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Virtual Surgical Planning And Navigation In Orthognathic Surgery: A Review

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Abstract

Orthognathic surgery has evolved from traditional two-dimensional (2D) planning methods to advanced digital approaches that integrate virtual surgical planning (VSP), computer-assisted navigation, and patient-specific implants (PSIs). VSP enables three-dimensional (3D) evaluation of dentofacial deformities, virtual osteotomies, and precise simulation of skeletal repositioning, thereby enhancing diagnostic accuracy and surgical predictability. Computer-assisted navigation provides real-time intraoperative spatial guidance, ensuring accurate translation of the virtual plan and minimizing risks such as nerve injury or malpositioning. Clinical studies demonstrate sub-millimetric accuracy in maxillary positioning, improved facial symmetry, reduced reoperation rates, and high patient satisfaction compared to conventional workflows. Although initial costs, training requirements, and integration of multimodal imaging remain challenges, these technologies improve efficiency, reduce intraoperative adjustments, and are particularly cost-effective in complex or high-volume cases. Emerging applications of augmented and virtual reality promise to further expand the role of digital navigation in orthognathic surgery.

Keywords: Orthognathic surgery, Virtual surgical planning, Computer-assisted navigation, Accuracy, Oral and Maxillofacial Surgery

Introduction

Orthognathic surgery plays a critical role in correcting skeletal malocclusion and restoring facial balance, thereby improving both function and aesthetics. Traditionally, presurgical planning depended on two-dimensional (2D) cephalometric analysis, facebow-mounted dental casts, and acrylic splints to guide surgical execution. While effective, these conventional methods were limited in accuracy and visualization, particularly in appreciating the three-dimensional (3D) complexity of dentofacial deformities.[1] Over the past decade, the introduction of Virtual Surgical Planning (VSP) has transformed the field by enabling precise 3D assessment of skeletal and dental structures. VSP allows surgeons to perform virtual osteotomies, simulate repositioning of skeletal segments in all spatial planes, and rehearse surgical steps prior to the actual procedure.[2] This not only enhances diagnostic accuracy but also improves surgical predictability and efficiency. Furthermore, the integration of computer-aided design and manufacturing (CAD/CAM) facilitates the fabrication of patient-specific cutting guides, positioning jigs, and splints, thereby reducing intraoperative errors and operative time. In addition, computer-assisted navigation systems have introduced a new level of intraoperative precision, functioning much like a “GPS for the skeleton.”[3] These systems provide real-time spatial awareness and instrument tracking, ensuring that surgical maneuvers correspond exactly with the virtual plan while reducing risks such as nerve injury or malpositioning of bone segments. With the aid of advanced imaging modalities such as cone-beam computed tomography (CBCT) and digital dental scans, VSP empowers clinicians to comprehensively evaluate bone and soft-tissue relationships, predict surgical outcomes, and communicate treatment goals more effectively with patients.[4] Taken together, these technological advancements have established VSP and computer-assisted navigation as the emerging standard of care in orthognathic surgery, offering superior precision, safety, and reproducibility compared to traditional approaches.[5] This article gives an overview on Virtual Surgical Planning and Navigation in Orthognathic Surgery

Digital Workflow in Orthognathic Surgery

The digital workflow in orthognathic surgery begins with high-resolution 3D data acquisition, typically using cone-beam CT (CBCT) or helical CT for skeletal structures, intraoral optical scans or desktop scans of dental casts to overcome CBCT-related dental artifacts, and 3D facial surface imaging through stereophotogrammetry, structured light, or even smartphone-based photogrammetry to integrate soft-tissue details. Following this, segmentation and registration are performed using threshold-based or AI-assisted algorithms to generate STL/mesh models, after which dental scans are rigidly aligned to CBCT data through fiducials or occlusal best-fit techniques, and facial meshes are incorporated to visualize soft tissues.[6] The virtual model then allows comprehensive occlusion setup and surgical simulation, including procedures such as Le Fort I, bilateral sagittal split osteotomy (BSSO), intraoral vertical ramus osteotomy (IVRO), segmental osteotomies, autorotation, and yaw/roll corrections, along with genioplasty. Collision detection, mapping of nerve canals, assessment of condylar position, and predictive soft-tissue simulations further enhance planning accuracy and facilitate patient counseling, while recognizing inherent limitations of soft-tissue modeling.[7] Surgical transfer of the virtual plan is achieved through 3D-printed occlusal splints, tooth- or bone-borne cutting and positioning guides, and patient-specific implants (PSIs) such as pre-bent or fully customized fixation plates designed with planned screw trajectories, in some cases eliminating the need for intermediate splints. Real-time navigation systems either optical or electromagnetic support intraoperative precision through point or surface matching and fiducial-based registration, functioning as a dynamic guide during execution.[4] Finally, postoperative validation involves superimposing CBCT or low-dose CBCT scans onto the virtual plan to evaluate linear and angular deviations, confirm condylar seating, and assess functional outcomes such as airway changes, thereby closing the loop from digital planning to clinical verification.

Outcomes and Cost-Effectiveness of Virtual Surgical Planning

Virtual surgical planning (VSP) in orthognathic surgery leverages digital imaging formats such as DICOM for CBCT/CT and mesh or implant design files (STL, PLY, OBJ, STEP, IGES) processed through commercial software like Dolphin 3D, ProPlan CMF, IPS CaseDesigner, Blue Sky Plan, or open-source platforms such as 3D Slicer. Standardization of coordinate systems, consistent metadata management, and careful documentation of transformations ensure reproducibility and interoperability across workflows.[6] The use of custom surgical guides and patient-specific implants (PSIs) has been shown to minimize discrepancies between planned and postoperative outcomes, with studies demonstrating sub-millimetric accuracy in maxillary repositioning and small but clinically relevant rotational errors in yaw and roll.[8] While mandibular segments and segmental osteotomies exhibit greater variability due to condylar seating and soft tissue influences, navigation systems enhance multiplanar control and reduce repeated adjustments. Efficiency gains are notable, as planning time is shifted preoperatively but significantly reduces intraoperative time, particularly in complex multi-segment maxillary cases or asymmetries, with fewer splint adjustments and improved interdisciplinary communication. Clinically, VSP provides outcomes comparable to or better than conventional methods, offering improved occlusal endpoints, enhanced facial symmetry, and quantifiable though variably correlated airway changes, while complication rates remain similar.[9] Importantly, the technology has been associated with reduced reoperation rates, with studies reporting a decrease from 7.69% to 3.82%, underscoring its role in improving surgical predictability. Although initial costs for software, 3D printing, PSIs, and navigation systems are significant, these expenses are offset by reductions in operating room time and fewer revisions, making VSP particularly cost-effective in complex cases and high-volume centers.[10]

Review of Literature

The accuracy of virtual surgical planning (VSP) in orthognathic surgery has been widely evaluated using various methods, most commonly through mean error differences in superimposition between virtual plans and postoperative outcomes. Baan et al. demonstrated that the largest discrepancies occurred in vertical positioning of the maxilla and mandible, reflecting limited intraoperative vertical control, while right–left translations showed the least variation.[11] They further noted that both jaws tended to be positioned more posteriorly than planned, potentially due to condylar seating changes influenced by muscle tone and gravity in the supine position, a view also supported by Stokbro.[12] Franz et al. cautioned that relying solely on mean error as an endpoint restricts generalizability, as confidence intervals represent statistical ranges rather than true method errors.[13] Alternative approaches such as root mean square difference (RMSD) analyses, as used by Ho and Sun, revealed acceptable deviations of less than 1 mm for both jaws, with slightly greater errors in the mandible compared to the maxilla.[14] Similarly, Hsu reported sub-millimeter accuracy in maxillary translation, while Stokbro's group found mean linear differences for the maxilla, mandible, and chin segments within 0.5 mm, with minimal superoinferior deviations.[15] De Riu's investigations highlighted overall high accuracy, averaging 1.98 mm for linear and 1.19° for angular discrepancies, but emphasized that anterior facial height control and vertical dimensions remain challenging due to limitations in virtual soft tissue modeling.[16] Other studies, including those by Zhang, confirmed progressive improvements in accuracy through surgical experience, 3D printing, and enhanced template materials, while Baan and Stokbro noted greater errors in pitch due to bone interferences such as the pterygoid plates.[17] Comparative analyses consistently show superior or at least equivalent accuracy of computer-assisted planning versus conventional methods, with Ziesner demonstrating better maintenance of condylar position and Hsu reporting greater precision in chin repositioning.[18] Ritto's findings indicated VSP offered better anteroposterior accuracy, whereas conventional model surgery provided slightly improved precision in certain transverse midline corrections, though all deviations remained clinically acceptable at less than 2 mm.[19] Collectively, these studies underscore that VSP achieves high accuracy across most parameters, though vertical control and rotational movements present ongoing challenges.

Computer-Assisted Navigation and Soft Tissue Simulation

Computer-assisted navigation in orthognathic surgery employs either optical tracking systems using infrared cameras with passive or active markers, or electromagnetic tracking in situations with limited line of sight. Registration methods vary and may include bone screws or miniplates as fiducials, splint-based registration, anatomical landmark matching, or 3D surface registration, with intraoperative CBCT providing opportunities for verification and closed-loop correction.[20] Navigation is particularly valuable in complex cases such as severe facial asymmetry, yaw deformities, syndromic craniofacial conditions like microsomia, secondary corrections, situations with limited occlusal guidance such as edentulous or post-trauma cases, and in controlling genioplasty symmetry. Key practical considerations include ensuring rigid fixation of reference frames, preventing marker occlusion, validating accuracy through independent checkpoints both before osteotomy and after fixation, and always maintaining a fallback option such as conventional splints.[21] Complementing navigation, soft tissue simulation using both physics-based and data-driven models allows prediction of perioral and midfacial changes, with greater reliability for maxillary than mandibular or chin movements. These simulations are increasingly used for shared decision-making and patient counseling, though they must be presented with clear disclaimers regarding limitations, and ideally integrated with patient-reported outcome measures (PROMs) to align surgical planning with patient expectations.[22]

Technological Integration, Clinical Outcomes, and Considerations

The integration of advanced technologies such as augmented reality (AR) navigation and virtual reality (VR) simulation has further enhanced orthognathic surgery by providing real-time augmented 3D models and immersive preoperative planning environments, thereby simplifying surgical execution without always requiring complex simulations or printed guides. While virtual surgical planning (VSP) has demonstrated improved accuracy, enhanced facial symmetry, and greater midline precision compared to traditional methods, its time-saving benefits remain inconsistent across studies, likely due to variations in protocols and designs.[23] Navigation-assisted techniques consistently achieve sub-millimetric deviations between planned and postoperative skeletal positions, while also reducing neurovascular risks, and both VSP and navigation contribute to lowering reoperation rates. Patient satisfaction remains high for both conventional and virtual methods, although VSP provides superior objective reproducibility and aesthetic predictability.[24] Despite these advantages such as reduced manual error, better visualization of potential bony interferences, and improved safety near delicate structures several challenges persist, including significant costs, the need for specialized user training, and difficulties in integrating multimodal imaging data. Furthermore, while patient-specific implants (PSIs) offer additional precision, their cost-effectiveness compared with navigation or VSP remains under investigation, and emerging mixed-reality platforms may expand clinical applications by bridging current limitations.[25]

Conclusion

Virtual surgical planning and navigation have revolutionized orthognathic surgery by significantly enhancing surgical precision, reducing planning errors, and improving patient outcomes. These technologies enable meticulous preoperative simulations, real-time intraoperative guidance, and more predictable surgical results. Despite challenges such as higher costs and learning curves, VSP and navigation have become essential tools in modern orthognathic surgery, offering superior accuracy, efficiency, and safety for both surgeons and patients

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