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From Image-Guided Surgery to Autonomous Decision-Making: Artificial Intelligence, Computational Anatomy and Intelligent Surgical Ecosystems in Oral and Maxillofacial Surgery: A Narrative Review

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Abstract

Oral and maxillofacial surgery has moved from two-dimensional planning toward computational, patient-specific workflows and artificial intelligence now extends beyond image interpretation into diagnosis, navigation, robotics and postoperative monitoring, raising unresolved questions about autonomy, accountability and surgical oversight. This narrative review examines the role of computational anatomy, artificial intelligence and digital biomarkers in improving diagnosis, personalized planning, intraoperative guidance and prediction of surgical outcomes, tracing the evolution of virtual surgical planning into artificial intelligence-assisted and robotic surgery. Computational modeling augmented and mixed reality, robotics and digital biomarkers improved planning accuracy, spatial orientation and postoperative monitoring while reducing cognitive workload, although registration accuracy, latency, dataset quality and the scarcity of prospective multicenter validation remain important limitations. Artificial intelligence is advancing the specialty within an emerging intelligent surgical ecosystem, yet broader adoption requires robust validation, ethical governance, multicenter studies and continued surgeon oversight.

Keywords: Artificial Intelligence; Computational Anatomy; Virtual Surgical Planning; Augmented Reality; Surgical Robotics; Digital Biomarkers

Introduction

Digital technology entered oral and maxillofacial surgery through diagnostic imaging and has since extended across the entire treatment pathway. Two-dimensional radiography, which for decades supplied the anatomical information on which treatment decisions were based, was progressively complemented by computed tomography and subsequently by cone-beam computed tomography, which made isotropic three-dimensional imaging of the craniofacial skeleton available at radiation doses and costs compatible with routine practice. Optical intraoral and facial surface scanning, computer-aided design and manufacturing and additive manufacturing then allowed these digital records to be converted into physical devices such as occlusal splints, cutting guides and patient-specific implants. Over the past decade these previously separate tools have converged into continuous digital workflows in which acquisition, planning, manufacturing and intraoperative transfer form a single data pipeline. It is on this infrastructure that computational anatomy and artificial intelligence now operate and the capabilities described in this review should be understood as extensions of it rather than as independent developments.

The incorporation of digital technologies into oral and maxillofacial surgery has shifted surgical planning from two-dimensional interpretation toward individualized three-dimensional computational workflows. Computational anatomy provides a framework for converting imaging data into measurable representations of craniofacial structures [1]. Computed tomography and cone-beam computed tomography datasets can be combined with intraoral and facial surface scans to represent the skeleton, dentition and external facial anatomy within a single virtual environment. This approach allows complex anatomical relationships and deformities to be examined before surgery rather than being assessed exclusively during the operative procedure and it establishes the structured data on which later computational tools depend [2].

A central application of computational anatomy is the creation of a patient-specific virtual model, sometimes described as a digital twin [3]. Construction of this model involves segmentation of the relevant anatomical structures, registration of datasets acquired from different imaging systems and three-dimensional reconstruction. Because cone-beam computed tomography images may contain dental artifacts or insufficient surface detail, supplementary intraoral or model scans can improve representation of the dentition [4]. Lee, et al., reported that intraoral scans and promptly digitized alginate impressions could be integrated with cone-beam computed tomography data with discrepancies below the voxel size, supporting their use in building accurate dental digital twins [5].

Once the virtual patient has been assembled, virtual surgical planning enables clinicians to simulate osteotomies, reposition skeletal segments, evaluate occlusion and compare alternative treatment strategies [6]. The resulting plan can then be transferred to the operating room through computer-aided surgical splints, cutting guides, customized fixation plates or patient-specific implants. These technologies are applied across orthognathic surgery, craniofacial reconstruction, traumatic deformity correction and oncologic reconstruction. Contemporary reviews indicate that virtual planning can improve predictability and anatomical accuracy and may reduce operative or planning time in selected procedures, although the reported benefits vary according to the surgical indication and the specific workflow adopted [7,8].

Patient-specific devices provide a direct physical link between the planned and the achieved skeletal position. In a randomized clinical trial of patients undergoing orthognathic surgery, patient-specific implants produced a smaller discrepancy in postoperative maxillary position than conventional CAD/CAM surgical splints [8]. A systematic review and meta-analysis subsequently evaluated virtual surgical planning across craniomaxillofacial procedures in relation to accuracy, operative time and cost-effectiveness. Its findings supported the clinical advantages of virtual planning while also revealing persistent heterogeneity in study design, outcome measurement and economic reporting, which complicates direct comparison between protocols [9].

Despite this potential, patient-specific modeling depends on high-quality imaging, reliable segmentation, software interoperability, specialized expertise and faithful transfer of the virtual plan to the patient. Thin craniofacial structures remain particularly difficult to segment and manual correction is time-consuming [10]. Emerging artificial intelligence systems may reduce this burden by automating anatomical recognition and model generation.

Computational anatomy should therefore be understood as the foundation of an evolving intelligent surgical ecosystem rather than merely a visualization tool [12]. By supplying structured, patient-specific data, it creates the basis for artificial intelligence-assisted diagnosis, predictive modeling and increasingly automated surgical decision support [13].

The aim of this article is to review how computational anatomy, artificial intelligence and digital biomarkers are transforming oral and maxillofacial surgery across the full surgical pathway and to assess how far these technologies can progress from assisting the surgeon toward independently optimizing surgical planning and intraoperative decision-making, while defining the validation, ethical and regulatory conditions required for their safe adoption under continued surgeon oversight.

Artificial Intelligence-Assisted Diagnosis and Surgical Risk Prediction

Artificial intelligence is rapidly transforming oral and maxillofacial surgery, extending its role well beyond image interpretation to become an integral component of clinical decision-making [7]. Advances in machine learning and deep learning allow these systems to analyze large volumes of radiographic and clinical data with high accuracy, supporting earlier diagnosis, more consistent treatment planning and increasingly personalized surgical strategies [14]. Rather than replacing the clinician, artificial intelligence functions as a complementary tool that strengthens diagnostic confidence, reduces variability in interpretation and supports evidence-based decisions throughout the surgical workflow [15].

Diagnostic imaging remains the most mature and widely adopted application. Deep learning models, including convolutional neural networks, ResNet, U-Net and YOLO architectures, have shown excellent performance in the automated analysis of panoramic radiographs and cone-beam computed tomography [16]. These models facilitate the identification of anatomical landmarks, impacted teeth, cystic lesions, tumors and fractures while improving efficiency and reducing interobserver variability. As a result, automated image analysis is becoming a valuable resource for improving diagnostic accuracy and informing subsequent surgical planning [17]. A comparative study of maxillary segmentation on cone-beam computed tomography reported submillimeter performance for a specialized artificial intelligence method, although algorithm performance varied and conventional three-dimensional repair techniques remained superior for some measurements [11]. Performance of this kind illustrates both the maturity of automated segmentation and the residual variability between algorithms that continues to require expert verification.

The benefits extend to some of the most challenging diagnostic situations in routine practice. The assessment of impacted teeth is a clear example, because algorithmic models can determine tooth position, characterize the relationship between an impacted tooth and adjacent anatomical structures and estimate surgical difficulty [18]. This information gives clinicians a more objective preoperative evaluation, facilitating safer planning and reducing uncertainty, particularly in anatomically complex cases [19].

Recent developments have also expanded artificial intelligence into personalized treatment planning. By integrating demographic, radiographic and clinical information, machine learning algorithms can support therapeutic decisions and identify patient-specific factors that influence treatment selection [20]. This capability represents an important step toward precision surgery, allowing recommendations to be tailored to each patient's characteristics rather than relying exclusively on standardized protocols [10].

Orthognathic surgery has become one of the most promising areas for implementation. Deep learning models can identify patients who are suitable candidates for a surgery-first approach by analyzing preoperative clinical and imaging data [11]. Such predictive models reduce subjectivity during patient selection, improve consistency in planning and help surgeons reach more individualized decisions for patients with complex dentofacial deformities [21].

Beyond patient selection, artificial intelligence is beginning to contribute directly to computational surgical planning. Transformer-based deep learning models can generate individualized orthognathic plans from three-dimensional cephalometric analyses by integrating skeletal, dental and soft-tissue information [22]. In addition to predicting jaw repositioning with clinically acceptable accuracy, these systems can provide interpretable information about the variables that influence the plan. Developments of this kind represent a meaningful move toward computational surgery, in which artificial intelligence supports not only diagnosis but also preoperative planning and complex surgical decision-making (Fig. 1) [12,23].

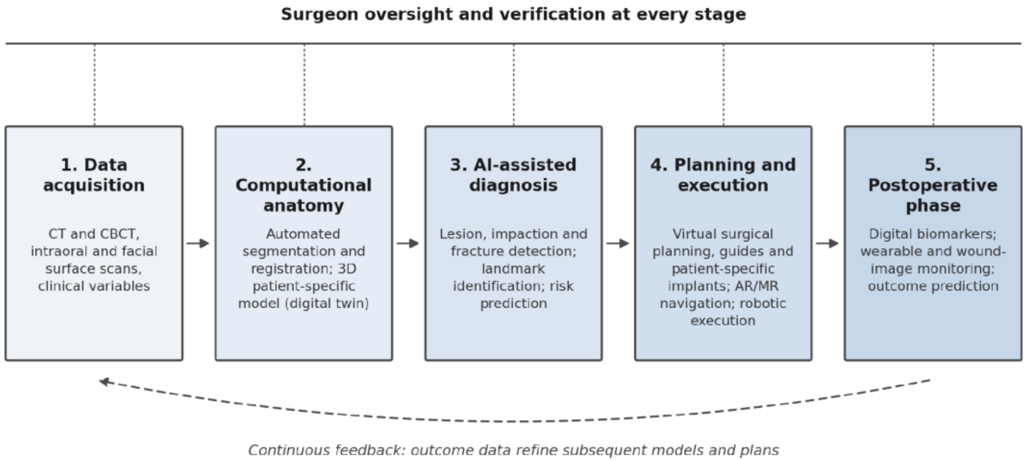

Figure 1: The intelligent surgical ecosystem in oral and maxillofacial surgery, from data acquisition to postoperative monitoring. Each stage supplies structured data to the next, outcome data feed back into subsequent models and plans and surgeon verification is retained at every stage. CT, computed tomography; CBCT, cone-beam computed tomography; AR, augmented reality; MR, mixed reality; 3D, three-dimensional.

Taken together, the current evidence indicates that artificial intelligence is progressively changing how oral and maxillofacial surgeons diagnose, plan and manage care. Its capacity to improve diagnostic accuracy, support personalized planning and assist computational planning underlines its potential to become a core element of modern practice [24]. Important challenges nevertheless remain before these technologies can be fully integrated into routine care. Most available models have been developed on retrospective datasets, many originate from single-center studies and relatively few have undergone rigorous external validation. Future work should therefore prioritize multicenter prospective studies, standardized evaluation frameworks, transparent and interpretable algorithms and robust clinical validation, so that these systems prove safe, reliable and generalizable across diverse patient populations [25].

Intelligent Navigation Through Augmented and Mixed Reality

Artificial intelligence has reshaped preoperative planning in oral and maxillofacial surgery by enabling automated segmentation, patient-specific anatomical reconstruction and predictive planning. The value of these computational outputs ultimately depends, however, on their effective translation into the operative field [26]. Intelligent navigation through augmented reality and mixed reality addresses this gap by integrating digital surgical planning with real-time intraoperative visualization. Rather than acting only as display technologies, augmented and mixed reality operate as spatial interfaces that co-register patient-specific virtual models with the surgical anatomy, allowing surgeons to interact with three-dimensional information while maintaining continuous attention on the operative field [27]. This paradigm marks a clear evolution from conventional image-guided surgery toward context-aware navigation capable of enhancing intraoperative decision-making [13,14].

Unlike conventional navigation, which requires repeated visual shifts between the patient and an external monitor, augmented and mixed reality superimpose virtual structures directly onto the surgical field through accurate registration, optical tracking and continuous spatial alignment [28]. This integration lowers the cognitive burden of translating two-dimensional images into three-dimensional anatomy and improves spatial orientation during technically demanding procedures [29]. Mixed reality extends the concept further by allowing interactive manipulation of holographic patient-specific models, so that surgeons can visualize hidden structures, rehearse maneuvers and adapt the preoperative plan to intraoperative findings. Intelligent navigation thereby moves digital technologies from passive image consultation toward active surgical guidance [30].

Clinical applications have expanded rapidly across the specialty. In orthognathic surgery, mixed-reality navigation supports accurate transfer of the virtual plan by improving the execution of osteotomies and maxillary repositioning while reducing discrepancies between planned and postoperative skeletal outcomes [16]. In craniofacial trauma and reconstruction, projecting the patient-specific model onto the operative field helps the surgeon locate fracture margins and adjacent neurovascular structures and makes the spatial relationship between displaced segments easier to judge intraoperatively, which supports more accurate reduction [30]. Navigation-assisted visualization has also proven useful in implant and oncologic procedures by improving spatial orientation, optimizing implant trajectory and assisting intraoperative assessment of planned resection margins. Reported experiences across these indications, although still largely derived from small series and preclinical validation, consistently describe improved intraoperative confidence and more faithful reproduction of the preoperative plan. Collectively, these applications show that the principal contribution of augmented and mixed reality is not simply better visualization but the integration of digital planning into real-time execution, improving precision while preserving the surgeon workflow [31].

Current Limitations of Intelligent Navigation

Several challenges nevertheless continue to limit routine implementation. Navigation accuracy depends critically on robust image registration, stable tracking and maintenance of spatial fidelity throughout the procedure [32]. Intraoperative soft-tissue deformation, latency, calibration errors, restricted fields of view and the ergonomic constraints of current head-mounted displays can all reduce overlay accuracy and diminish surgeon confidence [33]. Cost, the learning curve associated with head-mounted systems and limited interoperability between planning and navigation software represent additional practical barriers to adoption. The absence of standardized validation protocols and of high-quality prospective studies further restricts direct comparison between platforms and their incorporation into everyday care. Addressing these technical and clinical limitations will be essential before intelligent navigation becomes a standard element of digital surgical workflows [34].

Translational Role of Intelligent Navigation

Ultimately, intelligent navigation represents the critical translational layer between computational intelligence and surgical execution. By converting patient-specific digital planning into actionable intraoperative guidance, augmented and mixed reality establish the foundation on which robotic platforms and semi-autonomous systems can progressively build [35]. As registration accuracy, computational processing and artificial intelligence continue to mature, intelligent navigation is expected to become a central component of future intelligent surgical ecosystems, delivering progressively higher levels of intraoperative decision support while preserving surgeon oversight and clinical judgment [36].

Robotics and Autonomous Intraoperative Assistance

Virtual surgical planning and patient-specific computational models have improved the accuracy and predictability of preoperative planning in craniomaxillofacial surgery, yet translating a virtual plan into the operating room requires tools capable of preserving that precision during execution [37]. Robotic systems address this need by converting the digital plan into controlled mechanical motion, improving instrument stability and maneuverability and compensating for physiological tremor within small anatomical corridors. In this sense, robotics is best viewed not as a replacement for the surgeon but as a mechanism for enacting computational planning with greater fidelity [38].

Robotic technology in head and neck surgery evolved initially to overcome the problem of limited anatomical access. Early feasibility work demonstrated that platforms such as the da Vinci system could navigate the complex anatomy of the upper aerodigestive tract and perform controlled movements within a confined surgical field [39]. These findings established the basis for transoral robotic surgery, which expanded the treatment of selected laryngopharyngeal and deeply situated lesions without the morbidity of extensive open access [20]. The clinical success of these soft-tissue applications provided an important proof of concept for robotic assistance in regions that are difficult to reach with conventional instrumentation [40].

Over the past decade, robotic technology has been explored beyond soft-tissue procedures and applied to oral and maxillofacial indications, including reconstructive surgery, osteotomies, navigated interventions and implant placement. A recent systematic review and meta-analysis reported that robotic systems can achieve high implant-placement accuracy, with mean deviations below one millimeter and three degrees, substantially outperforming conventional freehand techniques and supporting predefined surgical trajectories [21,41]. Reported advantages include enhanced motion scaling and greater reproducibility of planned trajectories, whereas current constraints involve instrument size, cost, restricted haptic feedback and the limited availability of platforms designed specifically for bony craniofacial work. Even so, most of these applications remain at an early stage of clinical adoption and further comparative studies are required to define their true benefit across the range of craniomaxillofacial procedures [42].

The integration of artificial intelligence with robotic platforms represents a further step beyond purely mechanical computer-assisted devices [43]. Algorithms can analyze imaging, surgical workflow and instrument position to provide context-dependent intraoperative assistance and robotic autonomy can be described along a spectrum that extends from simple task assistance, such as camera control or instrument stabilization, toward the conditional execution of defined surgical steps [44]. Progression along this spectrum is what distinguishes a tool that supports the surgeon from a system that performs part of the operation.

This prospect, however, remains largely unexplored in practice. Greater degrees of autonomy raise substantial questions regarding validation, patient safety, liability and the nature of surgical supervision [45]. As robotic systems advance from discrete task assistance toward conditional autonomy, it becomes essential to define the boundaries within which autonomous functions genuinely improve surgical care rather than introduce new and poorly characterized risks [46]. These boundaries cannot be established by engineering alone and depend on rigorous clinical evidence and clear professional standards.

Future Implications

Three developments would most plausibly change practice within the next decade. The first is the extension of validated robotic assistance from soft-tissue transoral procedures to bony craniofacial work, which requires platforms designed for osteotomy and implant placement rather than adapted general-purpose systems. The second is the coupling of intraoperative imaging and navigation to robotic execution, so that a plan can be updated during surgery rather than executed as a fixed trajectory. The third is the emergence of prospective multicenter trials reporting patient-level rather than accuracy-only outcomes, without which comparative effectiveness against conventional and navigation-assisted techniques cannot be established. Until these conditions are met, robotic and autonomous assistance in oral and maxillofacial surgery should be regarded as a developing capability rather than an established standard of care.

Future intelligent surgical systems are likely to rest on continuous interaction among four components: computational planning, artificial intelligence, robotics and patient-specific data. Rather than displacing the surgeon, such systems may assume progressively more complex tasks intended to support decision-making and enhance precision [47]. Their successful and responsible implementation will therefore require not only technical advances but also scientific validation, regulatory standardization and the deliberate retention of surgeon control, so that increasing capability is matched by mechanisms that safeguard the patient (Fig. 2, Table 1) [48].

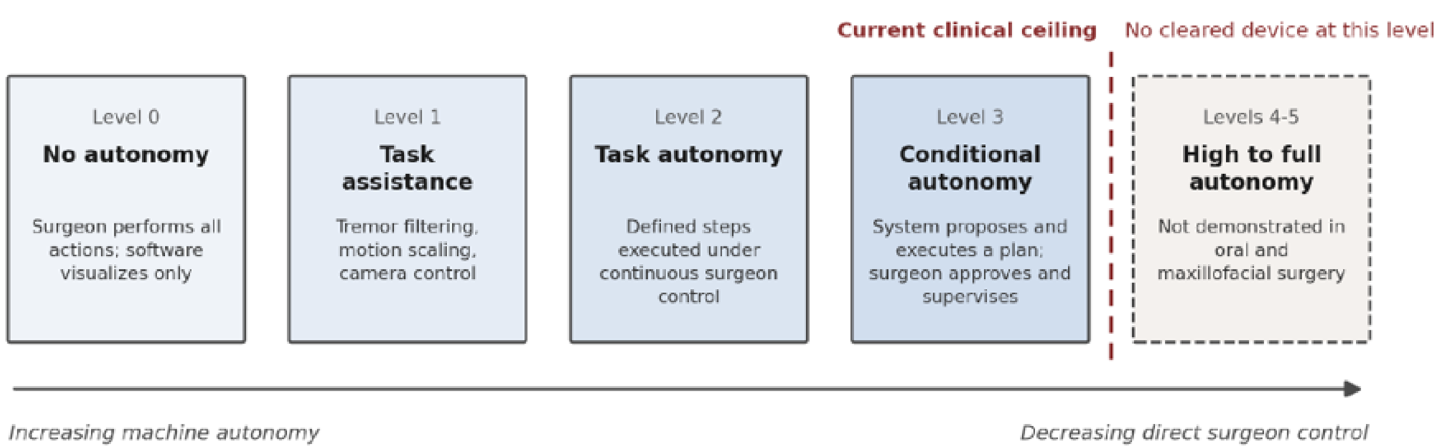

Figure 2: Spectrum of autonomy in robotic surgical systems and its current ceiling in oral and maxillofacial surgery. Clinically deployed platforms operate at levels 0 to 2, with conditional autonomy (level 3) confined to experimental settings; no device cleared for oral and maxillofacial indications operates above surgeon-supervised task execution.

Autonomy level	Definition	Representative status in oral and maxillofacial surgery	Requirement for surgeon oversight
Level 0: no autonomy	Software presents information; the surgeon performs every action	Conventional planning software and static navigation displays	Complete; the surgeon executes all steps
Level 1: task assistance	The system modifies or stabilizes surgeon-directed motion	Tremor filtering, motion scaling and camera control on transoral platforms	Continuous; motion originates with the surgeon
Level 2: task autonomy	The system executes a discrete, predefined task under direct supervision	Robotic implant placement and guided osteotomy along a planned trajectory	Continuous; the surgeon initiates, monitors and can abort
Level 3: conditional autonomy	The system proposes and executes a plan that the surgeon approves	Experimental only; not represented among cleared craniofacial devices	Approval before execution and supervision throughout
Levels 4-5: high to full autonomy	The system plans and executes without case-specific approval	Not demonstrated in oral and maxillofacial surgery	Not defined; no regulatory or liability framework exists
Levels adapted from published frameworks for autonomy in surgical robotics REF [42,57,66].			

Table 1: Levels of autonomy in robotic surgical systems and their current status in oral and maxillofacial surgery.

Digital Biomarkers for Postoperative Prediction and Recovery

Following oral and maxillofacial surgery, postoperative outcomes depend on dynamic biological processes that include tissue healing, the inflammatory response, functional recovery and the potential development of complications [49]. Conventional postoperative evaluation relies mainly on scheduled visits and subjective assessments performed at fixed time points, which may delay recognition of early biological change. Digital biomarkers offer an alternative by continuously capturing objective, patient-specific information through wearable sensors, physiological signals, imaging-derived features and patient-generated data [50]. When combined with artificial intelligence and machine learning, these biomarkers can support predictive models that identify patients at increased risk and refine individualized postoperative management [51].

The incorporation of digital biomarkers reflects a shift from traditional surveillance toward predictive and preventive care. In oral and maxillofacial surgery, machine learning models can analyze complex clinical variables associated with treatment outcomes and biological complications [52]. In implant dentistry, algorithms have been developed to predict implant failure and peri-implant disease by integrating patient characteristics, systemic conditions and treatment-related variables, demonstrating that risk patterns can be recognized before clinical deterioration occurs [24]. Complementary evidence has documented the expanding role of artificial intelligence in implant prognosis and outcome assessment, while emphasizing that dataset quality, external validation and clinical implementation remain important limitations [53].

Beyond dentistry, digital biomarkers have attracted attention in surgical medicine as tools for continuous monitoring and early complication detection, providing a framework that can be translated to oral and maxillofacial care [54]. Analysis of patient-generated data, such as wound images and physiological measurements, may allow abnormal healing to be identified earlier than conventional follow-up permits. Artificial intelligence systems have been shown to analyze postoperative wound images and detect features associated with surgical site infection, supporting remote monitoring and reducing delays in intervention [55].

Wearable technologies combined with artificial intelligence similarly enable continuous assessment of physiological parameters relevant to recovery. Although these applications have been studied mainly in broader surgical populations, their principles apply directly to oral and maxillofacial procedures, where earlier recognition of infection, inflammation, impaired healing or functional limitation may improve outcomes [56]. Artificial intelligence-enhanced wearable systems have demonstrated potential to detect abnormal physiological patterns and to support personalized postoperative surveillance through continuous data collection [27].

Digital biomarkers may also provide a foundation for future patient-specific computational models, including digital-twin approaches. By integrating clinical information, biological measurements, imaging data and artificial intelligence, such systems could dynamically represent individual recovery trajectories [57]. Such models could continuously update as new physiological data arrive, allowing predicted and observed recovery to be compared and enabling timely, individualized adjustment of postoperative care. Within an intelligent surgical ecosystem, digital biomarkers may therefore connect preoperative prediction, surgical intervention and postoperative adaptation, allowing artificial intelligence to extend from image interpretation toward continuous biological decision support [58].

Although current applications in oral and maxillofacial surgery remain concentrated in diagnosis, imaging analysis and surgical planning, digital biomarkers broaden these capabilities toward postoperative prediction and recovery optimization. Integrating clinical data, radiological information and real-time monitoring may improve risk stratification and support precision-based follow-up after procedures such as implant placement, reconstructive surgery and trauma management [59]. Overall, digital biomarkers mark an essential transition from episodic assessment toward continuous, predictive and personalized recovery monitoring. By uniting artificial intelligence with patient-specific biological data, future surgical ecosystems may enhance early complication detection, optimize follow-up and strengthen clinical decision-making in oral and maxillofacial surgery, provided that the underlying models are validated prospectively and applied under appropriate clinical oversight [60].

Ethical, Legal and Regulatory Challenges of Autonomous Surgical Systems

The preceding sections describe a progressive transfer of tasks that once belonged to the surgeon alone, yet it remains unresolved who is accountable when such a system is wrong. Precision about the current degree of autonomy is therefore useful [30]. Among 49 surgical robots cleared by the United States Food and Drug Administration between 2015 and 2023, most required continuous surgeon control, a small proportion executed pre-programmed tasks and a smaller proportion generated patient-specific operative plans; none performed independent intraoperative decision-making and the large majority reached the market through a substantial-equivalence pathway [61]. That pathway was designed for devices whose behavior is fixed at approval and fits awkwardly with models that are retrained or updated after deployment [62].

Responsibility is distributed uneasily among the surgeon who accepts a recommendation, the manufacturer who trained the model and the institution that deployed it [31]. For the clinician, a practical hazard is automation bias, because a system that is usually correct discourages independent verification and can gradually erode the skills needed to recognize an erroneous output [63]. In oral and maxillofacial surgery, this concern is concrete, since a planning error is not confined to a screen but is manufactured into a cutting guide, splint or patient-specific implant and may only become apparent once the guide is seated on bone [64]. Preserving the surgeon's capacity for independent judgment therefore becomes a safety requirement rather than a matter of preference and it argues for workflows that keep verification steps explicit rather than implicit [65].

Opacity is also transmitted to the consultation, because a surgeon who cannot explain why a model produced a recommendation cannot fully convey it to the patient. Consent documents currently in institutional use rarely address the algorithmic contribution, data handling or model limitations and plain-language disclosure supported by clinician training has been proposed as a remedy [32]. Comparable concerns regarding patient autonomy, accountability and professional ethical literacy have been raised within dentistry [66] and within oral and maxillofacial surgery specifically [7].

Data introduce a further difficulty. Models are frequently trained on retrospective, single-center datasets whose demographic composition is rarely reported, while craniofacial morphology varies between populations, so performance does not transfer automatically [68]. Access remains concentrated in well-resourced centers and facial scans and cone-beam computed tomography volumes are inherently identifiable, which makes conventional anonymization incomplete [69]. Moreover, the provenance and labeling quality of training data are seldom auditable by the clinician who ultimately relies on the output, which complicates any assessment after the fact of why a particular recommendation was made [14].

Liability frameworks compound this uncertainty. Existing product-liability and medical-negligence doctrines were not designed for systems that learn, adapt and act with partial independence and they provide little guidance on how fault should be apportioned when a continuously updated model contributes to an adverse outcome [10]. Equity is a further and frequently neglected concern, because advanced planning, navigation and robotic platforms remain concentrated in well-resourced centers, so their unregulated expansion could widen rather than narrow existing disparities in access to complex craniofacial care. Consent practices that assume digital literacy may likewise disadvantage some patients, reinforcing the need for disclosure that is both accurate and accessible [69]. International regulatory harmonization also remains incomplete, so comparable systems may be governed very differently across jurisdictions and clear pathways for reporting and learning from algorithm-related errors are still largely absent (Table 2) [48].

Technological layer	Core function	Representative application	Principal current limitation
Computational anatomy and digital twins	Convert multimodal imaging into structured, patient-specific 3D models	Virtual surgical planning, cutting guides and patient-specific implants in orthognathic and reconstructive surgery	Segmentation of thin structures, imaging quality and software interoperability
AI-assisted diagnosis and risk prediction	Automated image interpretation and individualized risk and plan prediction	Detection of impacted teeth, lesions and fractures; surgery-first selection; AI-generated orthognathic plans	Retrospective, single-center data and limited external validation
AR and MR intelligent navigation	Superimpose the virtual plan onto the operative field in real time	Osteotomy and maxillary repositioning, trauma reduction and implant or oncologic guidance	Registration accuracy, latency, soft-tissue shift and headset ergonomics
Robotics and autonomous assistance	Convert the digital plan into controlled, tremor-free motion	Transoral robotic surgery and robotic implant placement or osteotomy	Early clinical adoption and unresolved safety, liability and autonomy limits
Digital biomarkers and postoperative monitoring	Continuous, objective capture of recovery data with AI analysis	Prediction of implant failure, wound-image infection detection and wearable recovery monitoring	Data quality, validation and reliance on evidence extrapolated from general surgery
AI, artificial intelligence; AR, augmented reality; MR, mixed reality; 3D, three-dimensional. REF [30,31,40].			

Table 2: The intelligent surgical ecosystem in oral and maxillofacial surgery.

Conclusion

Artificial intelligence now contributes across the surgical pathway in oral and maxillofacial surgery, from computational anatomy and diagnosis to intraoperative guidance and postoperative monitoring and the optimization of surgical planning is already performed in part by machines. Independent intraoperative decision-making is not: no cleared device operates at that level, most published models remain retrospective and externally unvalidated and the governing legal instruments do not yet exist. The realistic trajectory is stronger decision support under human supervision, with autonomy extended only to well-defined and verifiable tasks. The surgeon who accepts a computational plan remains accountable for it.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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Data Availability Statement

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

Ethical Statement

The project did not meet the definition of human subject research under the preview of the IRB according to federal regulations and therefore was exempt.

Informed Consent Statement

Not applicable.

Authors' Contributions

All authors contributed equally to this paper.

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