, Web of Science, IEEE Xplore, and Cochrane Library were searched for English-language studies published from 2010 to 2026. Following duplicate removal and dual-reviewer screening, 20 sources were charted narratively. An institutional workflow was also developed and piloted using anonymised DICOM data with 3D Slicer, Meshmixer, Blender, and Unity. In addition, a 25-item anonymous survey was distributed to 20 orthopaedic clinicians, with eight responses (40%); open-text responses were analysed using template analysis. The evidence comprised cadaveric experiments, case reports/series, retrospective and comparative studies, technical feasibility studies, narrative reviews, and systematic reviews, with generally low-to-moderate methodological certainty. Reported benefits included improved implant positioning, reduced planning or operative time, enhanced anatomical understanding, and educational value. The institutional workflow was technically feasible but encountered print fragility in thin, comminuted regions, and dimensional accuracy was not formally validated. Six respondents (75%) perceived improved understanding of fracture morphology, while five (62.5%) had never personally used 3D printing or VR. Qualitative responses highlighted enhanced spatial understanding, planning confidence, educational and collaborative benefits, cost and accessibility barriers, and preference for selective rather than routine use. Overall, current evidence and preliminary clinician feedback support the feasibility and perceived value of 3D printing and VR in glenoid fracture planning; however, the evidence base remains immature. Rigorous dimensional validation and adequately powered clinical outcome studies are required before routine clinical adoption can be recommended.

Keywords

Glenoid Fracture, 3D Printing, Virtual Reality, Preoperative Planning, Scoping Review, Shoulder Arthroplasty, Surgical Education

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1. Introduction

Glenoid fractures, whether isolated or occurring as part of a complex scapular or shoulder girdle injury, remain among the more technically demanding problems in orthopaedic trauma and reconstructive shoulder surgery. The glenoid's small articular surface, variable version and inclination, and propensity for comminution in high-energy injury mean that even experienced surgeons can find it difficult to fully appreciate fracture morphology, fragment displacement, and bone loss from two-dimensional (2D) axial, sagittal, and coronal computed tomography (CT) images alone. Preoperative planning built on 2D imaging requires the surgeon to mentally reconstruct a three-dimensional (3D) structure from sequential 2D slices. This cognitively demanding step is a recognised source of intraoperative surprise, implant malposition, and prolonged operative time [1].

Over the past decade, patient-specific 3D printing and immersive virtual reality (VR), often alongside augmented reality (AR), have been increasingly explored as adjuncts to conventional imaging in orthopaedic preoperative planning. Physical 3D-printed models allow direct handling and inspection of fracture fragments; VR/AR platforms allow immersive, manipulable visualisation and, in some intraoperative applications, real-time surgical navigation. Early reports across shoulder arthroplasty and glenoid reconstruction describe improvements in implant positioning accuracy, reduced operative time, and gains in trainee confidence [2-4]. However, this literature is markedly heterogeneous: it spans cadaveric biomechanical studies, single-patient case reports, small case series, technical feasibility papers, and narrative reviews, using outcome measures ranging from millimetre or degree deviations in guide-pin placement to validated shoulder function scores to purely descriptive accounts of surgeon experience. This heterogeneity has two consequences for anyone attempting to summarise the field: first, formal meta-analytic pooling of effect sizes is not statistically defensible, because the outcome constructs are not commensurable across studies; second, a review that seeks to establish the current extent and nature of the evidence instead of estimating the pooled treatment effect will be a methodologically appropriate tool.

This is the rationale for adopting scoping review methodology in the present work, following the framework originally described by Arksey and O'Malley [5] and subsequently refined by the Joanna Briggs Institute [6] and reported using the PRISMA extension for scoping reviews, PRISMA-ScR [7]. Scoping reviews are indicated when the purpose is to map the breadth of available evidence, identify gaps, and clarify concepts in an emerging or heterogeneous field, as opposed to

systematic reviews, which are best suited to answering a narrowly defined question from studies sharing comparable designs and outcomes [8]. Given the composition of the available literature on 3D printing and VR in glenoid fracture planning, a scoping approach with narrative, tabulated charting is more appropriate than quantitative synthesis. This was judged the only methodologically honest option.

Alongside this evidence map, the research reports the development of a reproducible institutional workflow for converting routine CT DICOM data into both a physical 3D-printed model and an immersive VR environment, and then presents preliminary, exploratory survey data on how a small group of orthopaedic clinicians perceive these tools. The researcher also presents the workflow and survey as hypothesis-generating technical and pilot findings, not as a validation study or a definitive account of clinical utility; the distinction is deliberate and is returned to throughout. The following are the research objectives:

- 1) To systematically identify, chart, and narratively synthesise the published literature describing the development, application, or evaluation of 3D printing and VR/AR technologies in preoperative planning for glenoid fractures and related shoulder reconstructive procedures.
- 2) To describe the development and technical feasibility of an institutional, reproducible workflow converting patient CT DICOM data into a physical 3D-printed glenoid model and an interactive VR anatomical environment.
- 3) To explore, through a small cross-sectional survey, how orthopaedic surgeons and trainees currently perceive the utility, accuracy, accessibility, and educational value of 3D printing and VR relative to conventional 2D CT in glenoid fracture planning.

2. Methods

2.1. Protocol and Registration

This scoping review was not yet prospectively registered as of the last update of this work. Prospective registration (e.g., via the Open Science Framework) is recommended for any subsequent update of this review.

2.2. Eligibility Criteria

Eligibility was defined using the Population-Concept-Context (PCC) framework recommended for scoping reviews [6], summarised in Table 1.

Table 1. Population-Concept-Context (PCC) framework defining eligibility.

Element	Definition
Population	Patients with glenoid fractures, glenoid bone loss, or glenoid pathology undergoing preoperative planning for fixation or shoulder arthroplasty; orthopaedic surgeons and trainees involved in that planning.
Concept	Development, technical description, clinical application, or evaluation (including user-perception evaluation) of 3D printing, virtual reality, and/or augmented reality technologies in preoperative planning.
Context	Any clinical, cadaveric, technical, or educational setting reporting an application relevant to glenoid fracture or shoulder arthroplasty preoperative planning; peer-reviewed, English-language sources published 2010-2026.

Full inclusion and exclusion criteria are shown in [Table 2](#).

Table 2. Inclusion and exclusion criteria for source selection.

Criterion	Inclusion
Peer review	Peer-reviewed journal articles
Publication date	2010-2026
Language	English
Focus	Glenoid fracture/shoulder arthroplasty preoperative planning using 3D printing, VR, or AR
Study type	Human clinical, cadaveric, or technical feasibility studies
Duplicates	Unique records only

2.3. Information Sources and Search Strategy

Five databases were searched, selected for their coverage of clinical and biomedical engineering literature: PubMed, Scopus, Web of Science, IEEE Xplore, and the Cochrane Library. Search strings combined controlled vocabulary (MeSH terms) and free-text keywords using Boolean operators, truncation, and proximity operators, for example: (“3D printing” OR “additive manufacturing”) AND (“virtual reality” OR “VR” OR “augmented reality” OR “AR”) AND (“preoperative planning” OR “surgical simulation”) AND (“glenoid fracture” OR “shoulder fracture” OR “shoulder arthroplasty”). Each query was adapted to the syntax of the individual database (e.g., PubMed MeSH mapping). The identical search strategy was re-run across all five databases in August 2026 to extend the coverage window from 2010-2025 to 2010-2026 and to identify any evidence published since the original search; this updated search and its screening are reported alongside the original results throughout Sections 3 and 4.

2.4. Selection of Sources of Evidence

Records were imported into Zotero for duplicate detection and citation management. Screening was conducted by two

reviewers in two stages: title/abstract screening followed by full-text assessment against the eligibility criteria in [Table 2](#). Dual independent screening was adopted to avoid and minimise selection bias. The full selection process is shown as a PRISMA-ScR flow diagram ([Figure 1](#)).

2.5. Data Charting Process and Data Items

A structured charting form was used to extract, for each included source: author(s) and year, journal, country/setting (where reported), study design, sample or context, technology used (3D printing, VR, AR, or combined), key reported outcomes, and the review objective(s) each source addressed. Charted data are presented narratively and in tabular form ([Table 3](#)); no attempt was made to recode heterogeneous outcome measures onto a common numerical scale.

2.6. Critical Appraisal of Sources of Evidence

Consistent with JBI scoping review guidance, critical appraisal was used descriptively to characterise the design and methodological features of included sources. This method was adopted as an alternative basis for exclusion [\[6\]](#). Design features (cadaveric vs. clinical, sample size, presence/absence of

a comparator) were charted for each source and are summarised in Table 3 and Figure 2; no numerical quality score is reported, and readers should interpret the charted evidence with this in mind rather than inferring a formal risk-of-bias rating.

2.7. Synthesis of Results

Given the heterogeneity of study designs (cadaveric experimental, case series, retrospective comparative, technical feasibility, narrative review) and outcome constructs (linear/angular deviation, correlation coefficients, validated shoulder outcome scores, descriptive surgeon feedback) across the 20 included sources, meta-analytic pooling of effect sizes was not undertaken. This is a deliberate methodological decision, not an omission: pooling incommensurable outcome types into a single effect-size metric would misrepresent the underlying data and cannot be meaningfully interpreted. Findings are instead synthesised narratively, organised by review objective, and supplemented with a purely descriptive summary of study design frequencies (Figure 2).

2.8. Development of the 3D Printing and VR Workflow

An institutional workflow was developed and technically piloted using anonymised patient CT DICOM data obtained, with Caldicott Guardian and NHS Tayside approval, from Ninewells Hospital (University of Dundee teaching hospital).

Step 1 — Imaging data acquisition

High-resolution CT of the shoulder was acquired and exported in DICOM format, the international standard for medical imaging data interchange.

Step 2 — Segmentation and 3D print preparation

DICOM data were imported into 3D Slicer. Volume rendering with a CT bone preset was used to generate a detailed anatomical model of the glenoid and simulate the fracture pattern; segmentation tools isolated the fractured region from surrounding soft tissue and bone. The resulting model was exported in STL format. Because the comminuted, multi-fragment glenoid geometry proved difficult to print as a single piece, the model was split (Meshmixer, 90° vertical section) prior to printing on a LulzBot TAZ printer (Cura slicing software).

Step 3 — VR model creation

The same segmented model was imported into Blender and converted from STL to FBX format, preserving geometric fidelity, before import into Unity, where a pre-built interactive VR environment enabled rotation, zoom, and manipulation of the glenoid model in an immersive three-dimensional space.

2.9. Survey of Surgeons

An anonymous, cross-sectional online questionnaire (Google Forms) was distributed to 20 orthopaedic clinicians

(consultants, residents, and medical officers) with an interest in shoulder and trauma surgery; 8 responded (response rate 40%). The questionnaire combined single-select categorical items, a small number of Likert-type items, and open-text questions covering familiarity with 2D CT, prior experience with 3D printing/VR, perceived advantages and limitations of each modality, and views on accessibility and future adoption. No formal psychometric validation or piloting of the instrument was undertaken, which is disclosed as a limitation (Section 6.5).

Given the small sample ($n = 8$), analysis of categorical/Likert items was restricted to descriptive statistics (frequencies and percentages); no inferential statistical testing was performed, as the sample size does not support meaningful parametric or non-parametric hypothesis testing. Open-text responses were analysed using template analysis [9], a flexible qualitative technique well suited to small, applied datasets: an initial coding template was derived deductively from the three review objectives, then refined iteratively as codes were applied line-by-line to the verbatim free-text responses, producing the five themes reported in Section 3.5.3. All illustrative quotations reported below are reproduced verbatim, including original phrasing and minor typographical idiosyncrasies, from the underlying response data, and are attributed to the specific survey item under which each was recorded.

2.10. Ethical Considerations

The study was conducted under Caldicott Guardian principles and with approval from NHS Tayside via Ninewells Hospital, University of Dundee, for access to anonymised CT DICOM data. Only publicly available, peer-reviewed sources were used for the scoping review component. Survey responses were collected anonymously; no personal health information was gathered from survey respondents; participation was voluntary with the right to withdraw; and data were handled in accordance with UK GDPR.

3. Results

3.1. Selection of Sources of Evidence

The initial search returned 387 records (PubMed $n=125$, Scopus $n=98$, Web of Science $n=74$, IEEE Xplore $n=52$, Cochrane Library $n=38$). After removal of 102 duplicates, 285 records underwent title/abstract screening, of which 199 were excluded as not relevant to glenoid fracture, 3D printing, or VR/AR in preoperative planning. The remaining 86 records underwent full-text assessment; 71 were excluded (28 not focused on 3D/VR preoperative planning, 19 not peer-reviewed, 12 animal/in-vitro studies, 12 judged to lack sufficient methodological detail for charting), leaving 20 sources of evidence for charting (Figure 1; updated 2026 search adds 5 sources to the original 15).

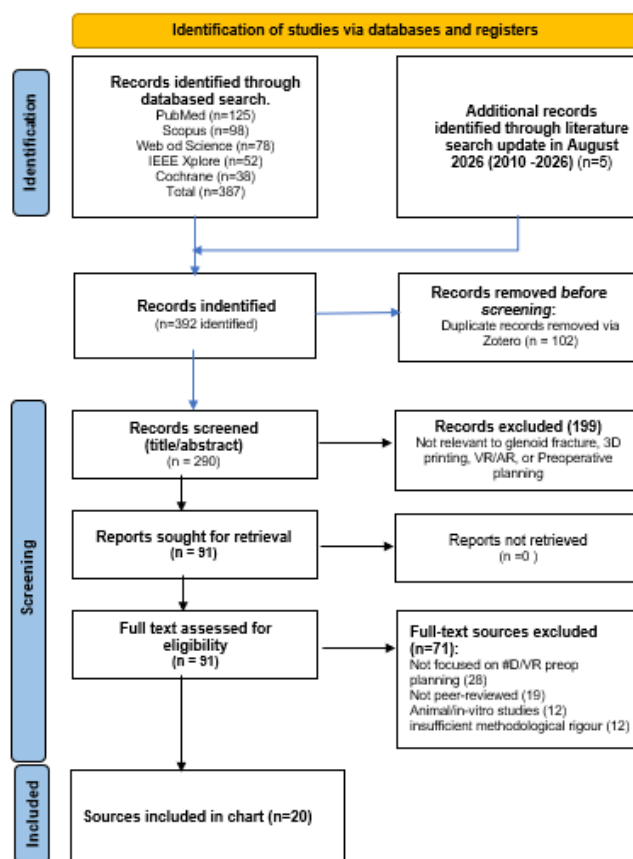


Figure 1. PRISMA-ScR flow diagram of source identification, screening, and inclusion.

3.2. Characteristics of Included Sources of Evidence

The 20 included sources were published between 2018 and 2026 and originated from a geographically diverse set of settings including Germany, Brazil, the United Kingdom, China,

Greece, Spain, Turkey, Chile, Canada, Italy, Switzerland, and the United States. Designs comprised 4 cadaveric experimental studies, 5 case reports/series, 4 retrospective/comparative anatomical or clinical studies, 2 technical feasibility studies, 2 integrative/narrative reviews, and 3 systematic reviews (Figure 2). Full charted details are shown in Table 3.

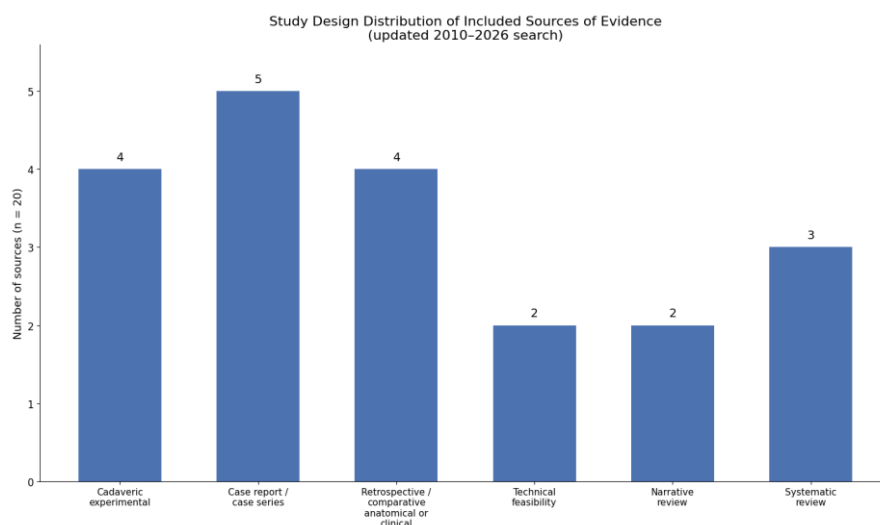


Figure 2. Study design distribution of the 20 included sources of evidence (descriptive count; not an effect-size synthesis).

Table 3. Characteristics of sources of evidence included in scoping review charting.

#	Author(s), Year	Focus	Design	Sample/Context	Key charted outcome(s)	Obj.
1	Dey Hazra et al. (2025)	AR-assisted navigation in RTSA	Cadaveric study	16 shoulders	Improved glenoid inclination accuracy, reduced surgeon-to-surgeon variability	I, II
2	Rojas et al. (2022)	HMD-based AR for glenoid component placement	Feasibility study (cadaver + in vivo)	Cadaver + clinical case	Enhanced trajectory control and intraoperative guidance	I, II
3	La Banca et al. (2023)	3D-printed anatomy mapping	Retrospective anatomical study	39 CT scapulae	Validated 3D-printed morphology for anatomical modelling	I
4	Archetti Netto et al. (2021)	3D vs CT planning comparison	Cadaveric comparative study	81 scapular models	Modest advantage of 3D over CT-only for glenoid component alignment	I, II
5	Handal et al. (2023)	VR surgical rehearsal	Case study	1 surgeon / 1 case	Enhanced trainee confidence, fewer intraoperative corrections	II, III
6	Al Najjar et al. (2018)	3D-printed morphometry	Comparative anatomical study	32 scapulae	Higher reported reliability of glenoid measurement with 3D models	I
7	Alemayehu et al. (2021)	General narrative review	Narrative review	Multiple studies	Time-saving and accuracy gains reported across orthopaedic applications	II, III
8	Fleet et al. (2024)	Surgical navigation comparison	Cadaveric biomechanical study	20 scapulae	Mixed-reality navigation reported most accurate for pin placement among compared modalities.	I, II
9	Kolac et al. (2024)	Clinical integration overview	Integrative/narrative review	Multi-centre literature	Reported improvements in planning and execution across shoulder arthroplasty literature	I, II, III
10	Huang et al. (2024a)	Implant biomechanics	Cadaveric biomechanical study	25 cadaver shoulders	Improved load distribution and glenoid stability with 3D-printed titanium pad	I
11	Schlueter-Brust et al. (2021)	AR-assisted K-wire placement	Phantom proof-of-concept study	9 phantom models	Entry-point deviation <2.4 mm; angular deviation <3.9 °versus free-hand technique	I, II
12	Yiannakopoulos et al. (2024)	3D print vs CT dimensional comparison	Anatomical validation study	62 CT scans	High correlation between 3D-printed and CT glenoid dimensions ($r > 0.89$)	I
13	Trikoupis et al. (2024)	Tumour-related glenoid reconstruction	Case series	4 patients	Satisfactory outcome and implant fit after 3D-planned partial scapulectomy/RTSA	I, III
14	Huang et al. (2024b)	Clinical implant outcomes	Retrospective clinical study	12 military patients	Significant postoperative improvement in ASES, Rowe, and Constant scores	I, II
15	Fillat-Gomà et al. (2021)	Full workflow with patient-specific instrumentation	Case series	8 trauma cases	Reduced operative time, high planning accuracy, no reported complications	I, II, III
16	Longo et al. (2024)	Metaverse/AR/VR in shoulder arthroplasty	Systematic review	22 studies (793 navigated patients; 53 trainees)	AR/VR navigation reported comparable or improved glenoid component accuracy versus conventional	I, II, III

#	Author(s), Year	Focus	Design	Sample/Context	Key charted outcome(s)	Obj.
				in 3 RCTs)	methods; VR training improved trainee performance in RCTs	
17	Orlewski et al. (2025)	AR applications in reverse total shoulder arthroplasty	Systematic review	Multiple studies across training, navigation, rehabilitation	AR supports training and intraoperative visualisation; clinical-outcome evidence remains largely feasibility-level	I, II, III
18	La Banca et al. (2024)	3D-printed patient-specific instrumentation beyond arthroplasty	Systematic review	Multiple studies, shoulder and elbow non-arthroplasty procedures	Predominant focus on corrective osteotomies (incl. glenoid/scapular); positive outcomes and minimal complications reported	I, II
19	Merolla et al. (2025)	Custom 3D-printed baseplates for severe multiplanar glenoid bone defects	Retrospective multicentre clinical study	23 shoulders (11 primary, 12 revision RSA)	Significant improvement in ROM, pain, and Constant-Murley scores at ≥ 24 months; no loosening; low complication rate	II
20	Gutowski et al. (2025)	Custom 3D-printed glenoid in bilateral RTSA	Case report	1 patient, bilateral RTSA	Comparable 1-year functional outcomes between custom 3D-printed and standard glenoid components despite severe deformity	I, II

3.3. Charted Findings by Review Objective

3.3.1. Development of 3D Printing and VR/AR Workflows

Most charted sources described a broadly similar pipeline: high-resolution CT acquisition, segmentation and 3D reconstruction (commonly using 3D Slicer or comparable software), followed by either physical 3D printing or import into a VR/AR simulation environment. Dey Hazra et al. [2] described a stepwise AR-assisted workflow for reverse total shoulder arthroplasty (RTSA) incorporating real-time navigation, digital reconstruction, and post-operative validation using 3D point-cloud analysis. Rojas et al. [10] reported one of the earliest in vivo applications of head-mounted-display AR in shoulder arthroplasty, combining intraoperative overlays with CT-based modelling. Fillat-Gomà et al. [3] and Fleet et al. [11] described complete workflows incorporating virtual planning, design, and intraoperative use of patient-specific instrumentation. Across these sources, there was consistent support for the technical feasibility and reproducibility of end-to-end 3D/VR/AR workflows, particularly for complex glenoid morphology.

3.3.2. Clinical Utility: Surgical Outcomes, Accuracy, and Planning Time

Sixteen of the 20 sources reported some form of feedback on accuracy, planning efficiency, or clinical outcome. Archetti Netto et al. [12] reported improved glenoid component placement accuracy with 3D printing compared with CT-only planning, particularly for less experienced surgeons. Schlueter-

Brust et al. [13] reported AR-guided K-wire placement with entry-point and angular deviations of <2.4 mm and $<3.9^\circ$, respectively. This is an improvement over the manual freehand technique in their proof-of-concept phantom model. Trikoupis et al. [14] reported satisfactory outcomes and implant fit following 3D-planned tumour-related glenoid reconstruction; Huang et al. [15] reported significant postoperative improvement in ASES, Rowe, and Constant scores in a small retrospective series of military patients. Fillat-Gomà et al. [3] reported reduced operative time and no complications when premodelled instrumentation was rehearsed preoperatively. These findings, while consistent in direction, derive from small, largely uncontrolled, single-centre studies and should be interpreted as suggestive rather than confirmatory of a clinical benefit.

3.3.3. Surgeon and Trainee Feedback on Effectiveness

Formal survey-based evaluation was uncommon in the charted literature. Handal et al. [4] reported that preoperative VR rehearsal increased a resident surgeon's self-reported confidence and preparedness in a single case study. Kolac et al. [16] and Alemayehu et al. [1], in narrative-review form, described general practitioner receptiveness to VR/AR and 3D printing, particularly for pre-surgical training and for explaining complex anatomy to trainees and patients. Across sources, physical 3D models were also reported as a communication aid between surgical team members. These findings are consistent in direction with, but not independently more rigorous than, the perception data collected in the present study's own survey (Section 3.5).

3.3.4. Update: Evidence Published 2025-2026

The original search (2010-2025) was re-run in August 2026 across the same five databases, extending coverage to 2010-2026 and identifying five additional sources meeting eligibility criteria. Three were systematic reviews synthesising the wider AR/VR/metaverse and 3D-printed patient-specific instrumentation literature in shoulder arthroplasty [17-19]; none was specific to glenoid fracture, and none attempted meta-analysis of clinical outcomes, reinforcing rather than resolving the heterogeneity noted in Section 2.7. Longo et al. [17] pooled 22 studies, including three randomised controlled trials of VR-based training, and reported that AR-assisted navigation achieved glenoid component accuracy comparable to, and in some series better than, conventional or computer-assisted methods; this is the highest level of trial evidence identified to date for any technology within the review's scope, though it addresses arthroplasty navigation rather than fracture-specific planning. Orlewski et al. [19] similarly found AR feasibility across training, intraoperative guidance, and rehabilitation domains, but concluded that high-quality clinical-outcome evidence remains sparse. La Banca et al. [18] extended the evidence base for 3D-printed patient-specific instrumentation beyond arthroplasty into corrective osteotomy and non-arthroplasty procedures, a domain closer to fracture and malunion management than most previously charted sources. Two further clinical sources were charted: a multicentre retrospective study of custom-made 3D-printed glenoid baseplates for severe multiplanar bone defects [20] reporting significant functional and radiographic improvement at a minimum 24-month follow-up in both primary and revision reverse shoulder arthroplasty; and a case report describing comparable one-year functional outcomes between a custom 3D-printed glenoid and a standard implant in bilateral reverse total shoulder arthroplasty [21]. This recent evidence strengthens the clinical-outcome signal for 3D printing and AR/VR in shoulder reconstruction generally, but does not materially change the review's central finding: fracture-specific, prospectively controlled evidence for glenoid fracture preoperative planning remains scarce, and the newly charted sources are predominantly drawn from the elective/degenerative arthroplasty literature rather than acute trauma.

3.4. Development and Technical Output of the Institutional Workflow

The workflow described in Section 2.8 was technically implemented end-to-end using anonymised patient CT DICOM data (Figure 3). Segmentation in 3D Slicer produced an anatomically detailed glenoid model; because the comminuted fracture pattern could not be printed reliably as a single piece, the model required sectioning prior to printing (Figure 4). The equivalent segmented model was successfully converted and imported into a Unity-based VR environment, enabling rotation, zoom, and manipulation of the glenoid model (Figure 4).

3D Printing Workflow for Glenoid Fracture Preoperative Planning

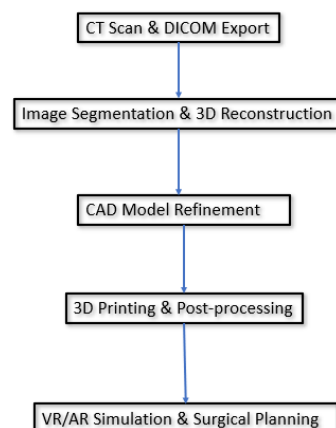


Figure 3. Institutional CT-to-print and CT-to-VR workflow (DICOM acquisition → 3D Slicer segmentation → STL export → Meshmixer sectioning → 3D printing; parallel STL → Blender FBX conversion → Unity VR import).



Figure 4. Left: physical 3D-printed glenoid model produced via the institutional workflow. Right: corresponding VR environment (Unity) rendering of the same segmented anatomy, viewed via head-mounted display.



Figure 5. Left: external surface detail of the printed glenoid segment, showing visible FDM layer lines and a fracture/seam line at the Meshmixer sectioning plane. Right: cross-sectional view of a fractured print, showing internal lattice infill and structural failure at a thin, comminuted region.

3.5. Survey Results

3.5.1. Participants

Of 20 clinicians invited, 8 completed the survey (response

rate 40%). Demographic characteristics are summarised in [Table 4](#). The qualification totals in [Table 4](#) sum to more than 8 respondents because the underlying form permitted free-text ‘Other’ entries alongside a categorical selection for two respondents; this is noted as a minor instrument design limitation (Section 4.5) rather than corrected by omission.

Table 4. Survey participant characteristics (n = 8).

Characteristic	n (%)
Professional role	Consultant 3 (37.5%); Resident 3 (37.5%); Medical officer 1 (12.5%); Other (MCh student) 1 (12.5%)
Years in orthopaedic practice	0-5 y: 2 (25%); 5-10 y: 2 (25%); 10-20 y: 3 (37.5%); >20 y: 1 (12.5%)
Highest qualification	Fellowship 2 (25%); Membership 1 (12.5%); MCh (Masters) 4 (50%); Other 2 (25%)*
Proportion of practice involving scapular/glenoid fractures	0-20%: 8 (100%)

*Two respondents provided an additional free-text qualification alongside a categorical selection, producing an apparent total of 9 across 8 respondents; see note above.

3.5.2. Descriptive Quantitative Results

All respondents (8/8) reported being “very” or “extremely” familiar with 2D CT for preoperative planning. Despite this, 5/8 (62.5%) reported never having personally used 3D-printed models or VR in their own surgical practice. Key descriptive

results across the remaining Likert-type and categorical items are summarised in [Table 5](#). Because denominators are small (n = 7-8 depending on item completion), percentages are reported alongside raw counts throughout, and no inferential comparison between subgroups (e.g., by grade or years of experience) was attempted.

Table 5. Descriptive survey results for key perception items.

Survey item	Descriptive result (n = 8 unless stated)
Perceived improvement in understanding fracture morphology (3D/VR)	Agree/strongly agree: 6/8 (75%)
Perceived improvement in surgical planning accuracy (3D/VR)	Agree/strongly agree: 5/8 (62.5%)
Perceived training/educational enhancement vs. 2D CT	Significant/extreme: 6/8 (75%); not at all: 1/8 (12.5%)
Ever personally used 3D-printed models or VR in practice	Never: 5/8 (62.5%)
Reliance solely on 2D CT for surgical planning	Often/always: 5/8 (62.5%); never/rarely: 3/8 (37.5%)
Altered surgical approach after 3D/VR insight	Never: 3/8 (37.5%); occasionally/sometimes/often: 5/8 (62.5%)
Overall opinion of 3D printing/VR in surgical management	Slightly/very positive: 5/8 (62.5%); neutral: 2/8 (25%); negative: 1/8 (12.5%)
Most valuable single modality for glenoid planning (forced choice)	3D-printed model: 4/8 (50%); 2D CT: 2/8 (25%); VR: 1/8 (12.5%); other: 1/8 (12.5%)
Likelihood that 3D/VR becomes a standard preoperative tool	Likely/very likely: 4/8 (50%); neutral: 2/8 (25%); unlikely: 1/8 (12.5%); other: 1/8 (12.5%)

Survey item	Descriptive result (n = 8 unless stated)
Judged overall improvement of 3D/VR vs. 2D in planning	50-100% improvement: 4/8 (50%); 30-50%: 3/8 (37.5%); no improvement/other: 2/8 (25%)

3.5.3. Template Analysis of Open-Text Responses

Five themes were derived from template analysis of open-text responses (Section 2.9). All quotations are reproduced verbatim from the underlying response data, including original spelling, and are attributed to the specific survey item under which they were recorded.

Theme 1: Perceived enhancement of three-dimensional spatial understanding

Respondents consistently described 3D printing and VR as providing a more complete spatial picture of fracture morphology than 2D CT alone. In response to the item asking how 3D printing visualises fracture patterns, one respondent wrote: “3D is much more than 2D in fracture management as it gives views from all planes.” In response to the corresponding item on VR, another wrote: “Allows for detailed exploration of the fracture.”

Theme 2: Enhanced planning confidence and fixation strategy

Several respondents linked 3D/VR use to more concrete operative planning decisions. Asked what 3D printing or VR contributes to a surgeon’s understanding of fracture morphology, one respondent wrote: “It gives surgeon information for improved fixation strategies.” Asked for their overall opinion on 3D printing and VR in surgical management, another wrote: “3D printing is best for pre-operative planning like choosing the appropriate implant type, size and plate pre-contouring, whereas the VR is better to understand fracture morphology.”

Theme 3: Persistent limitations in comminution and completeness of representation

Not all feedback was uncritical. One respondent, describing 3D printing’s visualisation of fracture patterns, noted: “Limited appreciation of comminution as small fragments either connect to main piece or are separate and not attached. When only the glenoid is printed, maintaining orientation is challenging without the rest of the scapula.” The same respondent, describing the corresponding VR item, added: “[VR] does not enable full appreciation of comminution. Less detailed than 3D reconstructions available on PACS.” This internal consistency across two related items from the same respondent lends the observation credibility and directly mirrors the print-fragility limitation documented photographically in Figure 5.

Theme 4: Cost, access, and infrastructure barriers

Barriers to routine use were raised by nearly all respondents. Asked directly what barriers they face in accessing these technologies, respondents wrote: “economic and training barrier as to how to take a 3d print. Availability of VR headsets and printers” [sic], and separately: “3-D is accessible on request, Virtual Reality is not our institution; due to costs.”

Theme 5: Preference for selective rather than routine use

A recurring position was that 3D/VR should be reserved for complex or high-stakes cases rather than used routinely. One respondent, asked about views on integrating these technologies into routine planning, wrote: “Only for complex cases, which need in-depth analysis for glenoid fixation” [sic]. A more sceptical respondent, asked for their overall opinion on 3D printing and VR in surgical management, wrote: “I think it does not add significantly to current available technology. Higher quality reconstruction of the fracture would be required to make it more useful.”

4. Discussion

4.1. Summary of Principal Findings

This scoping review charted 20 heterogeneous sources of evidence (15 identified in the original 2010-2025 search, plus 5 further sources were identified when the search was extended to 2010-2026) describing 3D printing and VR/AR applications in glenoid fracture and related shoulder preoperative planning, alongside an institutionally developed CT-to-print and CT-to-VR workflow and a small exploratory survey of orthopaedic clinicians. The charted literature consistently, though not uniformly rigorously, reports improved implant-positioning accuracy, reduced planning or operative time, and educational benefit; the 2025-2026 update strengthens this signal with the first randomised-trial-level evidence identified in this review (three RCTs of VR training pooled by Longo et al [17] and with multicentre clinical outcome data on custom 3D-printed glenoid components (Merolla et al. [20]), while confirming that fracture-specific evidence remains dominated by cadaveric, feasibility, and case-level designs. The institutional workflow demonstrated that a full CT-to-print and CT-to-VR pipeline is technically achievable using freely or commonly available software (3D Slicer, Meshmixer, Blender, Unity), but also surfaced a concrete limitation: printed models of comminuted glenoid fractures were structurally fragile at thin, fine-detail regions (Figure 5), consistent with the print-fidelity concerns raised independently by survey respondents (Theme 3). Survey respondents were, on balance, positive about the perceived value of these tools (Table 5), notwithstanding that most (5/8, 62.5%) had never personally used either technology. As such, it means that most reported opinion reflects anticipated rather than experienced utility, a distinction we consider important and return to below.

4.2. Interpretation and Comparison with Existing Literature

The convergence between the charted literature and the survey's qualitative themes is notable: both independently emphasise improved spatial/morphological understanding, value for implant/fixation planning, and persistent concerns about the fidelity of comminution representation. This convergence strengthens confidence that these are genuine, recurring themes in the field rather than artefacts of a single dataset. However, convergence in direction is not the same as convergence in strength of evidence: the charted clinical literature is dominated by cadaveric, feasibility, and small case-series designs (Table 3, Figure 2), and the survey is a small, non-validated, single round of self-report from a sample in which most respondents lacked direct experience of the technology being evaluated. Neither data source, alone or combined, is capable of establishing a causal clinical benefit; both are more accurately described as consistent, hypothesis-generating signals.

4.3. Implications for Practice and Training

Where a clinical or educational case for adoption exists in the charted literature, it is strongest for two specific applications: (1) complex, comminuted, or bone-deficient glenoid reconstruction, where spatial understanding from 2D CT alone is genuinely limited (Table 3, Objective I/II sources), and (2) trainee education and preoperative rehearsal, where the risk of an imperfect model is lower than in direct clinical application ([4]; Theme 2). This is also consistent with survey respondents' own stated preference for selective, complexity-triggered use rather than routine adoption (Theme 5).

4.4. Barriers to Adoption

Cost, infrastructure, and training featured heavily and consistently across the charted literature and survey free-text responses (Theme 4). Institutional access to 3D printers and VR head-mounted displays, and to personnel trained in segmentation software, remains inconsistent, and several survey respondents reported that access, where it existed, was limited to specific requests rather than routine workflow integration. These barriers are practical rather than purely evidentiary and would need to be addressed alongside, not instead of, further validation research.

4.5. Strengths and Limitations

Strengths of this work include a systematic, PRISMA-ScR-reported, five-database search strategy; transparent charting rather than an inappropriate quantitative synthesis of heterogeneous outcome data; a working, reproducible technical workflow with photographic documentation of both success and failure modes; and survey findings from orthopaedic staff of the hospital on VR process and models analysed with an

explicit qualitative method (template analysis) with verbatim, traceable quotations.

Several limitations should inform how these findings are used:

- 1) Small, non-representative survey sample. Eight respondents from 20 invitations (40%) is too small to support any claim of generalisability, and non-response bias (e.g., more technology-enthusiastic clinicians being more likely to respond) cannot be excluded.
- 2) No dimensional or accuracy validation was performed. The printed model and VR environment were assessed for technical feasibility only. No landmark measurements, inter-rater reliability testing, or comparison against source CT dimensions were undertaken; Figure 5 documents a failure mode, not a quantified accuracy metric. Claims of "accuracy" or "validation" should not be drawn from this study.
- 3) Heterogeneity precluding meta-analysis. This is by design appropriate to a scoping review, but it also means this review cannot report a pooled estimate of clinical effect, and readers should not interpret the consistency of direction across charted sources as equivalent to a statistically pooled effect.
- 4) Single-institution workflow. The workflow was developed and piloted at one centre using one printer, one segmentation pipeline, and one VR platform; generalisability to other hardware/software combinations is untested.

4.6. Recommendations for Future Research

- 1) *Undertake a dedicated dimensional validation study:* measure a defined set of anatomical landmarks (e.g., glenoid height, width, version angle, fracture-line length) on source CT and on the corresponding physical print using digital callipers, with ≥ 2 independent observers and calculation of mean absolute error and an intraclass correlation coefficient.
- 2) Conduct a larger, multi-institution survey using a piloted, validated instrument, with sufficient sample size to permit subgroup comparison (e.g., by grade, prior technology exposure) and formal reliability testing.
- 3) Pursue prospective clinical outcome studies (ideally randomised or comparative cohort) directly comparing 2D CT-only planning against 3D/VR-augmented planning for a defined glenoid fracture population, using validated shoulder outcome measures and operative time as primary endpoints.
- 4) Explore lower-cost or open-source segmentation and printing solutions to address the accessibility barriers identified in Theme 4.
- 5) Monitor the emerging role of automated, AI-based CT segmentation for glenoid and scapular anatomy, which is beginning to reduce the manual segmentation burden documented in the present institutional workflow (Sec-

tion 2.8) and may improve the reproducibility and scalability of future 3D printing and VR pipelines, although this was outside the technology scope defined by this review's eligibility criteria and was not itself charted as included evidence.

5. Conclusion

This scoping review and preliminary survey of orthopaedics is consistent, but predominantly low-to-moderate certainty, evidence that 3D printing and VR technologies are perceived to enhance spatial understanding, planning confidence, and surgical education in glenoid fracture management, alongside real and unresolved barriers of cost, access, and model fidelity for comminuted fractures. The 2025-2026 update strengthens the outcome evidence available for 3D printing

and AR/VR in shoulder reconstruction more broadly, including the first randomised-trial-level and multicentre clinical data identified within the review's scope. But this strengthened evidence is concentrated in elective/degenerative shoulder arthroplasty rather than acute glenoid fracture, so the review's central conclusion is unchanged: fracture-specific evidence remains immature. A reproducible institutional CT-to-print and CT-to-VR workflow was technically demonstrated, including a documented failure mode at thin, comminuted regions. Neither the charted literature nor the accompanying survey and technical work support a claim of validated clinical accuracy or demonstrated outcome benefit; both should be read as a map of current evidence and practice and as hypothesis-generating groundwork for the dimensional validation studies and adequately powered, fracture-specific clinical trials.

Abbreviations

AI	Artificial Intelligence
AR	Augmented Reality
ASES	American Shoulder and Elbow Surgeons (score)
CRedit	Contributor Roles Taxonomy
CT	Computed Tomography
DICOM	Digital Imaging and Communications in Medicine
EFORT	European Federation of National Associations of Orthopaedics and Traumatology
FBX	Filmbox (3D Model Exchange File Format)
FDM	Fused Deposition Modelling
GDPR	General Data Protection Regulation
HMD	Head-Mounted Display
ICMJE	International Committee of Medical Journal Editors
IEEE	Institute of Electrical and Electronics Engineers
JB	Joanna Briggs Institute
MCh	Master of Chirurgiae (postgraduate Surgical Degree)
NCT	National Clinical Trial (ClinicalTrials.gov Registry Identifier Prefix)
NHS	National Health Service
PACS	Picture Archiving and Communication System
PCC	Population, Concept, Context (JBI Scoping Review Framework)
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews
PSI	Patient-Specific Instrumentation
RCT	Randomised Controlled Trial
REC	Research Ethics Committee
ROM	Range of Motion
RSA	Reverse Shoulder Arthroplasty
RTSA	Reverse Total Shoulder Arthroplasty
STL	Standard Tessellation Language (Stereolithography File Format)
UK	United Kingdom
VR	Virtual Reality

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Data Availability Statement

The data are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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