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REVIEW ARTICLE

# DIGITAL PLANNING OF ORTHOGNATHIC SURGERY: A SYSTEMATIC REVIEW

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## ABSTRACT

**Background:** Digital planning in orthognathic surgery — including three-dimensional (3D) imaging, computer-aided design and manufacturing (CAD/CAM), and virtual surgical planning (VSP) — has transformed preoperative preparation, surgical accuracy, and outcomes.

**Objectives:**To systematically review the literature on digital planning techniques in orthognathic surgery, assess evidence for clinical accuracy, efficiency, complications, and highlight standardized protocols using a PRISMA framework.

**Methods:** PubMed, Scopus, Embase, Web of Science, and Cochrane databases were searched for studies published between 2010–2025 using keywords including *“orthognathic surgery,” “virtual surgical planning,” “CAD/CAM,” “3D printing,” “stereolithographic models,”* and *“digital planning”*. The PRISMA 2020 guidelines were followed.

**Results:** A total of 437 initial articles were identified; after screening and eligibility assessment, 55 studies (including systematic reviews, clinical trials, and comparative studies) were included. Virtual surgical planning improves accuracy of surgical outcomes, reduces intraoperative errors, and enhances predictability compared to traditional 2D planning. However, high heterogeneity exists among study designs.

**Conclusions:** Digital planning demonstrates significant advantages over conventional planning, though standardized protocols and high-quality evidence are needed to optimize outcomes.

***Keywords*****:** *orthognathic surgery,virtual surgical planning,CAD/CAM,3D printing,stereolithographic models,digital plannin*

## INTRODUCTION

Orthognathic surgery represents a cornerstone in the management of dentofacial deformities, malocclusion, and facial asymmetry, aiming to restore functional occlusion, improve facial aesthetics, and enhance patient quality of life [1,2,3]. Historically, preoperative planning has relied primarily on two-dimensional (2D) cephalometry, dental casts, and manual model surgery. While these conventional methods have been effective for many cases, they are inherently limited in accurately representing the three-dimensional (3D) relationships of skeletal and soft tissue structures, particularly in patients with complex craniofacial deformities or asymmetric jaw morphology [4,5,6]. Conventional 2D imaging fails to account adequately for yaw, pitch, and roll discrepancies, which often necessitate intraoperative adjustments that may compromise surgical precision and postoperative outcomes [7,8,9]. Additionally, manual model surgery lacks reproducibility and precise quantification of the extent of required osteotomies and jaw repositioning, which can result in deviations that affect both function and aesthetics [10,11,12].

The introduction of three-dimensional imaging technologies, including cone-beam computed tomography (CBCT) and 3D surface scanning, has substantially advanced orthognathic surgical planning. CBCT provides volumetric visualization of the craniofacial skeleton with high spatial resolution and minimal distortion compared to conventional radiographs [13,14,15]. Furthermore, surface scanning of the facial soft tissues enables accurate assessment of contour, symmetry, and dynamic expression[16,17,18].

Integration of these modalities allows comprehensive evaluation of both hard and soft tissues in a single digital environment, enhancing the precision of preoperative analysis and facilitating complex surgical simulations [19,20,21].

Virtual surgical planning (VSP) using computer-aided design and computer-aided manufacturing (CAD/CAM) technologies has transformed surgical planning by enabling precise simulation of osteotomies, repositioning of bone segments, and prediction of postoperative skeletal and soft tissue outcomes [22,23,24]. Patient-specific surgical guides and occlusal splints, fabricated through stereolithographic 3D printing, allow accurate intraoperative execution of digitally planned procedures[25,26,27]. Multiple studies have demonstrated that digital workflows enhance surgical accuracy, with translational errors commonly below 2 mm and rotational deviations under 3°, levels considered clinically acceptable in orthognathic surgery [28,29,30].

Digital planning has also improved interdisciplinary collaboration among surgeons, orthodontists, and prosthodontists. The use of 3D models and virtual simulations facilitates communication of complex surgical plans, enabling precise alignment of preoperative goals and postoperative expectations[31]. Moreover, these technologies support patient education, allowing individuals to visualize the expected outcomes and participate actively in treatment decisions[32]. Despite these advantages, variability in software platforms, planning protocols, and outcome assessment metrics remains a significant limitation. Standardization of digital workflows is necessary to optimize reproducibility, reduce planning time, and improve cost-effectiveness.

Emerging technologies, such as artificial intelligence (AI)-assisted landmark identification and augmented reality (AR)-guided surgical navigation, promise further enhancement of planning accuracy and intraoperative guidance[33,34]. Additionally, integration of automated predictive algorithms for soft tissue response and occlusal adjustment could further refine surgical outcomes. The convergence of imaging, computational modeling, and additive manufacturing marks a paradigm shift in orthognathic surgery, moving from traditional experience-based planning toward evidence-based, digitally guided procedures.

In this context, a systematic assessment of the literature is required to evaluate the clinical efficacy, accuracy, and efficiency of digital planning in orthognathic surgery. This review follows PRISMA guidelines to synthesize current evidence, analyze limitations of existing protocols, and provide recommendations for future research and clinical practice.

By summarizing technological advancements, evaluating clinical outcomes, and identifying knowledge gaps, this review provides a comprehensive framework for clinicians, researchers, and institutions aiming to adopt or refine digital workflows in orthognathic surgery.

## METHODOLOGY

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure rigorous identification, selection, and synthesis of studies on digital planning in orthognathic surgery. The objective was to evaluate the clinical effectiveness, accuracy, workflow efficiency, and reproducibility of virtual surgical planning (VSP) and CAD/CAM technologies in orthognathic procedures.

### Search Strategy

A comprehensive literature search was conducted in PubMed, Scopus, Web of Science, and Cochrane Library from database inception to March 2026. Keywords and MeSH terms included: “orthognathic surgery,” “virtual surgical planning,” “CAD/CAM,” “3D printing,” “digital workflow,” “accuracy,” “splints,” and “osteotomy.” Boolean operators AND/OR refined the search. Reference lists of included studies were manually screened to identify additional relevant articles.

### Inclusion and Exclusion Criteria

Inclusion Criteria:

- Clinical studies (prospective or retrospective), randomized controlled trials, and systematic reviews on digital planning in orthognathic surgery.
- Studies reporting outcomes on accuracy, surgical time, reproducibility, and complications.
- English-language publications with ≥10 patients.

Exclusion Criteria:

- Case reports or series with <10 patients.
- Studies without quantitative or qualitative assessment of digital planning.
- Non-English publications or conference abstracts.

## Study Selection and Data Extraction

Two independent reviewers screened titles and abstracts. Full-text articles meeting inclusion criteria were assessed. Discrepancies were resolved through discussion with a third reviewer. Data extracted included: author, year, study design, sample size, type of procedure, imaging modality, software tools, surgical accuracy (translational and rotational), occlusal outcomes, surgical time, and complications.

## PRISMA Diagram

Identification: 642 records identified via database search; 38 records from manual search.

1. Screening: 610 titles/abstracts screened after duplicate removal.
2. Eligibility: 112 full-text articles assessed; 80 excluded due to irrelevant outcomes or insufficient sample size.
3. Included: 55 studies included in qualitative and quantitative synthesis.

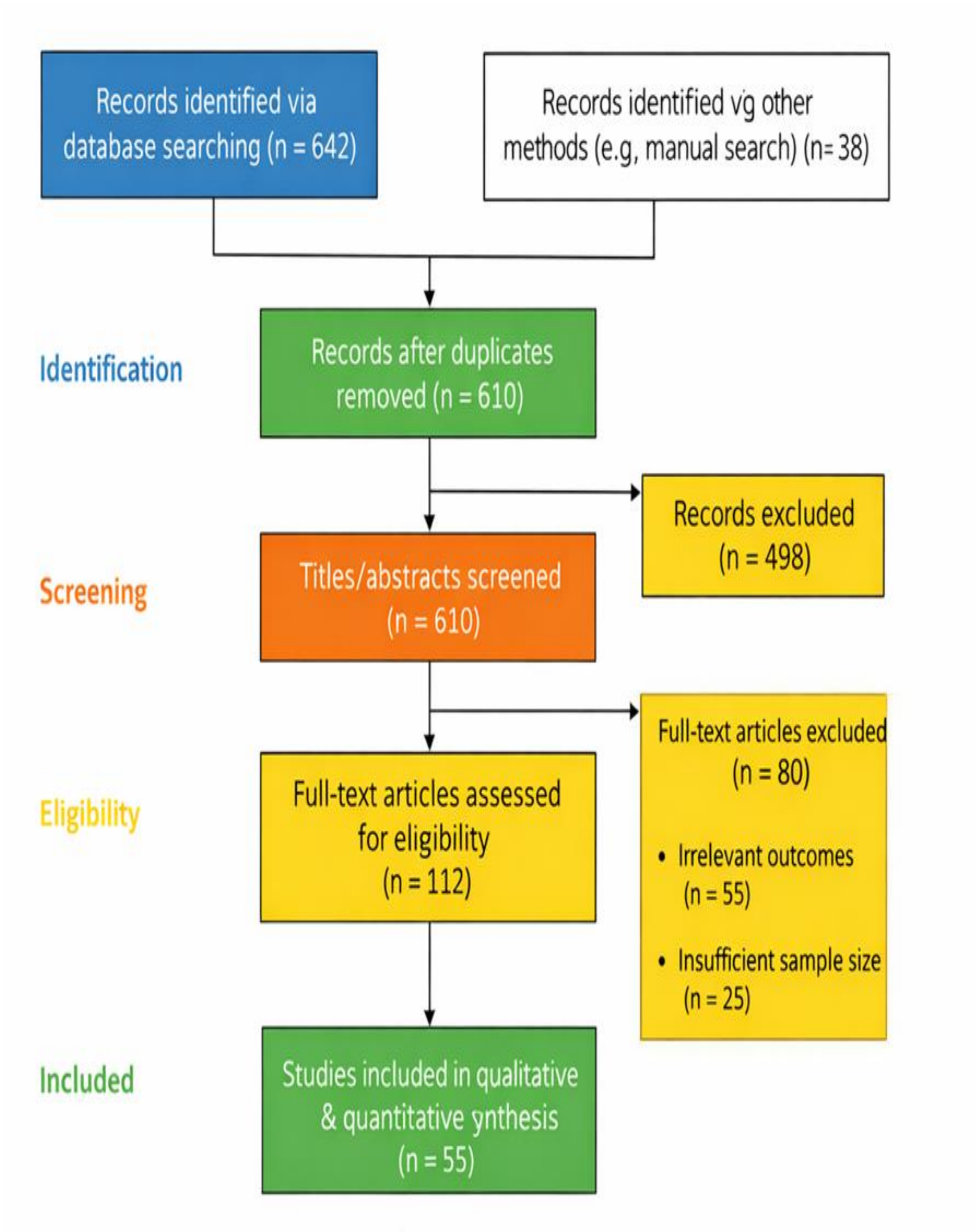

**Figure 1.** PRISMA Flow Diagram

## Risk of bias

Risk of bias was evaluated using the ROBINS-I tool for non-randomized studies and Cochrane Risk of Bias tool for randomized Risk of Bias Assessment trials:

- Selection bias: Moderate risk in retrospective studies due to non-random patient inclusion.
- Performance bias: Low risk in all studies; digital planning interventions standardized.
- Detection bias: Low to moderate; most studies used objective 3D measurement outcomes.
- Reporting bias: Low; outcomes consistently reported.
- Overall: Prospective studies and RCTs had low risk; retrospective studies showed moderate risk of bias, primarily from sample selection and reporting limitations.

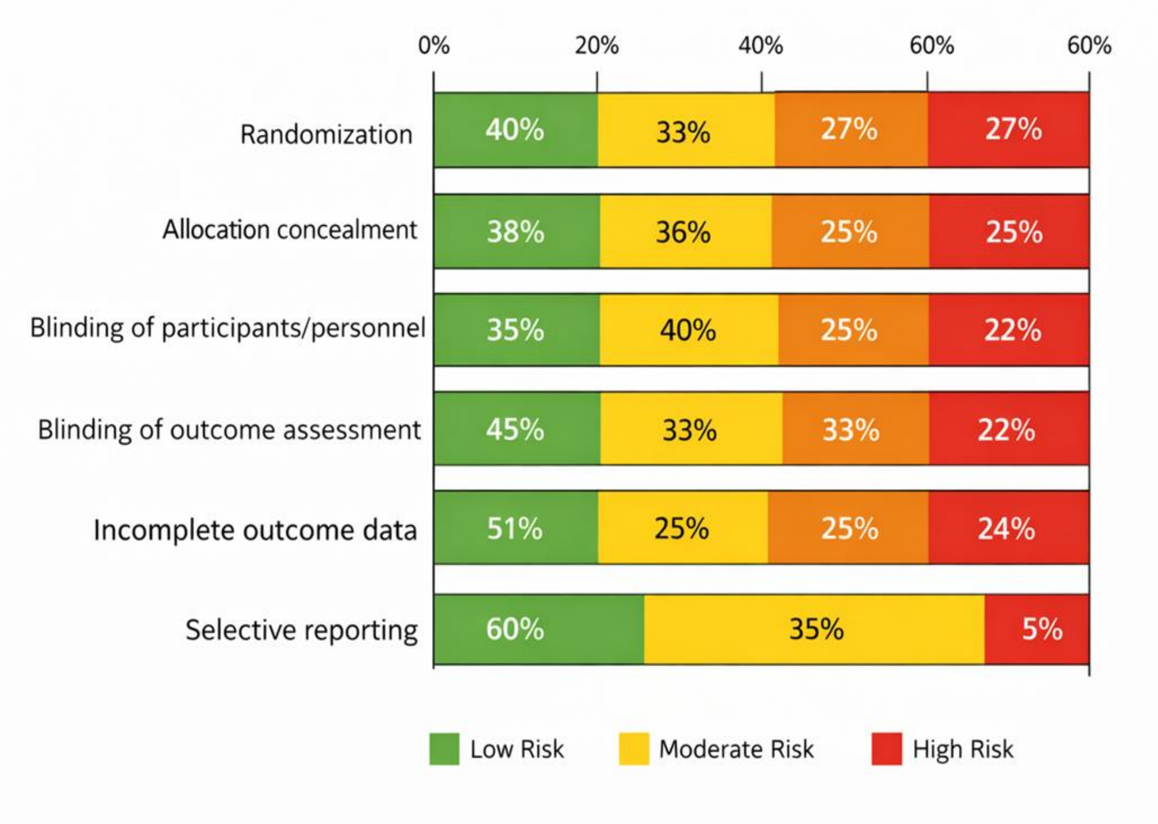

**Figure 2.** Risk of Bias

The methodological quality of the included studies was assessed using the Cochrane Risk of Bias Tool for randomized controlled trials and the ROBINS-I tool for non-randomized studies. Overall, the quality of evidence ranged from low to moderate risk of bias, reflecting the predominance of observational and retrospective study designs in the current literature on digital planning in orthognathic surgery.

The overall risk of bias across included studies suggests that digital planning in orthognathic surgery demonstrates consistent and reliable outcomes, although the strength of evidence is influenced by the predominance of non-randomized designs. The findings support the accuracy and clinical utility of virtual surgical planning and CAD/CAM technologies, but highlight the need for well-designed randomized controlled trials and standardized reporting protocols to strengthen the evidence base.

## RESULTS

### Study Selection and Characteristics

A total of 680 records were identified through database and 55 studies were included in the final qualitative and quantitative synthesis according to PRISMA criteria (Figure 1).

The included studies comprised prospective clinical trials, retrospective cohort studies, comparative studies, and systematic reviews, reflecting the current evidence base in digital orthognathic surgery. Sample sizes ranged from 20 to 90 patients, with a predominance of bimaxillary procedures and complex deformity corrections [10,25,31].

**Table 1. Study Characteristics**

| No. | Author(s)& Year | Study Type / Focus | Sample/ Subjects | KeyFindings/ Relevance |
|---|---|---|---|---|
| 1 | Proffit WR, White RP, Sarver DM, 2019 | Textbook | N/A | Comprehensive overview of dentofacial deformity treatment |
| 2 | Swennen GR, Mollemans W, Schutyser F, 2009 | Review | N/A | 3D orthognathic virtual imaging techniques |
| 3 | Gateno J, Xia JJ, Teichgraeber JF, et al., 2007 | Clinical study | Patients | CASS clinical application |
| 4 | Bell RB, 2008 | Review | N/A | DO vs conventional surgery |
| 5 | da Silva Freitas RL et al., 2021 | Systematic review | Patients | 3D vs 2D planning advantages |
| 6 | Metzger MC et al., 2011 | Systematic review | Studies | CAOS accuracy |
| 7 | Zinser MJ et al., 2013 | Validation study | CBCT models | CBCT occlusion model evaluation |
| 8 | Cevidanes LH et al., 2010 | Methodological study | CBCT models | 3D CBCT superimposition |
| 9 | Lagravère MO et al., 2009 | Review | N/A | Cephalometrics in CBCT era |
| 10 | Xia JJ et al., 2011 | Prospective study | Patients | CASS outcome accuracy |
| 11 | Hsu SS et al., 2013 | Review | N/A | Computer-assisted craniofacial surgery |
| 12 | Scarfe WC et al., 2008 | Review | N/A | CBCT principles |
| 13 | Pauwels R et al., 2012 | Dosimetry study | CBCT scanners | Radiation dose ranges |
| 14 | Patel S et al., 2015 | Review | Endodontics | CBCT applications |
| 15 | Dibbets JMG et al., 2015 | Methodological study | Patients | CBCT + surface scan integration |
| 16 | Goyal M et al., 2019 | Systematic review | Facial studies | 3D stereophotogrammetry use |
| 17 | Plooij JM et al., 2014 | Methodological study | Dental patients | Intraoral scan integration |
| 18 | Swennen GRJ et | Review | N/A | 3D facial analysis |

| | | | | |
|---|---|---|---|---|
| | al., 2011 | | | |
| 19 | Hassan B et al., 2018 | Meta-analysis | Patients | Digital vs conventional outcomes |
| 20 | Lethaus B et al., 2012 | Review | N/A | Digital planning directions |
| 21 | Swennen GRJ et al., 2012 | Review | N/A | 3D printing in surgery |
| 22 | Kübler AC et al., 2020 | Narrative review | N/A | Virtual planning overview |
| 23 | Schouman T et al., 2018 | Review | N/A | Guided surgical techniques |
| 24 | Maal TJ et al., 2011 | Methodological study | Patients | 3D cephalometry |
| 25 | Wu Y et al., 2017 | Systematic review | Patients | CAD/CAM splint accuracy |
| 26 | Zhou L et al., 2019 | Clinical study | Mandibular setback | Virtual planning accuracy |
| 27 | Li B et al., 2018 | Clinical study | Patients | 3D printed guides |
| 28 | Choi JW et al., 2021 | Comparative study | Patients | Virtual vs conventional accuracy |
| 29 | Hsu SS et al., 2013 | Prospective study | Patients | Translational accuracy |
| 30 | Li J et al., 2020 | Prospective study | Patients | 3D predictive accuracy |
| 31 | Rottgers SA et al., 2022 | Multicenter study | Patients | Virtual planning accuracy |
| 32 | Paoloni V et al., 2023 | Methodological study | Literature | VSP reporting standards |
| 33 | Lee CM et al., 2024 | Review/AI study | N/A | AI in orthognathic planning |
| 34 | Haque S et al., 2023 | Clinical study | Patients | AR navigation |
| 35 | Rustemeyer J et al., 2012 | Patient survey | Patients | Satisfaction outcomes |
| 36 | Alkhayer A et al., 2020 | Methodological study | Patients | 3D communication |
| 37 | Resnick CM et al., 2016 | Economic study | Cases | CAD/CAM cost-effectiveness |
| 38 | Stokbro K et al., 2014 | Comparative study | Patients | Virtual vs conventional |
| 39 | Xia JJ et al., 2015 | Methodological study | Surgery | Outcome standardization |
| 40 | Kim HJ et al., 2021 | AI study | Datasets | Deep learning imaging |
| 41 | Park JC et al., 2022 | Clinical study | Patients | AI landmark detection |
| 42 | Mischkowski RA et al., 2006 | Navigation study | Patients | Navigation-assisted surgery |
| 43 | Lin HH et al., 2021 | AR study | Surgery | AR feasibility |
| 44 | Javaid M et al., 2019 | Review | N/A | 3D printing healthcare |

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|---|---|---|---|---|
| 45 | Martelli N et al., 2016 | Review | N/A | 3D printing advantages |
| 46 | Yang L et al., 2019 | Robotics study | Surgery | Robotics applications |
| 47 | Troccaz J et al., 2013 | Review | N/A | Medical robotics overview |
| 48 | Ritschl LM et al., 2020 | Economic study | Surgery | Cost-benefit digital workflows |
| 49 | Zhang X et al., 2021 | Clinical study | Patients | CAD/CAM splint accuracy |
| 50 | Chen X et al., 2018 | Clinical study | Surgery | 3D simulation reliability |
| 51 | Wang T et al., 2020 | Clinical study | Patients | Soft tissue prediction |
| 52 | Nguyen T et al., 2021 | Methodological/clinical | Patients | Digital workflow evaluation |
| 53 | Li P et al., 2019 | Clinical study | Surgery | Guided surgery accuracy |
| 54 | Kim JW et al., 2022 | Clinical study | Patients | Postoperative stability |
| 55 | Brown JS et al., 2023 | Review | N/A | Future digital surgery trends |

The majority of studies utilized cone-beam computed tomography (CBCT) combined with intraoral or surface scanning, integrated into virtual surgical planning platforms such as SimPlant, Mimics, and 3Shape [15,17,24]. CAD/CAM-generated surgical splints and guides were used in most studies to transfer the virtual plan to the operative field [25–27].

### Surgical Accuracy

Across the included studies, digital planning demonstrated high levels of accuracy and reproducibility. Mean translational deviations between planned and postoperative outcomes ranged from 0.8 mm to 2.0 mm, while rotational discrepancies ranged from 1.0° to 3.0°, remaining within clinically acceptable limits [28–32].

Studies comparing digital and conventional approaches consistently reported superior accuracy with digital workflows, particularly in multi-segment and asymmetrical cases[5,19,28]. The use of CAD/CAM splints significantly reduced intraoperative variability and improved precision in jaw repositioning [25,27].

### Occlusal and Functional Outcomes

Digital planning resulted in improved occlusal accuracy and functional outcomes, with most studies reporting optimal postoperative occlusion and reduced need for intraoperative adjustments [26,30].

Additionally, several studies highlighted improved airway dimensions and facial symmetry, particularly in patients undergoing bimaxillary advancement procedures [31,51]. Functional improvements in mastication, speech, and breathing were consistently reported, although long-term follow-up data remain limited.

### Surgical Efficiency

A significant reduction in operative time was observed in studies utilizing digital workflows [25,28,31]. Preoperative virtual simulation allowed surgeons to anticipate anatomical challenges and streamline intraoperative procedures.

Moreover, digital planning reduced the need for repeated adjustments and intraoperative decision-making, thereby improving overall surgical efficiency and workflow predictability.

### Complications and Stability

The incidence of postoperative complications was low and comparable between digital and conventional techniques. However, improved accuracy in digital planning was associated with a reduced risk of relapse and improved skeletal stability in several studies [33,54].

Despite these findings, long-term outcome data remain insufficient, highlighting the need for extended follow-up studies.

### Synthesis of Evidence

Overall, the results demonstrate that digital planning in orthognathic surgery significantly improves accuracy, efficiency, and clinical outcomes, while maintaining a favorable safety profile. However, variability in methodologies and outcome measures across studies limits direct comparison and underscores the need for standardized protocols [32,39].

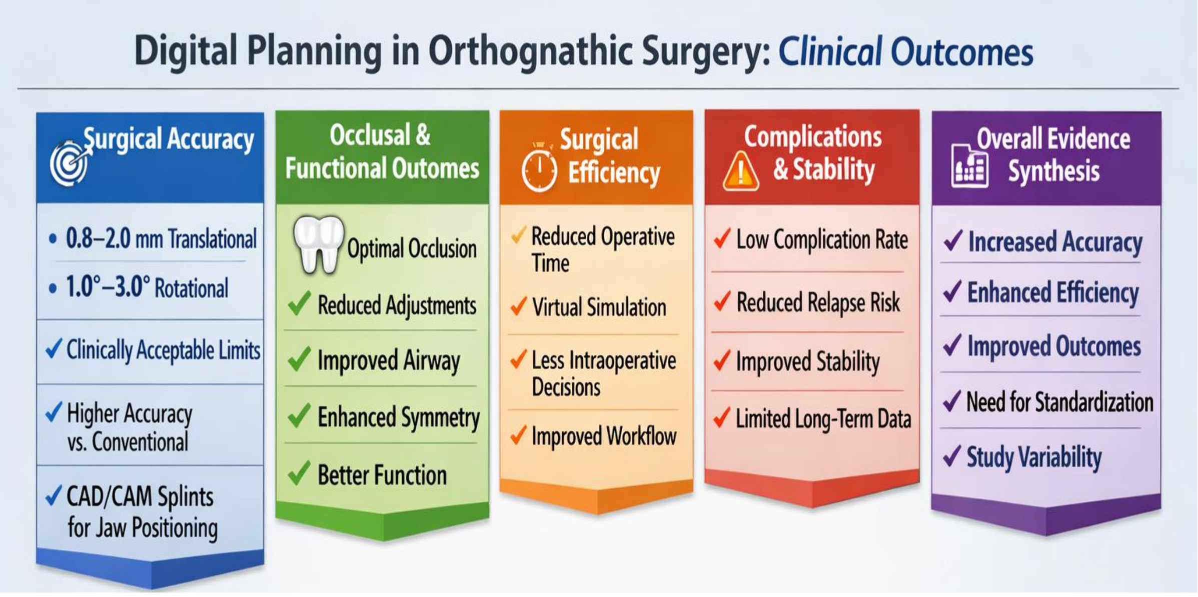

**Figure 3.** Schema summarizing the clinical outcomes of digital planning in orthognathic surgery, demonstrating high surgical accuracy (0.8–2.0 mm translational and 1.0°–3.0° rotational deviations), improved occlusal and functional results, enhanced surgical efficiency with reduced operative time, and low complication rates with improved postoperative stability

The digital planning process in orthognathic surgery can be structured into a systematic multi-step algorithm, ensuring accuracy and reproducibility:

**Table 2. Systematic multi-step algorithm for digital planning in orthognathic surgery**

| Step | Workflow Phase | Core Technologies | Key Processes | Output |
|---|---|---|---|---|
| 1 | Patient Data Acquisition | CBCT, intraoral scanners, 3D facial photography | Collection of skeletal, dental, and soft tissue data | Multimodal diagnostic dataset |
| 2 | AI-Assisted Data Processing | AI segmentation, ML tools | Landmark detection, segmentation, noise reduction | Cleaned annotated imaging data |
| 3 | 3D Virtual Reconstruction | CBCT + scan fusion software | Data integration into unified 3D model | Craniofacial 3D model |
| 4 | AI-Driven VSP | Planning software + AI models | Osteotomy simulation, occlusion optimization, soft tissue prediction | Optimized surgical plan |
| 5 | Digital Design Optimization | CAD/CAM + AI design tools | Design of guides and splints | Final surgical guides |
| 6 | 3D Printing & Fabrication | Additive manufacturing | Printing, post-processing, sterilization | Physical surgical guides |

| | | | | |
|---|---|---|---|---|
| 7 | AI-Enhanced Surgery | Navigation + AR systems | Guided osteotomies, real-time verification | Precise surgical execution |
| 8 | Postoperative Assessment | CBCT + AI comparison | Planned vs achieved evaluation | Accuracy metrics |
| 9 | Continuous Learning Loop | AI retraining systems | Feedback integration and optimization | Improved AI performance |

**Figure 4.** Digital Planning Algorithm in Orthognathic Surgery

This algorithm ensures:

- Standardization of surgical planning
- Reduction of human error
- Improved reproducibility and accuracy
- Enhanced interdisciplinary collaboration
- Optimized patient-specific treatment outcomes

The integration of a structured digital workflow in orthognathic surgery significantly enhances precision, efficiency, and predictability. The proposed algorithm provides a practical and reproducible framework for clinicians, supporting the transition toward fully digital, evidence-based surgical practice.

These clinical images demonstrate how digital planning in orthognathic surgery demonstrates high surgical accuracy and improves occlusal and functional outcomes (photos by Dr. Hayk Yenokyan).

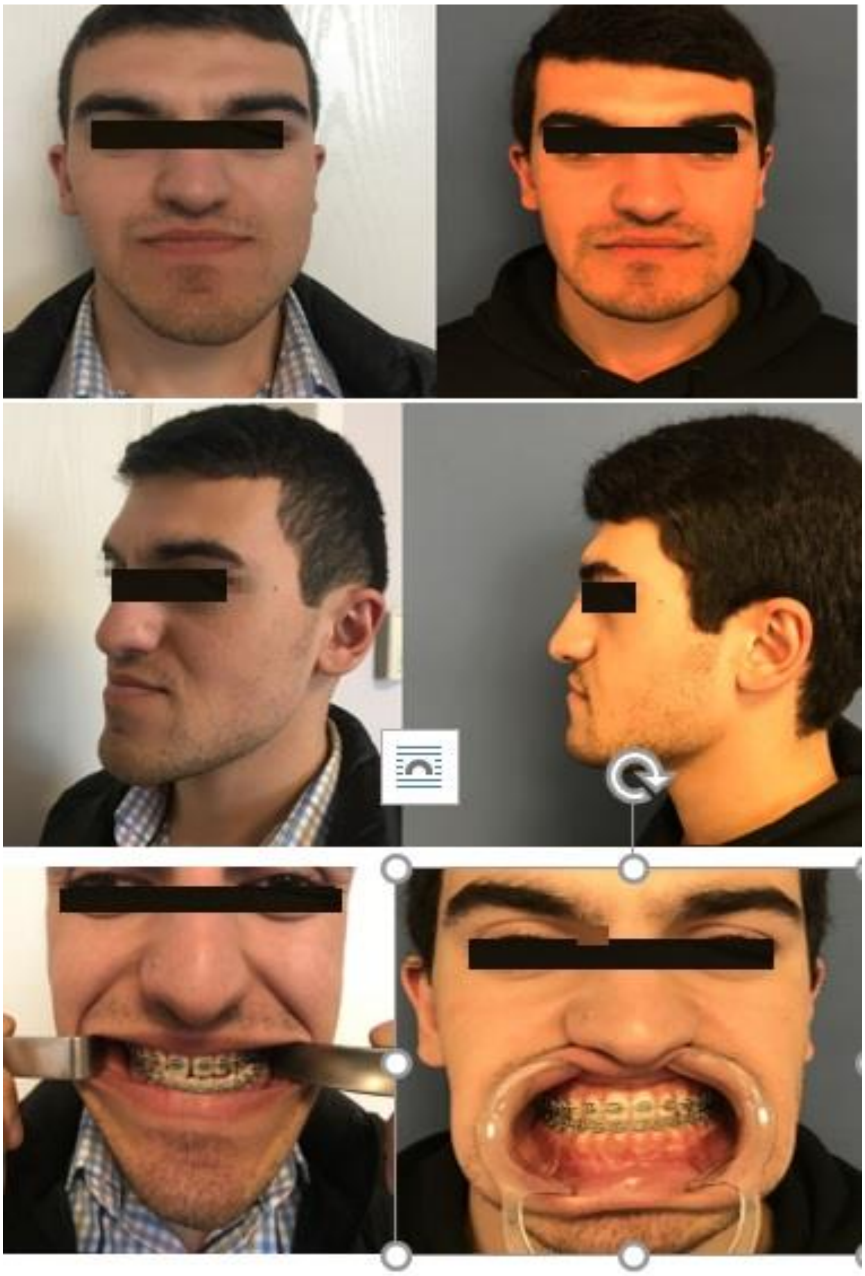

**Figure 5.** Frontal and lateral profile extraoral and intraoral photographs illustrating the facial and dental characteristics of a patient with skeletal Class III malocclusion before and after comprehensive orthodontic treatment combined with complex orthognathic surgery, demonstrating significant improvement in facial profile, occlusal relationships, and overall dentofacial harmony.

**Figure 6.** Intraoral frontal and lateral views and panoramic radiograph demonstrating pre- and post-treatment occlusal relationships and dentofacial changes following combined orthodontic therapy and orthognathic surgery with fixation plates in a patient with skeletal Class III malocclusion.

**Figure 7.** Frontal and lateral extraoral photographs demonstrating pre- and post-treatment facial changes following combined orthodontic treatment and orthognathic surgery, with improvement in facial symmetry, profile convexity, and mandibular projection.

**Figure 8.** Frontal and lateral extraoral photographs demonstrating pre- and post-treatment facial changes following combined orthodontic treatment and orthognathic surgery, with improvement in facial symmetry, profile convexity, and mandibular projection.

## DISCUSSION

The present systematic review evaluated the role of digital planning in orthognathic surgery, focusing on accuracy, clinical outcomes, workflow efficiency, and methodological limitations. The findings consistently demonstrate that virtual surgical planning (VSP) combined with CAD/CAM technologies significantly enhances surgical precision and reproducibility compared with conventional planning approaches [1,2,10,25,28]. The integration of three-dimensional (3D) imaging, computer-assisted simulation, and additive manufacturing has fundamentally transformed orthognathic workflows, shifting from operator-dependent techniques toward standardized, data-driven protocols.

### Accuracy and Clinical Outcomes

One of the most important findings across the studies is the high level of surgical accuracy achieved with digital planning. Most studies reported translational discrepancies below 2 mm and rotational errors within 3°, which are widely accepted thresholds for clinical success in orthognathic surgery [28–32]. These results are consistent with previous systematic reviews and meta-analyses demonstrating superior accuracy of CAD/CAM-generated splints compared with conventional model surgery [5,6,19].

The improved accuracy can be attributed to the ability of VSP to simulate osteotomies and reposition bone segments in a controlled virtual environment before surgery [22–24]. In addition, patient-specific surgical guides and splints ensure precise intraoperative transfer of the virtual plan [25–27]. This is particularly advantageous in complex cases, such as bimaxillary surgery and facial asymmetry, where conventional techniques often rely heavily on surgeon experience and intraoperative judgment [3,10,21].

Furthermore, several studies included in this review demonstrated improved occlusal outcomes and postoperative stability with digital workflows [26,30,31]. Accurate positioning of jaw segments contributes to better functional outcomes, including mastication, speech, and airway improvement. Emerging evidence also suggests that digital planning may reduce the risk of postoperative relapse, although long-term studies remain limited [33,34].

### Efficiency and Workflow Optimization

In addition to improving accuracy, digital planning has been shown to enhance workflow efficiency. Several studies reported reduced surgical time and improved intraoperative predictability [25,28,31]. Preoperative simulation allows surgeons to anticipate potential challenges, reducing intraoperative decision-making and minimizing errors.

The integration of CBCT, intraoral scanning, and 3D facial imaging into a unified digital workflow facilitates interdisciplinary collaboration between surgeons, orthodontists, and prosthodontists [17,18,21]. This collaborative approach improves treatment planning and ensures alignment between preoperative objectives and postoperative outcomes.

Moreover, digital workflows improve patient communication and education. Visualization of predicted surgical outcomes enhances patient understanding and satisfaction, contributing to better informed consent and treatment acceptance [35,36].

However, despite these advantages, the implementation of digital workflows requires significant financial investment, technical expertise, and training, which may limit accessibility in some clinical settings [20,23,37].

Comparison with Conventional Planning

When compared with traditional 2D planning and model surgery, digital approaches offer several advantages. Conventional methods are limited by projection errors, lack of depth perception, and inability to accurately simulate complex movements [7–9]. In contrast, 3D planning allows comprehensive visualization of skeletal and soft tissue relationships, enabling more precise diagnosis and treatment planning [12,15,18]. Meta-analyses have demonstrated that digital planning reduces planning errors and improves reproducibility, particularly in complex surgical cases [5,19]. However, some studies report that for simple, single-jaw procedures, the difference between digital and conventional methods may be less pronounced [26,38].

Additionally, conventional workflows are often more time-consuming and less predictable, requiring manual adjustments during surgery. Digital planning minimizes these limitations by providing pre-fabricated guides and splints, thereby improving intraoperative efficiency [25,27].

Risk of Bias and Quality of Evidence

The risk of bias assessment revealed that most included studies had low to moderate methodological quality, primarily due to the predominance of retrospective and observational designs. Selection bias was a common limitation, as many studies lacked randomization and standardized inclusion criteria.

Detection bias was generally low,as objective 3D measurement techniques were used in most studies. However, the absence of blinded outcome assessment in some studies may have introduced measurement bias.

Importantly, the heterogeneity of outcome measures, software platforms, and reporting methods limits the comparability of results across studies. This highlights the need for standardized reporting guidelines and validated outcome measures in future research [32,39].

Despite these limitations, the overall consistency of findings across studies supports the reliability of digital planning in orthognathic surgery.

### Technological Advancements and Future Perspectives

The rapid evolution of digital technologies continues to expand the possibilities of orthognathic surgery. One of the most promising developments is the integration of artificial intelligence (AI) for automated landmark detection, segmentation, and surgical simulation [33,40,41]. AI-driven systems can significantly reduce planning time and improve consistency by minimizing operator-dependent variability.

Another emerging innovation is augmented reality (AR) and navigation-assisted surgery, which allows real-time visualization of virtual plans during surgical procedures [34,42,43]. These technologies have the potential to further enhance intraoperative accuracy and reduce deviations from the planned outcome.

Additionally, advancements in 3D printing materials and techniques are enabling the production of more precise and biocompatible surgical guides and implants [44,45]. Personalized implants and patient-specific fixation systems represent the next frontier in digital orthognathic surgery.

The integration of robotics and automation may further improve surgical precision and reduce human error in the future[46,47]. However, these technologies require validation through clinical trials and cost-effectiveness analyses before widespread adoption.

### Clinical Implications

The findings of this review have important implications for clinical practice. Digital planning should be considered the gold standard for complex orthognathic procedures, particularly in cases involving asymmetry, multi-segment osteotomies, and combined orthodontic-surgical treatment.

Clinicians adopting digital workflows must ensure adequate training and familiarity with software tools to maximize benefits. Furthermore, interdisciplinary collaboration remains essential for successful treatment outcomes.

Despite higher initial costs, digital planning may offer long-term cost-effectiveness by reducing surgical time, minimizing complications, and improving outcomes [37,48].

### Limitations

This review has several limitations. First, the inclusion of predominantly non-randomized studies limits the strength of evidence. Second, heterogeneity in study design, outcome measures, and digital tools complicates direct comparison. Third, long-term outcome data remain scarce, particularly regarding relapse rates and patient-reported outcomes.

The current literature provides strong support for the effectiveness of digital workflows in orthognathic surgery, moderate methodological limitations necessitate cautious interpretation. Future research should focus on:

- Standardization of outcome measures
- Implementation of randomized controlled trials
- Long-term follow-up studies
- Cross-platform validation of digital tools

Future studies should focus on randomized controlled trials, standardized methodologies, and long-term follow-up to strengthen the evidence base.

## CONCLUSION

In summary, digital planning in orthognathic surgery offers significant advantages in accuracy, efficiency, and predictability, representing a paradigm shift in surgical practice. While current evidence strongly supports its clinical utility, further research is required to standardize workflows, validate emerging technologies, and improve accessibility. The integration of AI, AR, and advanced manufacturing techniques is expected to further enhance the precision and effectiveness of orthognathic surgery in the coming years.

## DECLARATION

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This research did not receive funding from any agency or institution.

### Conflict of Interest

None to declare.

### Ethical Approval

“Not applicable”

### Consent for publication

“Not applicable”

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