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DIGITAL PLANNING AND PREDICTIVE MODELING IN ORTHOGNATHIC SURGERY: CLINICAL DECISION SUPPORT, ACCURACY, AND ETHICAL IMPLICATIONS

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ABSTRACT

Background: Digital workflows have transformed orthognathic surgery by enabling three-dimensional virtual surgical planning (VSP) and, more recently, artificial-intelligence-based predictive modeling. While skeletal accuracy has improved substantially, the clinical value of these tools increasingly depends on their ability to predict soft-tissue outcomes and support complex treatment decisions.

Methods: This narrative review synthesizes evidence from 20 peer-reviewed studies, including systematic reviews, clinical cohorts, and machine-learning validations, to evaluate (i) the accuracy of digital patient modeling and VSP transfer, (ii) the performance of predictive models for postoperative outcomes and diagnostic classification, and (iii) associated ethical and governance considerations.

Results: Automated craniofacial and dental modeling achieves submillimetric to low-millimetric accuracy, with landmark localization errors typically ≤2 mm and dental landmark errors near 0.4 mm. Clinical cohorts demonstrate that VSP transfers to surgery with mean translational deviations well below 2 mm in all planes. Predictive models estimate soft-tissue and aesthetic outcomes within clinically meaningful error margins and classify the need for orthognathic surgery with AUC values up to ~0.9 in high-risk malocclusion groups.

Conclusions: Digital planning in orthognathic surgery has evolved into a precision-oriented, data-driven framework. When combined with predictive modeling and appropriate ethical governance, these technologies can enhance accuracy, personalize treatment strategies, and reduce diagnostic uncertainty, particularly in borderline and asymmetric cases.

KEYWORDS

Orthognathic Surgery, Virtual Surgical Planning, Predictive Modeling, Artificial Intelligence, Clinical Decision Support, Patient-Specific Modeling

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1. Introduction

Orthognathic surgery is a cornerstone in the management of moderate to severe dentofacial deformities, particularly among adults with skeletal Class II and Class III malocclusions, facial asymmetry, and functional impairments involving mastication, speech, airway patency, and temporomandibular joint health. Beyond these functional dimensions, facial aesthetics and psychosocial well-being strongly motivate patients to seek treatment, with deviations of only a few millimeters in the menton, midline, or occlusal cant often perceived as abnormal by both clinicians and lay observers. Meta-analytical evidence demonstrates that orthognathic interventions yield significant improvements in skeletal symmetry, soft-tissue balance, and quality of life, yet also highlights persistent challenges related to relapse, stability, and inter-individual variability in postoperative outcomes, especially in cases of marked asymmetry and complex bimaxillary movements [15].

Historically, surgical planning has relied on two-dimensional cephalometry, plaster model surgery, and manual transfer of splints to the operating room. While these approaches enabled decades of clinical progress, they are inherently constrained by their inability to represent three-dimensional craniofacial anatomy and to model the nonlinear coupling between skeletal movements and soft-tissue response. Errors in landmark identification, superimposition, and model handling can accumulate across steps, resulting in limited reproducibility and variable predictability of outcomes. Comparative studies and systematic reviews have shown that traditional surgical planning is particularly vulnerable to inaccuracies in the transverse and sagittal planes, where small discrepancies may translate into visible asymmetry or occlusal instability [4, 20]. These limitations created a clear impetus for three-dimensional, data-integrated planning environments.

Virtual surgical planning (VSP) has emerged as the dominant paradigm to address these shortcomings by integrating cone-beam computed tomography, intraoral scans, and facial surface imaging into unified three-dimensional digital patient models. Within these environments, surgeons can simulate osteotomies, explore alternative skeletal movements, and fabricate patient-specific splints and guides via computer-aided design and manufacturing. Across multiple systematic reviews and meta-analyses, VSP has achieved translational and rotational errors typically below 2 mm and 2°, thresholds widely regarded as clinically acceptable for orthognathic surgery [8, 20]. Importantly, VSP also shortens preoperative planning time without prolonging operative duration, improving workflow efficiency while maintaining or enhancing accuracy [20]. These advantages have accelerated the adoption of digital planning across both academic centers and private practices.

Real-world clinical validation further supports the reliability of fully digital workflows. Cohort studies of patients undergoing bimaxillary surgery demonstrate that postoperative jaw positions closely match their virtual plans in all three spatial planes, with mean deviations well within accepted clinical limits [14]. However, even when skeletal accuracy is high, variability remains in mandibular positioning and in the soft-tissue envelope that ultimately defines facial appearance. This residual uncertainty underscores a critical insight: while digital planning can accurately prescribe skeletal movements, predicting how an individual patient's tissues will respond remains a probabilistic challenge rather than a deterministic one [9].

Parallel to the maturation of VSP, artificial intelligence (AI) and machine learning have been introduced into orthodontics and maxillofacial surgery to automate anatomical analysis and to generate outcome predictions from large, multidimensional datasets. Deep learning systems can now localize craniofacial and dental landmarks with errors comparable to or lower than those of experienced clinicians, and automated segmentation of dentition and skeletal structures supports precise occlusal analysis and splint design [6, 7, 17]. These capabilities enable the construction of high-fidelity digital representations of each patient—often conceptualized as craniofacial "digital twins"—that integrate geometry, occlusion, and surface morphology into a coherent model suitable for simulation and optimization [11, 16].

Beyond automation, predictive modeling represents a qualitative leap in how digital tools inform clinical decisions. Machine learning algorithms trained on large orthognathic datasets have demonstrated the ability to estimate postoperative soft-tissue changes, facial profile evolution, and aesthetic parameters with clinically meaningful accuracy. Hybrid modeling approaches that combine deep learning with established statistical methods have shown that different facial regions may be best predicted by different algorithms, reinforcing the value of ensemble or human–AI collaborative strategies [5, 13]. In parallel, classification models can determine whether a patient is likely to require orthognathic surgery rather than orthodontic camouflage, achieving area-under-the-curve values approaching 0.9 in high-risk malocclusion groups [18]. Such tools are particularly valuable for borderline patients, where traditional criteria and clinician experience alone may yield divergent recommendations.

These advances collectively reposition digital planning from a visualization platform to a data-driven clinical decision support system. In this framework, virtual plans are no longer static prescriptions but are informed by probabilistic forecasts of skeletal and soft-tissue behavior, enabling clinicians to compare scenarios, quantify uncertainty, and tailor interventions to individual risk profiles. Similar to developments in other domains of precision medicine, this shift promises to improve consistency, transparency, and patient engagement by grounding treatment recommendations in reproducible analytics rather than solely in expert intuition [13, 18].

Nevertheless, the integration of AI into orthognathic planning introduces new challenges related to data quality, bias, transparency, and clinical accountability. Predictive models are only as reliable as the datasets on which they are trained; imbalances in ethnicity, age, or craniofacial morphology can compromise generalizability and fairness [10, 16]. Moreover, black-box algorithms risk obscuring the rationale behind recommendations, complicating informed consent and medico-legal responsibility. As digital twins and predictive models increasingly influence high-stakes surgical decisions, robust governance frameworks, explainable AI, and human-in-the-loop workflows become essential to ensure ethical and safe deployment [10, 16].

Against this background, the present review synthesizes quantitative evidence on (i) the geometric accuracy of digital patient modeling and virtual surgical plan transfer, (ii) the performance of predictive models for skeletal, soft-tissue, and diagnostic outcomes, and (iii) the clinical and ethical implications of AI-assisted decision support in orthognathic surgery. By integrating these dimensions, we aim to clarify how digital planning and predictive modeling are reshaping contemporary orthognathic care and to delineate the opportunities and limitations that will define their future clinical impact.

2. Methods

This narrative review was designed to evaluate the accuracy, predictive performance, and clinical implications of digital planning and artificial intelligence in orthognathic surgery. A focused corpus of 20 peer-reviewed publications was analyzed, including systematic reviews, meta-analyses, prospective and retrospective clinical studies, and machine learning validation studies addressing digital workflows, craniofacial modeling, and outcome prediction in surgical orthodontics [4,8,12–20].

A structured literature screening was conducted across studies published between 2018 and 2025, with particular emphasis on quantitative reporting of geometric accuracy, predictive error, and diagnostic or therapeutic decision support. Eligible studies were required to report at least one of the following: (i) translational or rotational deviation between virtual plans and postoperative outcomes, (ii) performance of predictive models using metrics such as mean absolute error (MAE), area under the receiver operating characteristic curve (AUC), or correlation coefficients, or (iii) clinical outcomes related to symmetry, occlusion, or esthetic profile [4–9,13–15,18–20].

Data extraction focused on sample size, imaging modalities, computational methods, validation strategy, and numerical outcome measures. To enable structured synthesis, extracted evidence was grouped into four analytical domains: digital patient modeling, virtual surgical plan transfer accuracy, predictive modeling of postoperative outcomes, and clinical decision support including ethical considerations [6–11,13,16,18]. Quantitative findings were interpreted relative to clinically accepted accuracy thresholds in orthognathic surgery, particularly the 2-mm and 2° benchmarks for skeletal movements [8,20].

3. Results

Skeletal Accuracy of Virtual Surgical Planning

Quantitative validation studies demonstrate that virtual surgical planning achieves a high level of skeletal accuracy across all spatial planes. In fully digital workflows for bimaxillary orthognathic surgery, mean translational deviations between planned and postoperative jaw positions remained below 2 mm for both the maxilla and mandible, with reported averages of 0.57 mm transversely, −0.88 mm sagittally, and 0.44 mm vertically [14]. These values fall well below the thresholds generally considered clinically perceptible and confirm that three-dimensional planning can be reliably transferred to surgical reality. Meta-analytical evidence further supports these findings, showing that rotational errors in pitch, roll, and yaw are typically below 2°, minimizing the risk of postoperative occlusal canting or midline deviation [8,20].

Comparative studies between digital and conventional planning further highlight the advantage of virtual workflows. In a systematic review and meta-analysis, virtual surgical planning demonstrated superior accuracy in the horizontal and transverse planes when compared with conventional model surgery, particularly in asymmetric cases where manual articulation of plaster models is prone to cumulative error [4]. These differences are clinically relevant, as even small transverse discrepancies can significantly affect facial symmetry and occlusal stability.

Maxillary and Mandibular Predictability

While both jaws show high levels of predictability, subtle differences emerge between maxillary and mandibular repositioning. The maxilla generally exhibits higher positional stability due to its rigid fixation to the cranial base, whereas the mandible remains more susceptible to intraoperative and postoperative variability caused by muscular forces and condylar seating [9,15]. Three-dimensional cephalometric analyses indicate that sagittal positioning of the maxilla is slightly less predictable than vertical or transverse movements, whereas mandibular advancement and rotation are more vulnerable to postoperative relapse [9]. These findings emphasize the need for predictive modeling that explicitly accounts for biomechanical and biological factors influencing postoperative stability.

Soft-Tissue Versus Hard-Tissue Prediction

A consistent pattern across studies is that skeletal movements are more predictable than soft-tissue responses. Although digital planning can prescribe bone repositioning with submillimetric precision, the translation of these movements into facial soft-tissue changes varies across individuals. Machine learning models trained on large orthognathic datasets have demonstrated that lower facial and cervical soft tissues can be predicted more accurately by deep learning than by traditional linear regression, whereas upper lip and midfacial regions often remain better modeled by classical statistical approaches [13]. This differential performance likely reflects regional differences in tissue thickness, elasticity, and muscular attachments, which introduce nonlinearities that are difficult to capture with a single modeling paradigm.

Validation of esthetic prediction methods supports the clinical relevance of these models. The modified chin point approach, for example, demonstrated that postoperative pogonion and lip positions could be estimated within ±2 mm of true values, a margin that is generally considered esthetically acceptable in facial analysis [19]. Such accuracy allows surgeons to provide patients with realistic visualizations of expected postoperative appearance, enhancing informed consent and expectation management.

Predictive Modeling of Surgical Planning and Occlusion

Beyond outcome prediction, artificial intelligence has been applied directly to surgical planning itself. Deep learning systems trained on three-dimensional cephalometric data can generate complete orthognathic surgical plans that closely approximate expert-defined targets, with mean absolute errors of approximately 1.3 mm [5]. This level of performance indicates that AI can capture the complex spatial relationships between skeletal landmarks and occlusal parameters that underpin surgical decision-making.

Digital occlusal modeling is further supported by automated segmentation of intraoral scans. Deep learning algorithms achieve intersection-over-union values exceeding 0.9 when delineating individual teeth and dental arches, providing a reliable basis for occlusal simulation and splint design [6]. High-resolution landmark localization on dental surfaces reaches mean errors near 0.4 mm, enabling precise registration of maxillary and mandibular arches in virtual space [17]. These capabilities are critical for ensuring that skeletal repositioning is translated into stable, functional occlusion.

Clinical Decision Support and Diagnostic Classification

The most direct clinical application of predictive analytics is in the classification of patients who require orthognathic surgery versus those who can be treated with orthodontic camouflage. In a multicenter cohort of 920 patients, machine learning models achieved AUC values of 0.79 in the overall sample, 0.82 in Class II malocclusion, and 0.89 in Class III malocclusion, outperforming expert panels in borderline cases [18]. These results suggest that data-driven decision support can reduce diagnostic ambiguity and inter-clinician variability, particularly in patients whose skeletal discrepancies fall near conventional treatment thresholds.

Taken together, these expanded findings demonstrate that digital planning and predictive modeling provide not only geometric precision but also clinically actionable insight into skeletal stability, soft-tissue response, and treatment necessity. In the next step, we will extend the Discussion to integrate these results into a broader clinical and translational framework.

4. Discussion

The expanded results confirm that digital planning has progressed from a visualization-based adjunct to a quantitatively reliable clinical infrastructure for orthognathic surgery. Sub-2-mm skeletal accuracy across all spatial planes demonstrates that modern virtual surgical planning systems can consistently meet or exceed the precision required for facial esthetics, occlusal stability, and functional restoration [4,8,14,20]. Importantly, this precision is achieved not only in controlled laboratory settings but also in real-world surgical environments, indicating that digital workflows are robust to intraoperative variability and operator-dependent factors [14]. These characteristics position VSP as a foundational technology for contemporary orthognathic care.

However, the review also reveals that geometric accuracy alone is insufficient to guarantee optimal clinical outcomes. Soft-tissue behavior, neuromuscular adaptation, and postoperative remodeling introduce biological variability that cannot be fully captured by deterministic surgical plans. The observed discrepancies between skeletal and soft-tissue predictability are consistent with biomechanical principles: the mandible, suspended by muscles and ligaments, remains more mobile and less stable than the maxilla, while perioral soft tissues exhibit nonlinear deformation in response to bony movements [9,15]. This explains why even highly accurate skeletal repositioning can yield heterogeneous esthetic outcomes, particularly in patients with thick or inelastic soft tissues.

Artificial intelligence provides a partial solution to this challenge by modeling these nonlinear relationships directly from data. Deep learning and hybrid statistical–machine learning frameworks have demonstrated region-specific predictive strengths, with deep neural networks outperforming linear models in the lower face and cervical region, while traditional regression remains competitive for upper lip and midfacial prediction [13]. These findings support a paradigm in which outcome prediction is no longer monolithic but rather modular, with different algorithms optimized for distinct anatomical subsystems. Clinically, this enables more nuanced counseling and scenario testing, allowing surgeons to quantify the uncertainty associated with different movement vectors and surgical strategies.

The value of predictive modeling extends beyond esthetic forecasting to diagnostic decision-making. In borderline cases, where skeletal discrepancies lie near conventional treatment thresholds, inter-clinician disagreement is common and may lead to either overtreatment or undertreatment. Machine learning–based classification systems achieved AUC values approaching 0.9 in identifying patients who would benefit from orthognathic surgery, particularly in Class III malocclusions, indicating a high level of discriminatory power [18]. When integrated into clinical workflows, such systems can serve as objective second opinions, reducing cognitive bias and improving consistency across providers.

From a translational perspective, these technologies facilitate a shift toward precision orthognathic surgery, analogous to developments in precision oncology and cardiology. Digital craniofacial twins—constructed from CBCT, intraoral scans, and surface imaging—enable iterative simulation, optimization, and outcome prediction within a single computational environment [11,16]. This approach supports not only surgical planning but also interdisciplinary coordination between orthodontists, surgeons, and restorative specialists, improving the coherence and efficiency of care delivery.

Nevertheless, the deployment of AI-assisted planning raises important concerns regarding data quality, algorithmic bias, and clinical accountability. Most existing models are trained on relatively limited and demographically homogeneous datasets, which may compromise their performance in underrepresented populations [10,16]. Moreover, black-box neural networks can generate highly accurate predictions without providing interpretable reasoning, complicating informed consent and medico-legal responsibility. To address these issues, explainable AI frameworks and human-in-the-loop decision architectures are essential, ensuring that clinicians retain ultimate authority over treatment decisions while benefiting from algorithmic insight [10].

Taken together, the evidence suggests that digital planning and predictive modeling are not merely technological enhancements but constitute a fundamental reconfiguration of orthognathic surgery into a data-driven, probabilistic, and patient-specific discipline. The challenge for the coming decade will be to integrate these tools into robust clinical, ethical, and regulatory frameworks that maximize their benefits while safeguarding patient trust and professional responsibility.

5. Ethical and Regulatory Framework

The integration of artificial intelligence, predictive modeling, and digital craniofacial twins into orthognathic surgery introduces ethical and regulatory challenges that extend beyond traditional surgical governance. Unlike conventional planning tools, AI-based systems actively generate diagnostic classifications, surgical plans, and outcome predictions that can influence high-stakes clinical decisions. As such, these systems must be evaluated not only for technical accuracy but also for transparency, accountability, and alignment with patient-centered care principles [10,16].

A central ethical concern is the quality and representativeness of the data used to train predictive models. Most contemporary algorithms are derived from retrospective datasets that may overrepresent specific ethnic groups, age ranges, or malocclusion types, thereby introducing systematic bias into clinical recommendations [10,18]. In orthognathic surgery, where facial morphology varies widely across populations, such bias could lead to misclassification of surgical need or inaccurate esthetic prediction in underrepresented groups. This risk underscores the importance of continuous model validation across diverse patient cohorts and the development of regulatory standards governing dataset transparency and demographic reporting [16].

Patient autonomy and informed consent represent another critical dimension. Digital twins and AI-generated facial predictions can strongly shape patient expectations and treatment choices. While such visualizations enhance understanding, they also carry the risk of being perceived as deterministic forecasts rather than probabilistic estimates. Ethical deployment therefore requires that clinicians communicate the inherent uncertainty of predictive models and ensure that patients understand the range of possible outcomes rather than a single algorithmically generated scenario [13,19].

From a legal and professional standpoint, the introduction of algorithmic decision support complicates the attribution of responsibility. When AI systems recommend a particular surgical plan or classify a patient as a surgical candidate, questions arise regarding liability in the event of adverse outcomes. Current regulatory frameworks place responsibility on the clinician, but the increasing autonomy of AI tools necessitates clearer guidelines on the appropriate scope of algorithmic influence and documentation of human oversight in clinical decision-making [10,16].

Data privacy and security are also paramount, as digital twins rely on highly sensitive biometric and imaging data. Unauthorized access or misuse of three-dimensional facial and dental models poses significant risks to patient confidentiality and identity protection. Robust cybersecurity standards, encrypted data storage, and strict access controls are therefore essential components of ethical digital orthognathic practice [10].

Taken together, these considerations indicate that the safe and equitable deployment of digital planning and predictive modeling requires not only technological innovation but also the establishment of comprehensive ethical and regulatory frameworks. Such frameworks must balance the benefits of precision medicine with safeguards for patient rights, professional accountability, and societal trust in algorithm-assisted surgical care [10,16,18]

6. Conclusions

Digital planning and predictive modeling are reshaping orthognathic surgery by enabling a transition from experience-based workflows to data-driven, patient-specific decision support. Evidence from clinical cohorts and meta-analyses demonstrates that virtual surgical planning achieves highly reproducible skeletal accuracy, with deviations typically below 2 mm and 2°, supporting reliable transfer of three-dimensional plans to the operating room [4,8,14,20].

Artificial intelligence extends this paradigm by enabling clinically meaningful prediction of postoperative soft-tissue outcomes and diagnostic classification of surgical need. Machine learning models can estimate facial profile changes within esthetically acceptable error margins and discriminate between orthodontic and surgical treatment pathways with AUC values approaching 0.9 in high-risk malocclusion groups [13,18,19]. These capabilities are particularly valuable for managing borderline cases and improving transparency in patient counseling.

However, the responsible implementation of these technologies requires careful attention to biological variability, data quality, and ethical governance. While digital systems now offer unprecedented precision and reproducibility, soft-tissue behavior and long-term stability remain influenced by patient-specific factors that are not yet fully predictable [9,15]. Moreover, explainability, bias mitigation, and clinician oversight are essential to ensure that AI-based tools function as supportive clinical instruments rather than opaque determinants of care [10,16].

When integrated within robust clinical and ethical frameworks, digital planning and predictive modeling hold substantial potential to advance orthognathic surgery toward a precision-based, patient-centered discipline.

Author Contributions

1. Łukasz Dominik Woźniak – Conceptualization; Methodology; Supervision; Writing – original draft; Project administration.
2. Łukasz Dominik Woźniak, Anna Kinga Tejchma – Literature review; Data curation; Formal analysis.
3. Aleksandra Włodarczyk, Łukasz Dominik Woźniak – Methodology support; Validation; Writing – review & editing.
4. Julia Weronika Mieszkowska, Łukasz Dominik Woźniak– Data analysis; Visualization; Language editing
5. Paulina Jarząbek, Łukasz Dominik Woźniak – Investigation; Interpretation of results.
6. Norbert Grabias, Łukasz Dominik Woźniak – Software; Technical support; Data processing.
7. Jędrzej Piotrowski, Łukasz Dominik Woźniak– Theoretical framework development; Conceptual validation.
8. Radosław Gryko, Łukasz Dominik Woźniak– Resources; Reference management; Bibliographic formatting.
9. Bernard Myszewski, Łukasz Dominik Woźniak – Quality control; Proofreading; Consistency checking.

Maria Rajkowska, Łukasz Dominik Woźniak - Writing – review & editing; Final manuscript preparation.

Declaration of the use of generative Al and Al-assisted technologies in the writing RICES.

In preparing this work, the authors used ChatGPT for the purpose of improving language and readability. After using this tool, the authors have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

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