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Digital planning and Personalized Fixation of Mandibular Condylar Fractures: A Rapid Systematic Review

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ABSTRACT: Digital planning may improve the execution of mandibular condylar fracture fixation, but its clinical value depends on whether anatomical precision translates into functional recovery and durable stability. This rapid systematic review examined clinical evidence and its biomechanical implications. PubMed-source records were searched through Europe PMC, with supplementary web and citation-based retrieval. Comparative studies and series of at least five patients undergoing digitally assisted primary fixation were eligible. Clinical and computational evidence were analyzed separately without meta-analysis. Two clinical searches yielded 721 records and 586 unique records after deduplication. Nine reports contributed 149 participants to a provisional synthesis, including a five-patient subgroup from a mixed-fracture series; five reports were assessed in full and four through abstracts. Two randomized trials involving 70 patients reported mean geometric deviations lower by 0.647 and 0.356 mm with digital assistance; consistent functional superiority was not established. Mixed-fracture evidence could not isolate the effect of condylar fixation. Biomechanical studies showed that fracture level, plate location, loading, and screw support alter construct behaviour. Bench validation supported comparative modelling while also identifying systematic prediction errors. Digital assistance therefore has stronger evidence for improving geometric execution than for preventing complications or fixation failure. A clinically useful personalized workflow should connect reproducible morphology, interfragmentary contact, fixation mechanics, and patient-important outcomes.

1. INTRODUCTION

A condylar fracture creates several problems at once. The proximal fragment may be displaced or rotated, the vertical dimension of the ramus may be reduced, and the relationship between the condylar head and the joint may be disturbed. The surgeon must restore a functional mandibular relationship while working through an exposure that limits direct inspection and implant placement. The AOCMF classification helps describe these injuries systematically, particularly their level, fragmentation, and displacement, but a descriptive classification does not by itself resolve how an individual fracture should be reconstructed¹.

The distinction between deciding to operate and deciding how to operate is important. Randomized investigations of open and closed treatment address the first question^{2,3}. They cannot establish the additional benefit of virtual planning, a printed guide, or a customized plate once open reduction and internal fixation (ORIF) has already been selected. Digital surgery therefore requires its own evidence: a comparison of alternative ways to deliver an otherwise indicated operation.

Digital planning offers a means of examining anatomy before surgical exposure. Individual fragments can be segmented, repositioned, and inspected for feasible screw trajectories. Navigation provides feedback during surgery, whereas a guide or patient-specific implant constrains how a planned position is reproduced. Clinical investigations have evaluated these approaches in condylar head and extracapsular fractures ⁴⁻⁷. Their endpoints, however, are not interchangeable. A small surface deviation measures fidelity to a plan; stable occlusion measures a functional relationship; freedom from plate fracture measures the endurance of a fixation system. Success in one domain cannot be assumed to establish success in another.

This distinction is particularly relevant to biomechanical personalization. An implant can fit the reconstructed surface closely yet provide limited rotational control or concentrate load in a small region of cortical bone. Conversely, an experimentally stiff construct may be difficult to insert without compromising exposure or fragment viability. The useful question is therefore not simply whether a procedure uses three-dimensional technology. It is whether that technology addresses a defined source of surgical or mechanical uncertainty.

The present review evaluates the clinical evidence for digitally assisted primary fixation of mandibular condylar fractures, separates anatomical from patient-important outcomes, and examines the implications of selected biomechanical studies. Does digital planning improve outcomes beyond geometric accuracy, and can current biomechanical evidence support patient-specific selection of fixation?

2. MATERIALS AND METHODS

2.1 Review design and framework

This rapid systematic evidence review used PRISMA 2020 as a reporting framework and the principles of synthesis without meta-analysis for presentation of heterogeneous findings^{8,9}. The question was: in patients undergoing primary operative fixation of traumatic mandibular condylar fractures, what anatomical, functional, and safety outcomes are associated with digital planning and its intraoperative transfer, compared with conventional surgery where a comparator exists?

2.2 Literature search strategy

A structured electronic literature search was conducted through Europe PMC, restricted to PubMed-source records (SRC:MED). The initial clinical search was performed on 3 September 2026 and the expanded clinical search on 4 September 2026. Publications dated from 1 January 2000 to the respective search date were eligible for retrieval. This interval was selected to capture both early computer-assisted fixation techniques and more recent virtual planning, navigation, and patient-specific manufacturing workflows. No language restriction was imposed.

The clinical strategy combined three required concept blocks. The first described the anatomical population, using “condyl*” and “subcondyl*”; “mandib*” was added in the expanded search to retrieve mixed mandibular-fracture cohorts that might not identify condylar involvement in the abstract. The second described the injury, using “fractur*”. The third described digital planning and operative transfer, using terms including “virtual planning”, “virtual surgical”, “computer assisted”, “computer aided”, “CAD/CAM”, “patient specific”, “custom made”, “surgical guide”, “drilling guide”, “3D printing”, “3D printed”, and “navigat*”. The initial query additionally included terms such as “digital workflow”, “computer guided”, and three-dimensional printing variants. Synonyms within each block were connected with OR, and the anatomy, injury, and technology blocks were connected with AND. Terms were searched in titles and abstracts using the TITLE_ABS field; asterisks denoted truncation.

The expanded clinical query was: (TITLE_ABS:mandib* OR TITLE_ABS:condyl* OR TITLE_ABS:subcondyl*) AND TITLE_ABS:fractur* AND (TITLE_ABS:"virtual planning" OR TITLE_ABS:"virtual surgical" OR TITLE_ABS:"computer assisted" OR TITLE_ABS:"computer aided" OR TITLE_ABS:"CAD/CAM" OR TITLE_ABS:"patient specific" OR TITLE_ABS:"custom made" OR TITLE_ABS:"surgical guide" OR TITLE_ABS:"drilling guide" OR TITLE_ABS:navigat* OR TITLE_ABS:"3D printing" OR TITLE_ABS:"3D printed") AND FIRST_PDATE:[2000-01-01 TO 2026-10-04] AND SRC:MED.

A fourth concept domain concerned outcomes: reduction accuracy, occlusal stability, maximum mouth opening, pain, temporomandibular function, nerve injury, implant failure, and reoperation. These outcomes guided screening and extraction but were not mandatory search terms. Similarly, no randomized-trial or other study-design filter was applied, because eligible evidence included uncontrolled surgical series. The executed searches used free-text terms rather than an explicitly specified

MeSH strategy; they should not be described as controlled-vocabulary searches. This distinction matters when reproducing or extending the search in the native PubMed interface.

The two clinical queries yielded 138 and 583 records, respectively; removal of 135 duplicate PMIDs left 586 unique records. A separate contextual query combined the condylar anatomy and fracture blocks with “finite element” or “biomechan*”, yielding 401 records. Selected computational and experimental studies informed the mechanistic discussion; this component was not an exhaustive systematic review. Targeted publisher, institutional-repository, and citation searches supplemented report retrieval, and one relevant ClinicalTrials.gov registration was examined. Full executed queries, dates, record exports, and selection decisions are retained in the accompanying evidence package. Direct searches of Scopus, Web of Science, Embase, and CENTRAL were not performed. Supplementary web and citation-based retrieval was used to locate reports and verify bibliographic information, rather than as a substitute for systematic searches of those databases.

2.3 Inclusion criteria

Eligible reports investigated human traumatic condylar head, neck, or base fractures treated by primary reduction and internal fixation. Digital planning had to inform fragment repositioning, implant selection or design, screw trajectory, or intraoperative transfer of the plan. Comparative studies were eligible irrespective of size; uncontrolled series required at least five treated condylar-fracture patients. This pragmatic threshold reduced reliance on isolated technical demonstrations; it was not a threshold for evidential certainty. Mixed-age cohorts were eligible, with age-related qualifications retained. Mixed anatomical cohorts required a separately identifiable condylar subgroup with extractable clinical outcomes. Complete treatment workflows could be included, but their outcomes were not interpreted as an isolated effect of condylar fixation. For mixed-fracture cohorts, the minimum series size applied to the identifiable condylar-fracture subgroup, not to the overall facial-fracture cohort.

2.4 Exclusion criteria

Reports limited to conservative treatment, secondary correction of established malunion, prosthetic joint replacement, non-traumatic reconstruction, cadaveric or computational experiments, or virtual repositioning without operative outcomes were excluded from the clinical synthesis. Conventional custom splints without an identifiable digital planning component were also excluded. Single cases and uncontrolled series below the five-patient threshold could inform technical discussion but did not contribute to the clinical count. Mixed-fracture reports without identifiable condylar outcome data were excluded or retained awaiting clarification if the available report was incomplete. Failure to obtain a complete text was not treated as evidence of ineligibility.

2.5 Study selection process

Records retrieved by both clinical searches were deduplicated by PMID; DOI and title information was available for bibliographic cross-checking. Titles and available abstracts were screened against the eligibility criteria, followed by detailed report assessment and full-text retrieval where needed. Screening and extraction were not independently duplicated by human reviewers. Reports were distinguished as full-text inclusions, provisional abstract-derived inclusions, full-text exclusions, or reports awaiting classification. Abstract-derived inclusion required an explicitly eligible intervention, sample size, and clinical outcomes; insufficient information led to an unresolved classification rather than exclusion on the basis of non-retrieval. Additional retrieval resolved four previously pending reports. For one mixed-fracture series, the condylar subgroup was reconstructed from patient-level tables. These categories are reported separately in Figure 1 and the selection log.

2.6 Data extraction

Extraction covered design, anatomical site, patient and fracture-side denominators, digital intervention, comparator, follow-up, geometric outcomes, mandibular function, complications, and resource use. For mixed cohorts, patient identifiers were used to link fracture location with follow-up and adverse events. Events were attributed to the complete treatment episode unless their anatomical location was stated. Data were not imputed; investigators were not contacted and participant-level datasets were unavailable. Each clinical report was marked as verified in full text or abstract-derived.

Geometric findings were interpreted within the definition and unit reported by each study; continuous deviations were not treated as interchangeable with categorical reduction ratings. Functional outcomes were considered at the reported follow-up interval, with patient-level denominators kept separate from fracture-side measurements. A missing adverse-event description

was not interpreted as evidence that no event occurred. Outcomes from a complete mixed-fracture treatment episode were not attributed specifically to condylar fixation unless their anatomical source was identifiable.

Published means, counts and P values were retained. Simple differences calculated for this review were labelled descriptive: the digitally assisted group mean minus the conventional group mean, or the difference between reported proportions in percentage points. No confidence intervals were reconstructed from incomplete or potentially clustered data. Patient-level function and fracture-side reduction were kept separate. A participant total was used only to describe the retrieved evidence, not as a denominator for pooled treatment effectiveness or complications.

2.7 Data analysis and synthesis

The synthesis grouped studies by design, fracture location, digital intervention, and outcome domain. Virtual planning, dynamic navigation, and physical transfer through guides, splints, or implants were distinguished. Continuous geometric deviations, categorical reduction ratings, function, complications, and resource use were examined separately. Meta-analysis was not undertaken because intervention content, fracture anatomy, outcome definitions, follow-up, and usable precision estimates were insufficiently compatible. In particular, bilateral injuries generated correlated side-level observations that could not be corrected from aggregate reports. Pooling would therefore risk treating non-equivalent outcomes or correlated fracture-side measurements as comparable independent observations. Descriptive mean differences and absolute differences in reported proportions were used to clarify individual comparisons, not to estimate a combined treatment effect. A qualitative check restricted interpretation to full-text reports to assess whether the principal conclusion depended on abstract-derived evidence.

Selected computational and experimental studies informed interpretation of morphology, interfragmentary contact, implant position, loading, and model validation. They were not combined with clinical participants or event rates. No formal assessment of small-study effects or publication bias was conducted; the small number of heterogeneous studies and unresolved reports precluded a defensible quantitative analysis.

2.8 Critical appraisal

Critical appraisal was preliminary and descriptive. The randomized trials were examined in relation to the concerns addressed by RoB 2, including the randomization process, deviations from assigned intervention, missing outcome data, outcome measurement, and selective reporting.¹⁰ Case-series reporting was considered in relation to the JBI framework, including participant selection, completeness of inclusion, outcome ascertainment, and follow-up.¹¹ The appraisal was not independently duplicated or adjudicated, and completed tool-based overall risk-of-bias ratings were not assigned. Abstract-derived reports could not be adequately assessed for recruitment, attrition, or complete adverse-event reporting. Formal GRADE certainty ratings were not produced because eligibility verification and independent full-text assessment remained incomplete.¹² The study-specific concerns are reported in Section 3.5 and the accompanying appraisal notes; no numerical quality score was used.

3. RESULTS

3.1 Study selection and evidence availability

Across the two clinical searches, 586 unique records were screened and 553 were excluded at the title-and-abstract stage. Thirty-three reports were selected for detailed assessment. Fifteen full texts were assessed: five supported inclusion and ten were excluded. Of 18 reports without a verified complete text, four supported provisional inclusion from explicit abstract data and 14 remained awaiting classification or retrieval. The clinical synthesis comprised nine reports contributing 149 participants: 144 in eight condylar-specific reports and five in a separately extractable subgroup of a ten-patient panfacial-fracture series (Figure 1; Tables 1 and 2). This total describes the included reports and is not a pooled effectiveness denominator. Supplementary material identifies all unresolved reports. An additional Chinese-language citation lead was recorded separately because an independently assessable report was not retrieved.

Two randomized trials included 70 participants^{4,5}. Seven uncontrolled reports contributed 79 patients, including the five-patient mixed-fracture subgroup^{6,7,13–17}. Among the six condylar-specific series, four concerned head fixation, one concerned neck fractures, and one evaluated low neck fractures described as subcondylar injuries. The additional subgroup included head and extracapsular injuries. Definitions and follow-up schedules differed. The two trials originated from the same institution but reported non-overlapping recruitment periods; their results should nevertheless not be treated as independent multicentre replication.

The study-selection pathway is presented in Figure 1.

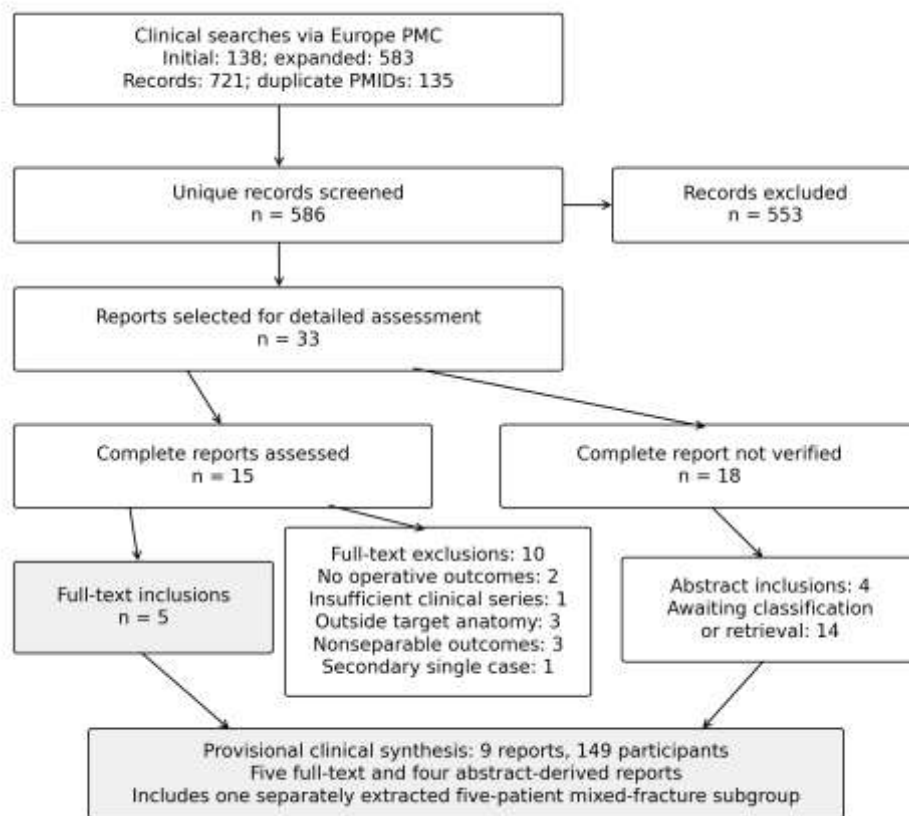


Figure 1. Adapted PRISMA flow of the clinical searches. Five full-text and four abstract-derived inclusions contribute 149 participants, including a separately extracted five-patient mixed-fracture subgroup. Fourteen reports remain unresolved. Contextual biomechanics, one trial registration and one unverified citation lead do not contribute clinical participants.

3.2 Comparative clinical evidence

In the 20-patient navigation trial by Han et al.⁴, mean deviation from the reference reconstruction was 0.5235 mm with navigation and 1.170 mm with conventional surgery ($P < .001$). The descriptive difference was -0.6465 mm. Anatomical or approximately anatomical reduction was reported for 15/16 versus 15/17 fracture sides ($P = .58$). Mean mouth opening was 34.45 versus 34.05 mm ($P = .25$), a difference of only 0.40 mm. Operating time was longer in the navigation group by 13.60 minutes, although this difference was not statistically significant (180.40 versus 166.80 minutes; $P = .12$). Thus, an image-based advantage was demonstrated without a corresponding functional or time advantage.

The 50-patient trial by Shakya et al.⁵ compared virtual-planning-assisted and experience-based surgery. Mean deviation was 0.639 versus 0.995 mm, a descriptive difference of -0.356 mm. Perfect reduction was recorded for 29/32 versus 24/35 sides (90.63% versus 68.57%; $P = .027$), an absolute difference of 22.05 percentage points. Operating times were 180.60 and 223.20 minutes, respectively, a descriptive reduction of 42.60 minutes. At three months, normal occlusion was reported in 24/25 versus 23/25 patients and normal mouth opening in 22/25 versus 20/25; neither functional comparison was significant.

The trials therefore agree on the direction of the geometric result but differ in operative-time findings. They also use different reduction categories: Han et al.⁴ combined anatomical and approximately anatomical reductions, whereas Shakya et al.⁵ distinguished perfect, satisfactory, and poor reduction. Their categorical results cannot be treated as the same endpoint. Table 1 retains these definitions and the original patient and fracture-side denominators.

Table 1. Randomized evidence on digital assistance in condylar fracture fixation

Study and design	Participants and technology	Geometric result	Clinical result and interpretation
Han et al. ⁴ 2018 Randomized trial; full text	20 patients; 33 sides Navigation versus conventional surgery Mixed ages, 13-54 years	Mean deviation 0.5235 vs 1.170 mm; P < .001. Anatomical/approximately anatomical: 15/16 vs 15/17; P = .58. Difference in means: -0.6465 mm.	Mean mouth opening 34.45 vs 34.05 mm; P = .25. Operating time 180.40 vs 166.80 min; P = .12. Follow-up to 12 months.
Shakya et al. ⁵ 2022 Randomized trial; full text	50 patients; 67 sides VSP-assisted versus experience-based surgery	Mean deviation 0.639 vs 0.995 mm. Perfect reduction: 29/32 vs 24/35; P = .027. Difference in means: -0.356 mm; perfect reduction +22.05 percentage points.	Operating time 180.60 vs 223.20 min. At 3 months, normal occlusion 24/25 vs 23/25; normal opening 22/25 vs 20/25; neither significant.

Several qualifications affect the clinical inference. Bilateral fractures introduce correlation between sides, yet the side-level analyses did not describe a corresponding adjustment. The confidence attached to categorical reduction differences is consequently uncertain. Neither trial specified a validated minimum clinically important difference for geometric deviation, and the samples were too small to resolve uncommon hardware or nerve complications. Non-significant functional tests do not demonstrate equivalence. A difference detectable by image registration may be technically useful while its patient-important value remains unestablished.

3.3 Uncontrolled clinical series

Earlier series used virtual simulation primarily to determine reduction and screw position, whereas later reports incorporated manufactured guides or individualized fixation components^{6,7,13-16}. Table 2 summarizes what can be extracted without treating postoperative improvement as proof of superiority. The preoperative-to-postoperative change in a treated fracture reflects reduction, fixation, recovery, and rehabilitation together; it does not isolate the contribution of the digital component.

Clinical series and source availability are summarized in Table 2.

Table 2. Uncontrolled clinical series and source availability

Study and source	Sample and technique	Extractable findings	Principal limitation
Yang et al. ¹³ 2013 Abstract only	11 patients; intracapsular CAD simulation, screw fixation	Satisfactory occlusion and opening; two temporary motor deficits resolved within 3 months; 6-month follow-up.	No comparator; complete adverse-event ascertainment cannot be checked.
Wang et al. ¹⁴ 2013 Abstract only	19 patients; intracapsular Virtual reduction, two resorbable screws	Occlusion and opening restored in all but one; mean follow-up 21 months, range 6-46.	Planning and fixation-material effects cannot be separated.
Guo et al. ¹⁵ 2016 Abstract only	13 adults; 19 sides CAD-planned single positional screw	18/19 sides matched planning; one fragment ruptured. Mean opening 12 to 43 mm at 6 months.	No control; side-level and patient-level outcomes differ.

Study and source	Sample and technique	Extractable findings	Principal limitation
Pavlychuk et al. ⁶ 2020 Full text	14 patients; 16 head fractures Guides and selected individualized reinforcement	Plan mismatch 1.05 ± 0.46 mm; opening ≥ 30 mm and good occlusion at 3 months; three temporary temporal-branch deficits.	Heterogeneous fixation; short follow-up; no comparator.
Chen et al. ¹⁷ 2022 Full text; extracted subgroup	5/10 patients; 9 condylar sides Digital model surgery and splint within panfacial repair	Follow-up 6–13 months; no orthognathic correction; one wound infection of unspecified site; one orthodontic treatment.	Outcome belongs to complete facial-fracture treatment; no isolated condylar effect.
Ying et al. ¹⁶ 2023 English abstract	7 patients; neck fractures Virtual reduction, printed model, guide	Union and stable occlusion at 6 months; no obvious TMJ disorder reported.	No quantitative error measure or comparator; full text not verified.
Saloniemi et al. ⁷ 2025 Full text	10 patients; low neck fractures Milled patient-specific plates	Mean last-follow-up opening 39.44 mm; mean follow-up 210.2 days; two radiological screw-loosening suspicions without reported clinical consequences or revision.	Retrospective; quantitative postoperative 3D assessment in 3/10.

Two full-text observations are relevant to interpretation. The Pavlychuk series reported transient temporal-branch weakness in three patients, although the abstract emphasized favourable technical results ⁶. In the Helsinki cohort, three-dimensional positional assessment was available for only three of ten patients, and radiological suspicion of screw loosening was recorded in two without a reported need for revision ⁷. These details illustrate why abstract-derived evidence cannot support an exhaustive safety assessment.

3.4 Mixed mandibular cohorts and trial registration

Full-text review of Chen et al.¹⁷ identified five condylar-fracture patients among ten patients treated with digitally planned model surgery and occlusal splints. Patient-level tables identified nine condylar fracture sides and linked these patients to follow-up (6–13 months). None required orthognathic correction; one had a wound infection during the complete treatment episode and one underwent orthodontic treatment. The infection site was not specified. This subgroup is included descriptively because its clinical observations are separable, but the contribution of condylar fixation cannot be isolated from simultaneous repair of other facial fractures.

Other mixed-fracture reports could not be added to the condylar denominator. Che et al. randomized 20 patients with mandibular fractures to patient-specific or conventional plates; a published figure confirms a condylar neck case, but separately extractable condylar outcomes were not available in the inspected abstract and preview¹⁸. The report remains awaiting classification. Its overall improvement in occlusal force cannot be assigned specifically to the condylar subgroup.

Troise et al. studied 30 patients with complex mandibular fractures, including condylar involvement in seven digitally planned and eight conventionally treated patients¹⁹. Outcomes were reported for the full groups. Because condylar injury, operative fixation, and outcomes could not be linked at patient level, this report was excluded from the condylar-specific synthesis. Similarly, Dong et al. included condylar fractures in eight patients in each arm of a 22-patient study of extensive comminution²⁰. The study compared complete occlusal-restoration workflows, without reporting a separable effect of digitally assisted condylar

fixation. These cohorts demonstrate why broader anatomical coverage improves retrieval without necessarily increasing the eligible sample.

ClinicalTrials.gov record NCT07231055 describes a randomized comparison of custom titanium and lambda plates, marked completed with an actual enrolment of 24²¹. The descriptive text refers to 24 fracture sites, so the unit requires clarification. The retrieved registration contained no posted results and was first posted after the stated completion date. It contributes no effect estimate or additional participant count to this review.

3.5 Preliminary appraisal of the evidence

Both trials described random-number-table allocation, but concealment procedures were not clearly established in the inspected reports. Surgical blinding was not feasible. Radiological evaluators were outside the operating team, which is helpful, although independence from the surgical team does not itself establish masking to allocation. Eligibility tied to the ability to complete follow-up creates a further concern if applied after treatment allocation. The navigation report additionally specified unsuccessful navigation as an exclusion condition; a pragmatic evaluation should retain such technical failures in the assigned group.

Uncontrolled studies could demonstrate that a workflow was executable but could not estimate its causal effect. Small samples, specialist operators, heterogeneous fracture morphology, short or variable follow-up, and incomplete descriptions of recruitment limited interpretation. Four reports were available only as abstracts, preventing reliable assessment of consecutive inclusion, losses to follow-up, outcome measurement, and selective reporting. No numerical quality score was calculated, because an apparently precise score would obscure these differences in evidence availability.

3.6 Synthesis by outcome domain

Geometric execution has the clearest comparative support: both trials reported lower mean deviations with digital assistance. Functional recovery has less discriminating evidence because favourable postoperative function was common in both trial arms and in uncontrolled series. Safety evidence remains descriptive and incompletely ascertained. Operating-time results are inconsistent between the trials, and neither evaluates the entire planning and manufacturing pathway. Table 3 separates these outcome domains and the remaining uncertainties.

Table 3. Clinical evidence by outcome domain and remaining uncertainty

Outcome domain	Clinical evidence	Interpretation and unresolved issue
Geometric execution	Han et al. ⁴ and Shakya et al. ⁵ 70 randomized patients Mean deviation differences -0.6465 and -0.356 mm.	Both trials favour digital assistance; measurement definitions differ and clinical importance is unestablished.
Function	Han et al. ⁴ : opening difference $+0.40$ mm. Shakya et al. ⁵ : normal occlusion 24/25 vs 23/25; normal opening 22/25 vs 20/25.	No significant advantage in these comparisons; small samples do not demonstrate equivalence.
Safety and implant survival	Pavlychuk et al. ⁶ : three transient nerve deficits. Saloniemi et al. ⁷ : two radiological loosening suspicions without revision.	Uncontrolled observations; adverse events may overlap and no pooled event rate is justified.
Operating time and resources	Han et al. ⁴ : $+13.60$ min. Shakya et al. ⁵ : -42.60 min. Descriptive differences in reported means.	Direction differs between trials; planning, manufacture and treatment delay are not fully costed.

Outcome domain	Clinical evidence	Interpretation and unresolved issue
Morphometric and mechanical selection	No included clinical report links a prespecified contact or finite element threshold to an independently tested treatment decision.	Mechanistic rationale remains a hypothesis for prospective validation; no numerical operative threshold is established.

Restricting interpretation to the five full-text inclusions leaves 99 participants, including both randomized trials. The principal finding of better geometric execution without established functional superiority therefore does not depend on the four abstract-derived series. This qualitative check cannot resolve incomplete retrieval, selective reporting, or missing safety data; it only establishes where the main inference originates.

3.7 Unresolved questions in personalized fixation

The included reports do not validate a numerical morphometric threshold for selecting digital assistance, a minimum contact area for safe fixation, or a patient-specific finite element threshold that predicts failure. They also do not establish which patients benefit sufficiently to justify a guide or customized implant instead of virtual planning alone. These are unresolved questions within the reviewed evidence, rather than proof that the technologies lack clinical value.

4. DISCUSSION

4.1 Anatomical fidelity and clinical benefit are different endpoints

The main finding is a separation between measurable surgical precision and demonstrated clinical benefit. Digital methods can make the intended reconstruction more explicit and provide a reference against which execution is judged. That is useful, especially where direct observation is restricted. Nevertheless, a reconstruction is valuable because it restores function and remains stable, not because it reproduces a chosen digital surface with a small average error.

The comparative evidence comprises only 70 randomized patients from two trials conducted at the same institution, while the remaining clinical observations come from small uncontrolled series.^{4,5} This limits both the precision of treatment comparisons and their applicability across surgical settings. The absence of statistically significant functional differences should not be interpreted as equivalence, particularly for uncommon complications or delayed implant failure. Differences in fracture level, displacement, fixation material, and the mechanism of digital assistance also prevent a single intervention effect from being assumed across head, neck, and base fractures. The most defensible conclusion is that geometric execution improved in the reported comparisons, whereas the magnitude and durability of patient-important benefit remain uncertain.

There are at least two uncertainties in a plan-to-result comparison. The first concerns whether the virtual target adequately represents the patient's pre-injury anatomy. The second concerns whether the operation reproduces that target. Agreement between the plan and the postoperative scan addresses mainly the second. A systematic error in virtual reduction can be reproduced accurately. Neither clinical trial directly tests whether improved geometry mediates a subsequent functional benefit^{4,5}. Average surface distances may also conceal a local articular discrepancy or rotational error, particularly when the registration includes the structure whose position is being evaluated. These are measurement issues that future studies should address through a prespecified registration region, independent landmarks, and separate translational and rotational outcomes.

Recent workflow studies help clarify the first uncertainty. Matschke et al. described a virtual repositioning method, while Elayah et al. evaluated a multiplanar workflow in 45 unilateral fractures^{22,23}. In the latter, reconstructed-side measurements were compared with the contralateral side using paired equivalence testing, and interobserver reliability was assessed²³. These analyses strengthen evaluation of the reconstruction workflow. They do not, however, establish that using the reconstructed target improves surgical accuracy or postoperative function.

4.2 Digital assistance should be matched to the operative problem

Virtual planning, navigation, guides, and patient-specific plates act at different points in the procedure. Planning supports decisions before exposure. Navigation supplies intraoperative positional feedback. A guide transfers selected trajectories or

positions. An implant must also withstand repeated loading after the guide has been removed and the wound closed. Combining these technologies into a single intervention category obscures both their benefits and their costs.

The Ulm report illustrates this distinction: a patient-specific implant and drill guide were clinically applied in one patient after design work using previous imaging datasets²⁴. It is a technical demonstration, not a clinical cohort of all patients whose scans contributed to development. Similarly, the four cases reported by Smolka et al. are informative because they describe insertion difficulties, obstruction of the fracture view, and implant interference with adjacent anatomy²⁵. These reports suggest that manufacturing feasibility and intraoperative usability require separate checks. A device that fits a stationary model may still lack a safe insertion path.

For clinical development, the digital intervention should therefore be specified by the problem it is intended to solve. If the uncertainty concerns screw trajectory in a small head fragment, a drilling guide may be the relevant addition. If it concerns intraoperative verification of reduction, navigation may be more appropriate. If the problem is inadequate mechanical support, a geometrically customized plate must still demonstrate that it changes load transfer favourably. This is an analytical framework for testing interventions, not a validated algorithm for choosing them.

Mixed-fracture studies introduce an additional problem of attribution. In the five-patient condylar subgroup of Chen et al., postoperative observations followed a complete panfacial repair workflow, and cannot distinguish the contribution of condylar fixation from restoration of the other facial buttresses and occlusal relationships.¹⁷ Similarly, favourable group-level findings in broader mandibular-fracture cohorts should not be transferred to condylar fixation when treatment and outcomes are not linked within an identifiable condylar subgroup.¹⁸⁻²⁰ Such reports provide information about digital reconstruction workflows but cannot establish a condylar-specific treatment effect.

4.3 Biomechanical personalization requires more than an individualized surface

Finite element analysis is valuable because it permits controlled comparisons that cannot readily be performed in patients. Its conclusions, however, remain conditional on the represented anatomy, material properties, interfaces, and loading. Aquilina et al. compared patient-specific condylar plates and found that the better custom configuration had performance comparable with a conventional straight plate²⁶. The result cautions against treating customization itself as a mechanical advantage.

Other investigations show why morphology and loading need to be considered jointly. Albogha et al. compared five plate designs within a patient-derived model²⁷. Pavlychuk et al. evaluated reinforcement of two-screw fixation in a type-p head fracture and reported reductions in calculated stresses and increased rigidity²⁸. Their model deliberately introduced a 0.25-mm fracture gap to remove bony contact and assumed bonded screw interfaces. These assumptions are relevant to the proposed mechanism, but they also limit what can be inferred about clinical loosening or healing. The reported mechanical gains should not be presented as observed improvements in a patient cohort.

Schöneegg et al. found that two- and three-screw configurations could both provide adequate stability within the investigated head-fracture model²⁹. Liokatis et al. demonstrated that the response of a lambda plate depended on fracture level and plate placement³⁰. Gupta et al. examined several masticatory load cases, highlighting the importance of loading direction³¹. Experimental work combining computational analysis with mechanical testing provides a further check on model behaviour³². Together, these studies support conditional comparisons, rather than a universal ranking of plate shapes.

The larger biomechanical literature sharpens this interpretation. Murakami et al. modelled a virtually reduced fracture from a patient's CT scan and compared six fixation configurations under a 478.1-N contralateral molar load³³. Their preferred construct was specific to that reconstructed fracture and loading case. Huang et al. used seven configurations and found that posterior placement and an additional plate reduced sliding, demonstrating that position and length can matter as much as the device label³⁴. Bu et al. similarly favoured double-plate over single-plate configurations in their extracapsular model³⁵. These findings provide hypotheses for fixation design; they do not establish a universal prescription for screw purchase or plate number.

Li et al. examined both fixation position and material in condylar base fractures³⁶. The configuration minimizing implant stress was not necessarily the one minimizing cortical stress around screws. Their later analysis of condylar-base-associated multiple fractures showed that the preferred arrangement also depended on the concomitant symphyseal, body, or angle injury³⁷. Thus, an isolated condylar model may omit a clinically important change in the mandibular load path. Relevant assumptions and decision implications are compared in Table 4.

Table 4. Selected biomechanical studies and their implications for personalized planning

Study and model	Design variable and observation	Interpretation for planning
Murakami et al. ³³ Patient CT; six constructs	478.1-N contralateral bite; device performance varied within the reconstructed fracture.	Anatomical individualization does not validate a prediction of clinical failure.
Huang et al. ³⁴ Seven fixation models	Posterior placement, increased plate length and an additional plate improved model stability.	Specify plate location and length, not only plate shape.
Li et al. ³⁶ Condylar base model	Changing material and position changed implant stress, cortical stress and displacement.	A construct can optimize one endpoint without optimizing another.
Helmer et al. ⁴¹ Unilateral joint-loading model	Shortening 2–16 mm and angulation 6.25–50° altered joint loading; contact changed around 6 mm/18.75°.	Model observations are not clinical treatment thresholds.
Li et al. ³⁷ Combined mandibular fractures	Preferred plate locations varied with associated symphysis, body or angle injury and endpoint.	Represent the full injury pattern when modelling load transfer.
Liokatis et al. ³⁸ Trapezoidal plate model	Plate position relative to fracture level affected rigidity under a 500-N load.	Do not assume a fixed plate position suits every fracture line.
Kumar et al. ³⁹ Five plate designs	Models evaluated at 135 N and 500 N showed load-dependent differences in fixation behaviour.	Stress-test plausible loading scenarios; avoid universal plate rankings.
Daqiq et al. ⁴⁰ FEA and printed-mandible tests	ICC 0.93; systematic displacement difference 0.59 ± 0.12 mm; failure at condylar fixture.	Indirect validation evidence: evaluate bias and boundary artefacts as well as correlation.

Liokatis et al. investigated trapezoidal plate positioning relative to different fracture lines under a 500-N load³⁸. Holding plate position constant while moving the fracture inferiorly increased fragment mobility; cranial repositioning improved stability for a low fracture line. The authors explicitly called for experimental validation. Kumar et al. compared five devices under 135-N and 500-N loading, with differences becoming more consequential at the higher load³⁹. These studies argue for testing several plausible loading conditions rather than declaring a construct safe from a single low-load simulation.

A clinically useful model should make the source of personalization explicit. Patient-derived geometry does not automatically imply patient-specific muscle forces, bone properties, or joint constraints. Literature-based loads can support comparative analysis, provided their uncertainty is explored. Likewise, a bonded screw-bone interface may approximate an initially secure fixation but cannot directly reproduce progressive loss of purchase. Model outputs should be reported with the assumptions that generate them, especially when the intended decision concerns fatigue, loosening, or failure.

Model validation deserves equal attention. Daqiq et al. compared finite element predictions with matched tests of three-dimensionally printed mandibles and reported an ICC of 0.93 (95% CI 0.80–0.96), alongside a systematic displacement difference of 0.59 ± 0.12 mm.⁴⁰ The high ICC therefore did not eliminate systematic error in displacement prediction. Failure at the condylar clamping region also indicated that the experimental boundary conditions could influence the apparent failure location. Because this was a mandibular fixation experiment rather than a condylar-fracture clinical cohort, its findings support

caution in model validation, not a patient-specific failure threshold. Comparative rankings of constructs may remain informative under shared assumptions, but absolute predictions intended to guide treatment require evaluation of bias, relevant loading and contact conditions, and transferability beyond the validation setup. A model intended to predict clinical failure would additionally need independent testing against observed outcomes.

4.4 Interfragmentary contact is a candidate planning variable

Contact between fragments deserves attention because it can alter how load is shared between bone and fixation. Its role should nevertheless be investigated rather than assumed from a single geometric measurement. A small fragment may provide less available contact and less space for screws, but fragment size alone cannot determine stability. Fracture orientation, local cortical support, implant position, and muscle loading can change the result.

Three quantities should be separated: the area of the reconstructed fracture surface, the area brought into geometric apposition after virtual reduction, and the area actually transmitting load under a specified condition. They need not be equal. A clinically meaningful contact metric would require a stated distance tolerance, assessment of segmentation sensitivity, and reproducibility between observers. A normalized contact fraction may be easier to compare across patients than an absolute area, but no validated threshold follows from the present synthesis.

Morphometric changes can also alter joint loading before any implant is considered. Helmer et al. varied ramus shortening from 2 to 16 mm and angulation from 6.25° to 50° in a finite element model⁴¹. Loading decreased on the fractured side, whereas the contralateral increase depended on mouth position. A change in the contact pattern was described around 6 mm and 18.75°. These are model observations, not validated thresholds for choosing ORIF. Their principal contribution is to demonstrate that shortening and angulation should be interpreted together and that joint loading is not invariant across mandibular movement.

This distinction also affects screw planning. The same nominal contact area may coexist with different lever arms or different cortical purchase around the screws. A prospective study should therefore assess contact alongside rotation, ramus shortening, available bone, fracture level, and fixation configuration. Selecting a threshold after observing complications in a small dataset would produce an optimistic rule unless it is subsequently tested in an independent cohort.

4.5 Retrospective failure reconstruction as a validation strategy

One productive direction is to reconstruct the fixation actually delivered in patients with stable healing and in patients with documented mechanical failure. Postoperative imaging, implant dimensions, and operative records can be used to examine whether calculated high-demand regions correspond to the observed failure location. This would test clinical relevance more directly than repeated comparisons among idealized constructs.

Such work must distinguish retrospective reconstruction from inverse parameter estimation. Rebuilding the as-implanted system and loading it is still a forward simulation. An inverse analysis would additionally estimate unknown parameters from observed responses. Neither approach is validated merely because a predicted stress concentration can be made to overlap a known failure after repeated model adjustment. Loading choices, material assumptions, failure definitions, and spatial comparison metrics should be specified before outcome evaluation, with assessors masked where feasible.

Successful and failed cases should be processed identically. Validation should include whether the model discriminates outcomes, whether its predictions are calibrated, and whether it adds information beyond fracture morphology and clinical covariates. A model may identify mechanically plausible vulnerability without predicting the probability of clinical failure. That distinction is especially important when the proposed output will influence operative decisions.

4.6 A clinically testable personalization pathway

The proposed pathway begins with a reproducible description of the fracture and then asks which uncertainty could change the operation. Morphometric measurements should establish fracture level, fragment rotation, ramus shortening, cortical support, and the available screw corridor. A virtual reconstruction can then be tested for apposition and access, rather than judged solely by its visual resemblance to an intact mandible. Mechanical analysis, where used, should compare feasible constructs under stated loading and contact assumptions. Finally, the delivered reconstruction must be verified against both the plan and subsequent clinical outcomes. This sequence is a proposal arising from the synthesis, not a validated treatment-selection rule.

The clinically relevant question is whether this additional information changes a decision and improves an outcome. For example, an implant chosen because it reduces calculated stress should be compared with the otherwise feasible conventional construct, with all planning and manufacturing failures retained. A guide chosen to improve screw placement should be evaluated for achieved trajectory, fragment damage, operative access, and subsequent stability. The same study need not test every technology, but it should identify the intended mechanism and the outcome through which benefit will be judged.

Larger prospective comparative studies should preferably involve multiple centres and define the digital intervention precisely, distinguishing planning alone from navigation, guide-assisted transfer, and patient-specific fixation. Fracture level, displacement, rotation, fragmentation, residual ramus height, associated mandibular injuries, operator experience, and rehabilitation should be recorded prospectively. Randomization, where feasible, and blinded outcome assessment would strengthen causal interpretation. Bilateral fractures should be analysed at patient level or with methods that account for correlated sides; technical failures and conversion to conventional treatment should remain in the assigned group in randomized comparisons.

A prespecified patient-important primary outcome, assessed with a consistent measurement method, should guide sample-size planning rather than geometric deviation alone. Secondary outcomes should include maximum interincisal opening, occlusal stability, pain, mandibular excursions, patient-reported function, nerve deficits, implant complications, and reoperation. Common assessment intervals, for example at 3, 6, and 12 months, would improve comparability, with longer follow-up where delayed hardware failure is relevant. Geometric endpoints should specify the reference anatomy, registration region, and measurement unit. A clinically meaningful target difference should be defined before recruitment, rather than inferred from statistical significance after analysis.

Resource evaluation should include planning labour, manufacturing, sterilization, navigation setup, operating-room time, conversion to conventional instruments, and any delay to treatment. Minutes saved during one part of surgery do not establish cost-effectiveness if additional work is displaced elsewhere. Technical failures and unused devices are outcomes of the intervention and should remain visible in the analysis.

The strength of these clinical inferences is constrained by incomplete retrieval and by the review process. The broader search increased coverage but also exposed unresolved mixed-fracture reports, including Che et al., alongside the earlier reports by Cho, Zhuang, and Iwai^{18,42–44}. Four included studies still rely on abstract-level data; 14 further reports remain unresolved. Such evidence is particularly vulnerable to incomplete reporting of adverse events. Excluding an inaccessible report as if it were ineligible would conceal this uncertainty; unresolved reports are therefore retained explicitly in the selection record.

The search did not include completed Scopus, Web of Science, Embase, or CENTRAL searches, and screening and extraction were not independently duplicated by human reviewers. Eligibility was refined during exploratory work, and experimental studies were selected for interpretation rather than comprehensively synthesized. Formal certainty grading and quantitative pooling were consequently not undertaken. The present findings should be interpreted as a rapid synthesis of retrievable evidence, with completion of database coverage and independent verification required before stronger claims of comprehensiveness can be made.

5 CONCLUSIONS

Digital planning and intraoperative transfer can improve the geometric precision of mandibular condylar fracture fixation. The available comparative evidence does not yet establish a corresponding advantage in function, safety, or long-term construct survival. Patient-specific fixation should therefore be evaluated through the mechanical and operative problem it resolves, rather than through customization alone.

The next step is to connect reproducible morphology, interfragmentary contact, fixation mechanics, and patient-important outcomes in prospectively tested workflows. Retrospective reconstruction of actual failures may help validate this connection, provided model development is separated from outcome testing. Until that validation is available, numerical stress reductions and submillimetre planning accuracy should remain supporting evidence rather than stand-alone treatment indications.

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AUTHOR CONTRIBUTIONS

Musayev Shamshodbek Shukhratovich: Conceptualization, Investigation.

Musayev Shamshodbek Shukhratovich: Methodology, Data Analysis.

Shomurodov Kakhramon Erkinovich: Data Curation, Formal Analysis.

Shomurodov Kakhramon Erkinovich: Supervision, Writing—Review & Editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Ethical approval was not required for this study.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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