Chapter

Computerized Workflow in Cranio-Maxillofacial Surgery for Skeletal Class III

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Abstract

The implementation of a digital workflow in cranio-maxillofacial surgery has revolutionized the management of skeletal Class III malocclusion. This chapter outlines a comprehensive approach that integrates orthodontic and orthognathic interventions with advanced digital planning tools. Post-treatment records demonstrate significant skeletal and dentoalveolar improvements, including normalization of hyperdivergent skeletal patterns and enhanced facial esthetics adhering to the golden facial proportions. Detailed cephalometric analysis confirms the achievement of optimal sagittal and vertical relationships, alongside a well-balanced soft tissue profile. The combination of traditional and digital approaches, including three-dimensional (3D) imaging, virtual surgical planning, and customized surgical guides, ensures predictable outcomes tailored to patient-specific anatomical and functional needs. This protocol facilitates not only precise execution of complex interventions but also minimizes procedural errors, reduces operative time, and enhances patient satisfaction. Postoperative follow-up protocols are essential to monitor skeletal stability, soft tissue adaptation, and long-term occlusal harmony. The integration of cone beam computed tomography (CBCT), digital models, and advanced imaging aids in evaluating the alignment between surgical outcomes and preoperative plans. Studies underscore the role of personalized surgical guides and digital tools in reducing relapse rates and improving stability in Class III cases. Advances in artificial intelligence (AI), augmented reality, robotics, and imaging technologies further extend the capabilities of cranio-maxillofacial surgery, paving the way for more personalized, minimally invasive, and precise interventions. This paradigm shift underscores the ongoing evolution in surgical practice, fostering outcomes that are functional, esthetic, and sustainable over time.

Keywords: skeletal class III, digital workflow, cranio-maxillofacial surgery, virtual surgical planning, customized surgical guides, 3D imaging, cephalometric analysis

1. Introduction

Conventional orthognathic surgery planning integrates clinical examinations with diagnostic tools, such as lateral cephalometric radiographs, dental casts, facebow transfers, articulators, and photographs. However, traditional planning approaches based on plaster models often overlook anatomical details of the entire craniofacial structure. In patients with severe craniofacial deformities, this limitation can lead to discrepancies with undesirable outcomes and potentially significant complications.

Skeletal Class III malocclusions continue to pose challenges for both orthodontists and maxillofacial surgeons. These challenges arise from the combined presence of a maxillary component, often characterized by transverse constriction, and a hypertrophic mandibular component, frequently exhibiting asymmetry.

1.1 Epidemiological and clinical background, incidence, prevalence, and distribution of narrow palate

A narrow palate, defined as a reduced transverse width of the maxillary arch, significantly impacts patient's quality of life, contributing to respiratory issues, masticatory inefficiencies, and increased susceptibility to malocclusion and occlusal dysfunctions. This anatomical condition is particularly relevant in orthodontics and maxillofacial surgery due to its association with complex clinical scenarios. Prevalence estimates for narrow palate range between 7 and 20% in the general population, with significant variations across age, gender, and ethnic groups. In children and adolescents, narrow palate incidence is strongly linked to oral breathing, often secondary to tonsillar hypertrophy, adenoidal enlargement, or chronic allergic conditions. Studies suggest that oral breathing adversely affects the growth and development of the maxilla, compromising palatal width and predisposing individuals to future malocclusions. Geographical distribution highlights a higher prevalence in urban and industrialized areas, where environmental pollutants exacerbate chronic respiratory disorders, a well-recognized predisposing factor for narrow palate [1].

1.2 Incidence, prevalence, and distribution of skeletal class III malocclusion

Skeletal Class III malocclusion represents one of the most challenging conditions in orthodontics and maxillofacial surgery, characterized by mandibular prominence relative to the maxilla, resulting in a prognathic profile and significant masticatory dysfunction. Its prevalence varies significantly across populations: approximately 10–15% in Asian ethnic groups compared to 1–5% in Western and Caucasian populations [2]. This dysmorphia exhibits a strong genetic predisposition, often inherited in an autosomal dominant pattern, as documented in numerous studies. In addition to genetic factors, Class III malocclusions are often associated with growth disturbances, where excessive mandibular growth relative to the maxilla leads to anteroposterior (AP) misalignment. Early diagnosis in pediatric cases can mitigate the progression of deformity through interceptive orthodontic interventions. Conversely, in adolescents and adults with a mature skeletal structure, combined surgical and orthodontic approaches are essential for correcting Class III discrepancies [3].

1.3 Association between narrow palate and skeletal class III malocclusion

The coexistence of a narrow palate and skeletal Class III malocclusion represents one of the most intricate challenges for maxillofacial surgeons. These conditions often exacerbate each other, complicating treatment. While the prevalence of this combination remains poorly documented, it is frequently observed in patients with chronic respiratory anomalies and swallowing dysfunctions, which predispose them to develop both conditions [4]. In adult patients, the combination of a narrow palate and prognathic mandible often leads to compromised respiratory function, affecting sleep quality and overall life satisfaction. Recent studies emphasize that addressing only one of these conditions often fails to achieve optimal esthetic and functional outcomes. Consequently, combined treatment protocols, including palatal expansion and mandibular prognathism correction, have become a cornerstone of advanced orthodontic and surgical management strategies [5].

1.4 Therapeutic alternatives for correcting narrow palate and skeletal class III

The management of narrow palate and skeletal Class III malocclusion requires a personalized approach, tailored to the patient's age and skeletal maturity.

1.4.1 Traditional orthodontic approaches

In growing patients, non-surgical palatal expansion is a first-line option to correct the transverse maxillary deficiency. Rapid palatal expanders (RPEs) are utilized in orthodontics to achieve gradual midpalatal suture separation. However, in adults with mature palatal bones and ossified midpalatal sutures, this approach is ineffective due to the lack of suture flexibility [6].

1.4.2 Traditional orthognathic procedures without SARPE (surgically assisted rapid palatal expansion)

In skeletal Class III cases, bimaxillary osteotomy is a well-established surgical solution to correct anteroposterior discrepancies. However, this procedure does not address the transverse dimension of the maxilla. When applied to patients with both narrow palate and Class III malocclusion, it may improve dental arch alignment but fails to resolve the transverse deficiency, leaving palatal expansion unaddressed [7].

1.4.3 Advanced technologies and computerized workflows

The combination of miniscrew-assisted rapid palatal expansion (MARPE) and digitally planned orthognathic surgery offers a comprehensive solution for narrow palate associated with skeletal Class III malocclusion. Computerized workflows represent the most advanced approach, ensuring precise planning and predictable outcomes [8]. The integration of cone beam computed tomography (CBCT) and 3D models allows for accurate design of both palatal expansion and corrective surgery, reducing intraoperative risks and enhancing post-operative stability. The use of 3D printing and patient-specific surgical guides further improves surgical accuracy, resulting in superior esthetic and functional outcomes [9].

2. Traditional vs. computerized workflows in surgical planning

Orthognathic surgery demands meticulous and precise planning to achieve optimal functional and esthetic results. Traditionally, surgical planning has relied on a comprehensive patient assessment involving clinical examinations and key diagnostic tools, including lateral cephalometric radiographs, plaster models, facebow transfers, articulators, and extra- and intraoral photographs. For decades, these tools have formed the foundation of orthognathic planning, enabling a two-dimensional (2D) evaluation of skeletal structure and dental relationships [10].

2.1 Lateral cephalometric radiographs and photographs

Lateral cephalometric radiographs are essential in traditional planning, providing a lateral view of the skull to analyze anteroposterior and vertical skeletal proportions. However, their 2D nature limits the visualization of the complete craniofacial anatomy. Extra- and intraoral photographs serve as complementary visual aids, facilitating the evaluation of facial esthetics and smile harmony. However, these images fail to deliver detailed insights into deeper skeletal structures [11].

2.2 Plaster models and articulators

Plaster models, created from traditional dental impressions, have long been the primary method for occlusal analysis and planning dental and skeletal movements. Mounted on mechanical articulators, these models enable the simulation of masticatory movements and the analysis of interocclusal relationships. While effective for assessing occlusion, these models have significant limitations in cases involving severe craniofacial deformities. Manual manipulation of plaster models does not provide precise insights into cranial structures or the skeletal interactions between the mandible and maxilla, often neglecting critical details necessary for comprehensive planning [12]. By addressing these limitations, computerized workflows and advanced technologies represent a transformative evolution in orthognathic surgical planning (**Figure 1**).

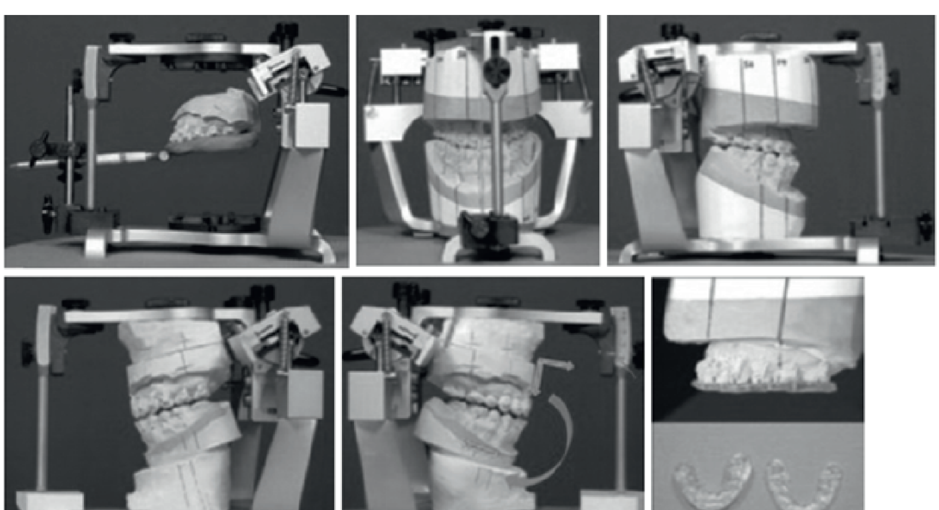


Figure 1.
Plaster models and articulators.

2.2.1 Facebow and articulator mounting

The facebow is employed to transfer the spatial position of the maxilla relative to the cranial base. This tool facilitates the mounting of plaster models in an articulator, replicating the patient's occlusal orientation. However, this procedure is prone to errors, as the facebow does not account for complex three-dimensional asymmetries that may be present in patients with severe craniofacial deformities [13].

2.2.2 Limitations of traditional planning in severe deformities

Conventional planning based on plaster models and two-dimensional tools has significant limitations when applied to patients with severe craniofacial deformities. In complex cases where skeletal structures are severely compromised or asymmetrical, two-dimensional planning and simulation using plaster models often fail to incorporate the complete anatomical information of the entire craniofacial skeleton. The lack of a global, three-dimensional perspective can result in errors in assessing the position and movement of skeletal structures, leading to undesirable variations in surgical outcomes. These errors, arising from the limited ability of plaster models to accurately replicate the patient's anatomical complexity, may cause unfavorable consequences, such as discrepancies in intermaxillary relationships, occlusal plane alignment, post-operative asymmetries, and patient dissatisfaction with the esthetic results [14]. Furthermore, the intricate correction process necessitates the fabrication of one or more surgical splints to guide the repositioning of the maxilla and mandible after their detachment from the cranial base. These splints often exhibit inaccuracies and low reproducibility due to the challenges in managing repositioning lines on plaster models, especially when adjusted based on two-dimensional planning from surgical or orthodontic treatment objectives (virtual treatment objectives (VTO)/surgical treatment objectives (STO)) [15].

2.2.3 The need for advanced solutions

The limitations of traditional planning highlight the necessity for more advanced techniques that incorporate three-dimensional representations of the patient's anatomy.

2.2.4 Digital innovations for comprehensive planning

- Imaging advances: Cone beam computed tomography (CBCT) provides a highly detailed three-dimensional visualization of skeletal structures, enabling an in-depth evaluation of anatomical relationships.

- 3D modeling: Digital models allow for precise simulation of surgical interventions, encompassing assessments of soft tissues, jaw positioning, and dental structures.

- Preoperative digital planning: Advanced digital techniques improve planning accuracy, minimize errors, and enhance the predictability of surgical outcomes.

- Custom surgical splints: Splints fabricated using 3D printing based on virtual models demonstrate superior precision and reliability compared to those created through traditional methods.

2.2.5 Integration of soft tissue analysis

A comprehensive planning approach must extend beyond skeletal evaluation to include facial soft tissues, jaw positioning, and the underlying skeletal structures. This integrated analysis ensures optimal functional and esthetic outcomes, ultimately enhancing patient satisfaction and surgical precision [16].

The adoption of computer-aided workflows represents the future of orthognathic surgery, providing a more comprehensive, precise, and predictable alternative to traditional techniques [17].

2.2.6 Advantages of digitalization

The introduction of digitalization in the field of orthognathic surgery has opened new horizons, making the planning and surgical process more efficient and secure. Beyond the primary benefits already mentioned, several additional clinical and operational advantages can be highlighted.

2.2.7 Enhanced precision and error reduction

Digital planning eliminates many human variables associated with the manual manipulation of models and two-dimensional tools. Advanced algorithms integrated into software platforms enable precise calculations of skeletal movements and allow for accurate predictions of both functional and esthetic outcomes. For instance, in cases involving complex asymmetries or three-dimensional rotations of skeletal bases, digital software provides highly accurate simulations that significantly reduce the risk of post-operative occlusal discrepancies [18].

2.2.8 Customized treatment plans

The digital workflow allows for treatments tailored to the specific needs of each patient. Every surgical intervention is planned according to the patient's unique morphology, incorporating considerations, such as mandibular biomechanics, joint function, and airway dimensions [19]. For example, in patients with obstructive sleep apnea (OSA), digital simulations can evaluate the impact of mandibular advancement on airway patency. This predictive capability ensures that the planned surgical intervention addresses both skeletal discrepancies and functional impairments, resulting in a comprehensive treatment strategy. Digitalization enhances the ability to foresee potential outcomes, providing a level of customization and precision unattainable through traditional methods. This paradigm shift not only improves surgical outcomes but also enhances patient satisfaction and confidence in the treatment process (**Figure 2**).

2.2.9 Speed and time optimization

The automation of multiple stages of treatment planning through digital workflows significantly reduces the time required for preoperative preparation. This translates into the ability to treat a greater number of patients and achieve better organization of surgical schedules. Additionally, rapid simulations enable real-time discussions with patients, improving communication and facilitating shared decision-making [19].

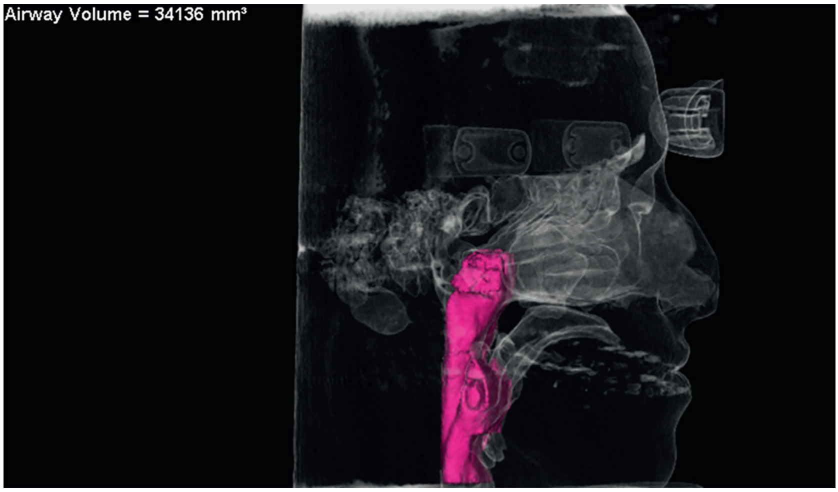


Figure 2.
Customized treatment plans.

2.2.10 Predictability and effective communication

The ability to present patients with a three-dimensional simulation of the planned procedure enhances their understanding of the expected results. This improves patient confidence and actively involves them in the treatment process. Furthermore, the increased predictability of outcomes reduces the likelihood of post-operative revisions, leading to greater overall satisfaction.

2.2.11 Summary of benefits

- Enhanced precision and error reduction
- Customized treatment plans
- Speed and time optimization
- Predictability and effective communication

2.3 Advanced imaging and diagnostic techniques

The use of advanced imaging techniques is a cornerstone of digital treatment planning. These tools provide detailed representations of anatomical structures, enabling precise diagnosis and meticulous surgical planning [20].

2.3.1 CBCT (cone beam computed tomography)

CBCT is considered the gold standard for craniofacial imaging due to its ability to capture high-resolution, three-dimensional images with a lower radiation dose compared to traditional computed tomography. This imaging modality allows for the evaluation of:

- The three-dimensional skeletal morphology.
- The relationships between the maxilla, mandible, and cranial base.
- The airway passages and dental structures with exceptional clarity.

2.3.2 3D intraoral and facial scans

Intraoral scans, obtained using digital scanners, provide virtual models of the dental arches, eliminating the need for traditional physical impressions. These datasets can be integrated with 3D facial scans, which realistically capture the patient's facial features, creating a comprehensive model that combines both skeletal and esthetic morphology [21].

2.3.3 Multimodal integration

The integration of data from CBCT, intraoral scanners, and facial scans results in a unified digital model. This comprehensive model serves as the foundation for surgical analysis and planning, offering a global, three-dimensional view of anatomical structures and occlusal relationships [22]. This advanced approach ensures an accurate and personalized treatment strategy, significantly enhancing the predictability and success of orthognathic surgery (**Figure 3**).

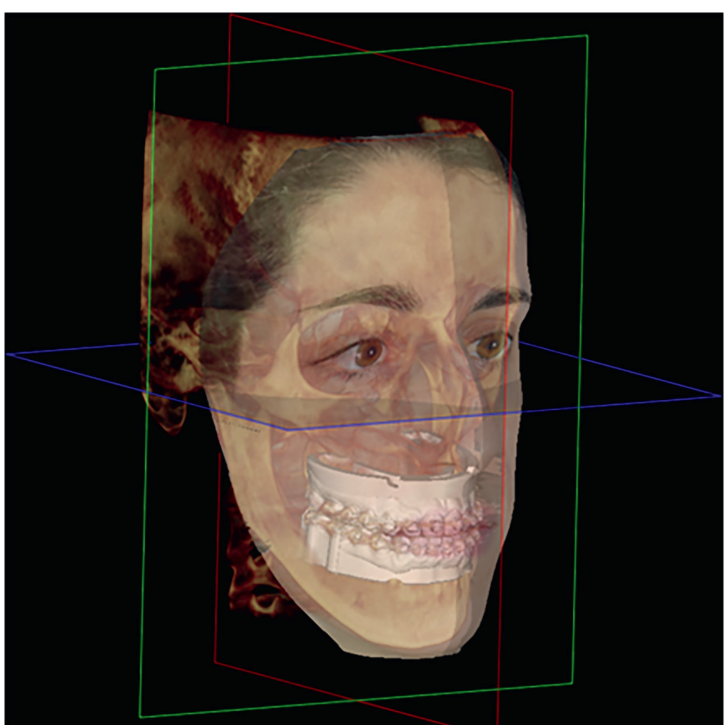


Figure 3.
Multimodal integration.

3. Digital workflow for simulation

3.1 Orthognathic surgery planning for skeletal class III malocclusion

The surgical correction of skeletal Class III malocclusion represents a significant challenge in cranio-maxillofacial surgery. Digital planning has revolutionized the approach to these cases, providing advanced tools to enhance precision, efficiency, and predictability of both esthetic and functional outcomes. This chapter explores the planning techniques, surgical procedures, and key clinical considerations in managing such patients [23–25].

3.2 3D model design for bimaxillary osteotomy

The creation of a three-dimensional (3D) virtual facial model is the foundational step in modern surgical planning. This model integrates data from advanced imaging techniques, allowing for a detailed visualization of craniofacial morphology and precise simulation of the necessary skeletal movements.

3.2.1 Required data inputs

- CBCT of the full craniofacial region
- STL files of the dental arches (3D model)
- 2D frontal facial photographs or facial scans

3.2.2 3D model creation process

1. CBCT (cone beam computed tomography): Provides high-resolution images of skeletal and dental structures while reducing radiation exposure compared to traditional CT scans.
2. STL of the arches: Intraoral scans deliver highly accurate models of dental arches, eliminating the need for physical impressions and improving overall precision.
3. Facial scans: Facial scanners complete the digital dataset by providing surface morphology that integrates seamlessly with CBCT imaging.

Specialized software, such as Dolphin Imaging with its surgical module, combines CBCT data with dental and facial scans to generate a virtual facial model. This model accurately represents the anatomical relationships between hard and soft tissues [26].

3.2.3 Anatomical model segmentation and surgical simulation

In the subsequent step, anatomical 3D models (virtual replicas of the patient's skeletal and dental structures) are segmented, mobilized, and repositioned according to the surgical plan. This involves:

- Precisely identifying osteotomy sites.
- Simulating skeletal movements.
- Evaluating both functional and esthetic impacts of the planned corrections.

The enhanced anatomical detail offered by this workflow minimizes intraoperative errors. The repositioning of anatomical structures is guided by esthetic and functional references (see the section on esthetic analysis), ensuring the restoration of proper functional, esthetic, and dental balance [27].

3.2.4 Real-time simulation and optimization

Digital planning software allows for real-time visualization of three-dimensional surgical simulations, including soft tissue predictions. This capability enables surgeons to simulate and optimize surgical outcomes while improving communication with patients. One of the key advantages of digital planning is its ability to predict esthetic and functional changes, aligning surgical objectives with the patient's specific needs and expectations.

3.2.5 Surgical splint fabrication

The final stage involves the production of a surgical splint (wafer), which is initially generated virtually and then fabricated using 3D printing technologies. These splints, made from biocompatible materials such as photopolymeric resins, serve as precise guides for maxillary and mandibular repositioning. This ensures the safety and efficacy of the surgical procedure [28–30]. The digital workflow not only enhances surgical precision but also streamlines the preoperative process, ultimately improving patient outcomes and satisfaction.

3.2.6 Advantages of the digital workflow

This method offers several advantages:

- Millimetric precision in osteotomies.
- Extreme personalization for patients with complex morphologies.
- Reduced operating times due to detailed preoperative planning.

3.3 Esthetic analysis

The correction of skeletal Class III malocclusion requires complex surgical interventions involving both the maxilla and the mandible. The primary goal is to restore esthetic and functional balance through precise and personalized techniques [31–33].

3.3.1 Role of 3D simulation

3D simulation enables:

- Visualization of facial proportions before and after surgery.

- Identification of disharmonies not evident in 2D examinations.
- Customization of surgical plans to optimize overall facial esthetics.

The visual representation of expected outcomes enhances doctor-patient communication, improving treatment understanding and overall satisfaction. Most importantly, it ensures that the correction of facial proportions, profile balance, and soft tissue harmony aligns with the achievable corrections and patient expectations. Furthermore, it emphasizes the adjustment and stabilization of occlusion, which, according to the author, represents the key element of stability. Achieving a final mandibular position that respects the primary components of the masticatory system, teeth, muscles, and temporomandibular joints (TMJs) is essential.

3.4 Facial proportions

Three-dimensional (3D) simulation is an indispensable tool for analyzing and harmonizing facial proportions. It ensures that surgical outcomes extend beyond skeletal corrections to achieve a balanced and esthetically pleasing appearance [34].

3.5 Facial proportions analysis

3.5.1 Vertical lines

According to Arnett and Gunson, the face is divided into vertical thirds:

- Upper third: From the trichion (hairline) to the glabella.
- Middle third: From the glabella to the base of the nose.
- Lower third: From the base of the nose to the menton.

A disproportionate lower third is a common characteristic in patients with skeletal Class III malocclusion and can be addressed through mandibular and/or maxillary repositioning.

3.5.2 Transverse relationships

The symmetry of the dental arches and the position of the zygomatic bones are assessed to ensure equilibrium between the two sides of the face.

3.5.3 Frontal balance

- The dental midline is compared with the facial midline.
- The width of the nasal base, zygomatic bones, and upper dental arch should be proportional to the lower third of the face.

This comprehensive analysis guarantees that the surgical approach not only corrects skeletal discrepancies but also achieves optimal esthetic and functional outcomes.

3.6 Facial profile

The facial profile is a critical parameter in esthetic evaluation. Orthognathic surgery, particularly in patients with skeletal Class III malocclusion, aims to enhance the projection of the nasolabial profile, chin, and lips [35, 36].

3.6.1 Reference lines

1. Ricketts' esthetic line

    - A line drawn from the nasal tip to the chin tip. Ideally, the upper lip should lie 4 mm behind this line, and the lower lip 2 mm behind [24].

2. Arnett-Gunson analysis

    - Upper lip position: The position of the upper lip relative to the nasal base and the projection of the upper incisors.

    - Chin-neck line: The line connecting the menton to the neck, crucial for assessing the cervico-mental angle, which should range between 105° and 120°.

    - Maxillary position: The position of the maxilla relative to the central face, essential for nasolabial harmony.

    - Soft tissue thickness: The thickness of soft tissues in the perioral and chin regions must be evaluated to predict esthetic outcomes.

    - Dynamic smile analysis: A dynamic assessment of the smile is essential to ensure that movement does not compromise esthetic results.

    - Symmetry and balance: Soft tissues should appear symmetric and harmonized with the underlying skeletal structures.

3. Facial mask

    - Marquardt beauty analysis: Based on biological and mathematical principles, this approach evaluates human visual esthetics.

3.7 Surgical objectives

Virtual skeletal movements were performed according to the following parameters:

- Correction of excessive mandibular projection or maxillary retrusion.

- Achieving balance between the upper and lower lips relative to the esthetic line.

- Improving chin projection, harmonizing the cervico-mental angle.

- Correction of midline discrepancies.

- Correction of the occlusal plane: a downward inclination of the maxilla.
- Adjustment of the anteroposterior position of the maxilla. Specific cephalometric parameters, such as the sella-nasion-A (SNA) angle, were monitored during movement simulations using the software.
- Adjustment of the anteroposterior and vertical position of the mandible.
- Correction of anterior facial proportions.
- Attainment of soft tissue balance.

This systematic approach ensures that both skeletal corrections and soft tissue harmony are achieved, optimizing esthetic and functional outcomes.

3.8 Impact on soft tissues

Skeletal changes induced by orthognathic surgery inevitably influence soft tissues, particularly in the perioral, nasal, and chin regions. A thorough analysis of soft tissue response is essential to ensure an esthetically satisfactory outcome [33, 34].

3.9 Preoperative simulation and evaluation

3.9.1 Perioral tissues

- The projection of the upper and lower lips is simulated based on the repositioning of the maxillary and mandibular incisors.
- The nasolabial angle is optimized during maxillary repositioning to enhance facial harmony.

3.9.2 Nasal tissues

- Maxillary advancement may alter the width of the nasal base. Surgical techniques should account for these changes, potentially integrating rhinoplasty to refine the nasal structure.

3.9.3 Chin region

- Mandibular repositioning affects the position and projection of the chin. Soft tissue analysis is critical to prevent undesirable outcomes, such as an overly prominent or recessed chin [34, 37].

3.9.4 Airway management and soft tissue considerations

- Mandibular setback can reduce airway volume. During planning, airway patency must be evaluated using volumetric analysis software to minimize the risk of post-operative complications.

4. Case report

4.1 Diagnosis and etiology

A 23-year-old female patient presented for orthodontic consultation to address craniofacial dysmorphosis and improve facial appearance and smile esthetics.

Extraoral examination revealed:

- A moderate skeletal Class III malocclusion.
- Pronounced elongation of the lower third of the face, contributing to an aged appearance.
- Thin lips with minimal vermilion show an underdevelopment of the midface region.
- Facial asymmetry in frontal view, characterized by:
  - Higher labial commissure on the right side.
  - Chin displacement toward the right.
  - Hemimandibular elongation on the left side (**Figure 4**).

4.2 Intraoral examination

The intraoral examination revealed a Class III malocclusion with a complete crossbite involving the entire arch, transverse maxillary deficiency, and dental crowding in both arches. The upper midline was centered, while the lower midline was shifted to the right (**Figure 5**: intraoral photographs taken post-expansion achieved with miniscrews). No clinically evident signs or symptoms of temporomandibular dysfunction were reported. A 3D model analysis (TRIOS, 3Shape A/S, Copenhagen, Denmark) was conducted to evaluate occlusal characteristics and identify potential abnormal contacts (**Figure 6**: intraoral scans, post-expansion achieved with miniscrews).

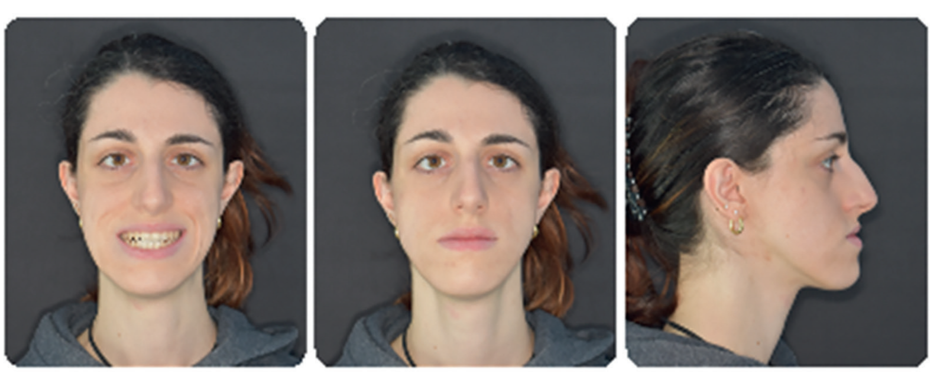


Figure 4.
Intraoral examination.

Figure 5.
Intraoral photographs taken post-expansion achieved with miniscrews.

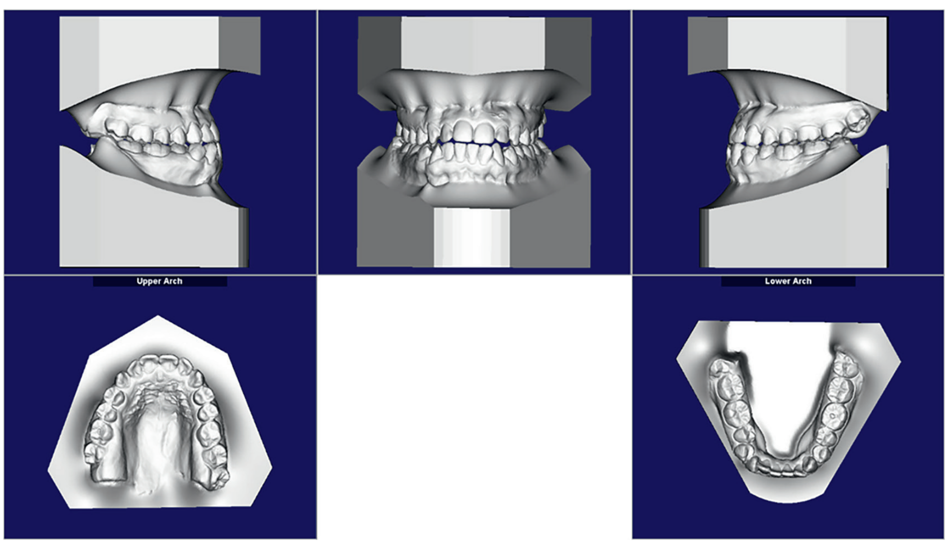


Figure 6.
Intraoral scans, post-expansion achieved with miniscrews.

The panoramic radiograph revealed impaction of both maxillary and mandibular third molars (**Figure 7**). Cephalometric analysis confirmed a severe skeletal Class III malocclusion in a hyperdivergent patient, with the following measurements:

SNA 82°,
SNB 85.2°,
ANB −3.2°,
WITS −9.9,
FMA (MP-FH) 28.1°,
IMPA 77.2°,
MP-SN 39.9°.

A soft tissue cephalometric analysis was also performed to assess the vertical and anteroposterior projection of the lips and other soft tissue components (**Figures 8** and **9**: cephalometric radiograph).

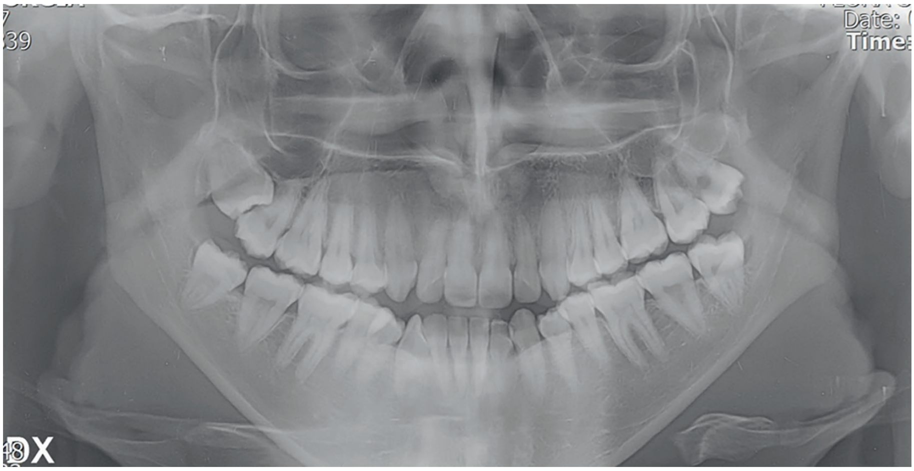


Figure 7.
High-definition intraoral scan with TRIOS (3Shape A/S, Copenhagen, Denmark).

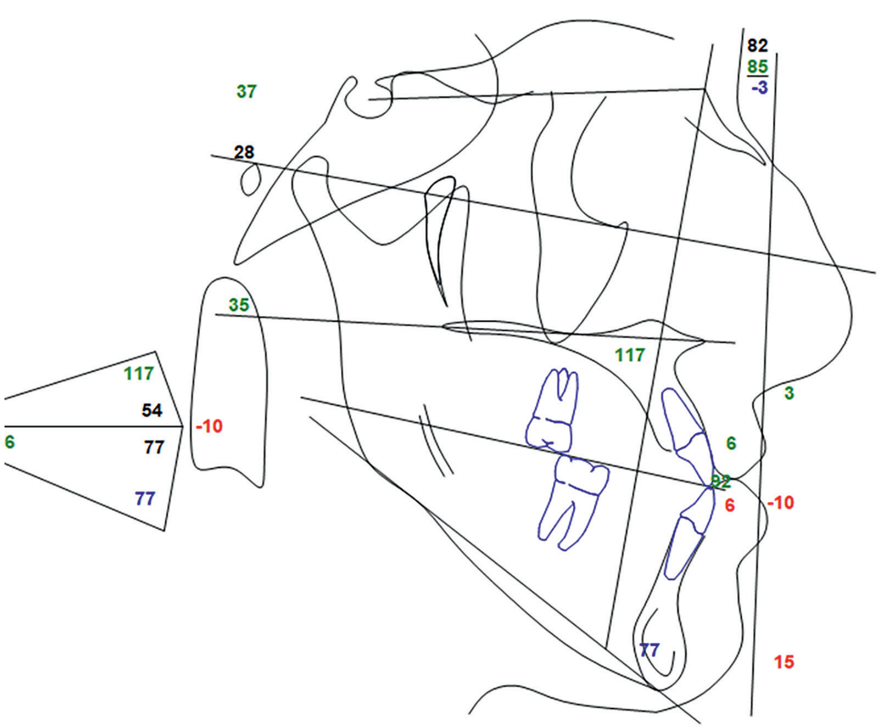
Figure 8.
High-definition intraoral scan with TRIOS (3Shape A/S, Copenhagen, Denmark).

4.3 Treatment objectives

The treatment objectives included:

- Correction of maxillary and mandibular dental crowding.
- Correction of sagittal and transverse skeletal discrepancies to achieve a Class I relationship.
- Enhancement of smile esthetics and facial profile.

DOI: http://dx.doi.org/10.5772/intechopen.1009503



Group/Measurement	Value	Norm	Std Dev	Dev Norm
* HORIZONTAL SKELETAL *				
SNA (°)	82.0	82.0	3.5	-0.0
SNB (°)	85.2	80.0	3.0	1.7 *
ANB (°)	-3.2	2.0	2.4	-2.2 **
Maxillary Skeletal (A-Na Perp) (mm)	3.5	1.0	3.1	0.8
Mand. Skeletal (Pg-Na Perp) (mm)	15.2	-2.0	5.3	3.2 ***
Wits Appraisal (mm)	-9.9	-1.0	1.0	-8.9 *******
* VERTICAL SKELETAL *				
FMA (MP-FH) (°)	28.1	26.0	5.0	0.4
MP - SN (°)	39.9	33.0	6.0	1.2 *
Palatal-Mand Angle (°)	35.0	28.0	6.0	1.2 *
Palatal-Occ Plane (PP-OP) (°)	9.2	10.0	4.0	-0.2
Mand Plane to Occ Plane (°)	25.8	17.4	5.0	1.7 *
Mx occlusal plane (MxOP-Na Perp) (°)	92.3	95.6	1.8	-1.8 *
* ANTERIOR DENTAL *				
U-Incisor Protrusion (U1-APo) (mm)	5.6	6.0	2.2	-0.2
L1 Protrusion (L1-APo) (mm)	6.1	1.0	2.3	2.2 **
U1 - Palatal Plane (°)	116.7	110.0	5.0	1.3 *
U1 - Occ Plane (°)	54.1	57.5	7.0	-0.5
L1 - Occ Plane (°)	77.0	72.0	5.0	1.0 *
IMPA (°)	77.2	95.0	7.0	-2.5 **
Subnasale - ST Menton	63.6	N/A	N/A	N/A
Soft tissue A pt to SnV (mm)	4.3	-2.0	N/A	N/A
Soft tissue B pt to SnV (mm)	-5.0	-5.0	N/A	N/A
Upper lip anterior (ULA - Sn Vertical) (mm)	0.2	3.0	1.0	-2.8 **
Lower lip anterior (LLA - Sn Vertical) (mm)	0.0	1.0	1.0	-1.0 *
Soft tissue Lower lip - Sn-7 (mm)	74.9	N/A	N/A	N/A
Soft tissue Pogonion - Sn-7 (mm)	96.1	N/A	N/A	N/A

Figure 9.
Comprehensive assessment of the patient's craniofacial structures.

4.4 Therapeutic options

Option 1: Orthodontic treatment with multibracket appliances, involving extraction of teeth 3.4 and 4.4, followed by space closure and resolution of maxillary dental crowding. However, this option would not improve the midface profile or address the skeletal Class III discrepancy as required by the patient.

Option 2: Miniscrew-assisted rapid maxillary expansion (MARPE) to correct the transverse maxillary deficiency, combined with the application of miniplates in the lower arch to manage the Class III correction using intermaxillary elastics. However, given the extent of sagittal discrepancy and the patient's age, this approach would not meet the patient's esthetic expectations.

Option 3: Combined orthodontic-surgical treatment, beginning with multibracket therapy to decompensate the skeletal discrepancy, followed by maxillofacial surgery including Le Fort I and bilateral sagittal split osteotomy (BSSO) for skeletal correction. However, this option would not provide adequate transverse expansion of the midface, limiting treatment to sagittal and vertical skeletal imbalances.

Option 4: Surgically assisted rapid palatal expansion (SARPE) to address transverse maxillary dimensions, followed by combined orthodontic-surgical treatment with maxillofacial surgery (Le Fort I and BSSO).

Patient's decision. The patient, supported by her parents, opted for the fourth treatment option to address dentoskeletal discrepancies, asymmetry, esthetic concerns, and dental crowding. Informed consent was obtained for the chosen treatment plan and the use of sensitive data. As part of the preparatory phase, the maxillary and mandibular third molars were extracted to facilitate surgical osteotomies, as well as repositioning and fixation maneuvers.

5. Orthodontic sequence

5.1 Phase 1: Maxillary expansion with MARPE

The initial phase of treatment involved miniscrew-assisted rapid palatal expansion (MARPE), which utilizes skeletal anchorage for expansion without surgical release of resistance sites, combined with the application of orthopedic forces [38, 39]. Virtual insertion of the miniscrews was planned using Dolphin software. Subsequently, Appliance Designer (TRIOS, 3Shape A/S, Copenhagen, Denmark) was used to design a surgical guide for precise miniscrew placement. Concurrently, intraoral scans (TRIOS, 3Shape A/S, Copenhagen, Denmark) were sent to a digital orthodontic laboratory for the fabrication of a HYRAX maxillary expander. The device featured bands on teeth 1.6 and 2.6, with extended arms reaching the second molars, positioned 1 mm above the gingival margin. The procedure was conducted in the surgical unit of a private dental clinic in Catania. Conscious intravenous sedation, administered by an experienced anesthesiologist, was utilized to minimize intraoperative stress. Local infiltration anesthesia with articaine was applied in the retroincisal area. Following this, the surgical guide was used for pilot drilling at 200 rpm (revolutions per minute) with irrigation and a torque of 60 N/m. Two miniscrews, measuring 2 mm in diameter and 13 mm in length (HDC, Thiene, Italy), were inserted using a surgical micromotor at 50 rpm and a torque of 20 N/m. No osteotomies were performed. The device was cemented with glass ionomer cement (KETAC, 3 M, Saint Paul, MN, USA) immediately after the miniscrew insertion. Post-operatively, the expander screw was activated four times, followed by one daily activation until the screw was fully opened (10 mm). Upon completion of activation, the screw was secured with 0.010-inch passive stainless-steel ligatures. After a six-month retention period, the appliance and miniscrews were removed. A comprehensive orthodontic follow-up was performed, including intraoral and extraoral photographs, intraoral scanning, and radiographic evaluations (panoramic and lateral cephalometric radiographs) [40, 41]. A self-ligating 0.022-inch fixed appliance with Damon prescription (Ormco, Orange, CA, USA) was placed on the labial surface of all erupted teeth. Both maxillary and mandibular arches were treated using the same archwire sequence: 0.014 Cu 155 NiTi, 0.018 Cu NiTi, 0.014 × 0.025 Cu NiTi, 0.018 × 0.025 NiTi, 0.017 × 0.025 TMA, and 0.019 × 0.025 SS with stops (**Figure 10**). This wire sequence facilitated alignment, leveling, and coordination of the arches, preparing them for the presurgical phase with rigid stainless steel (SS) archwires. The combination of self-ligating brackets and thermally activated NiTi wires created a biomechanical system that delivered low-force levels, enabling dentoalveolar discrepancy correction without causing iatrogenic damage to the periodontal tissues. Once the orthodontic archwire sequence was completed—ensuring full transfer of the bracket prescription and correcting all dentoalveolar compensations in both transverse and sagittal planes—a thorough presurgical diagnostic workup was initiated. This critical step included high-definition intraoral scans with TRIOS (3Shape A/S, Copenhagen, Denmark) (**Figures 7** and **8**) and a CBCT scan with a large field of view (FOV) to obtain a comprehensive assessment of the patient's craniofacial structures (**Figure 9**).

5.2 Acquisition and integration of patient data

The acquired data were imported into the Dolphin 3D Surgery module, where high-resolution intraoral scans and CBCT images were meticulously aligned to create a detailed virtual model of the patient's craniofacial anatomy, integrated with high-resolution dental arches. This integration combines all anatomical and dental

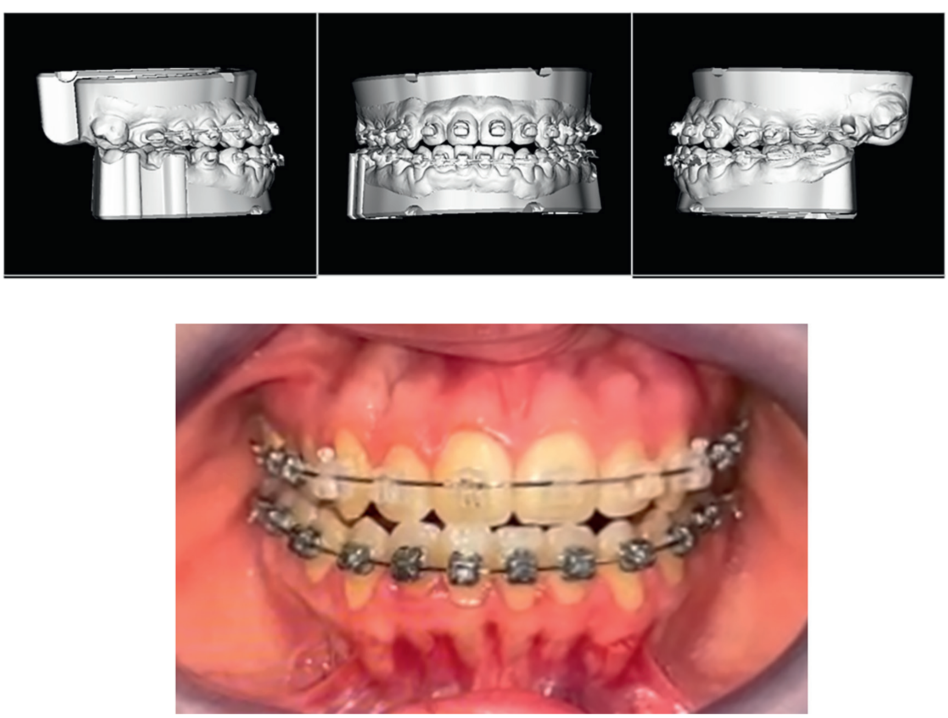


Figure 10.
Splints.

information into a single representation, providing the surgical team with a comprehensive foundation for treatment planning.

5.3 Integration of photographs and patient feature assessment

An additional level of detail was achieved by integrating the patient's extraoral frontal photographs with the 3D reconstructed cranial model. This approach facilitates a holistic assessment of skeletal and soft tissue characteristics (Supplementary Figures 2–4). This functionality allowed the team to accurately simulate jaw movements and predict the esthetic and functional impact of the surgical procedure, thus enhancing the precision of the planning process.

5.4 Virtual treatment objectives (VTO)

The virtual planning was executed using the Dolphin 3D Surgery module, guided by the objectives outlined by the orthodontist and surgeon. A complete iconographic workflow of the digital orthognathic surgery planning process using Dolphin 3D Surgery software has been documented comprehensively [42, 43].

6. Design and prototyping of surgical splints

Once the optimal final positions of the maxilla and mandible were determined, the "Splint Tool" in Dolphin 3D software was used to design intermediate and final digital splints. These splints included specific fixation holes for intermaxillary fixation (**Figure 10(a)**) and were customized according to the treatment plan

Figure 11.
The STL files exported for final prototyping.

Figure 12.
Digital splints were prototyped using a FORMLAB 3D printer (SLA technology, FORMLAB, Somerville, MA, USA) with a biocompatible transparent resin (Surgical Guide Resin) at a layer thickness of 50 μm.

parameters, such as width, thickness, and other functional characteristics. The STL files generated were exported for final prototyping (**Figure 11**). Custom surgical guides, essential for transferring the virtual plan to the operating table, were designed using advanced software and fabricated with 3D printing technology. These tools significantly enhance surgical precision and efficacy. Digital splints were prototyped using a FORMLAB 3D printer (SLA technology, FORMLAB, Somerville, MA, USA) with a biocompatible transparent resin (Surgical Guide Resin) at a layer thickness of 50 μm (**Figure 12**). The post-curing process followed the manufacturer's guidelines to ensure the stability and safety of the surgical instruments.

7. Surgical procedure and post-operative rehabilitation

The surgical intervention followed the detailed digital plan, employing Le Fort I and BSSO (bilateral sagittal split osteotomy) approaches to correct skeletal dysmorphisms. Final stabilization was achieved using rigid plates and screws to ensure long-term stability [44, 45].

7.1 Pre-surgical preparation

The digitization process streamlines and optimizes intraoperative workflows, ensuring accurate alignment between the virtual plan and the surgical procedure. Surgical guides were sterilized, adapted to the patient before surgery, and cross-verified against the virtual model and surgical plan (**Figures 13** and **14**). The guides were temporarily fixed to dental structures using fixation wires, guiding the precise angle and depth of osteotomy cuts.

8. Bimaxillary osteotomy techniques

8.1 Le fort I osteotomy procedure

An intraoral incision provided access to the maxilla. The osteotomy was performed above the dental apices to separate the maxilla from the cranial base, improving soft

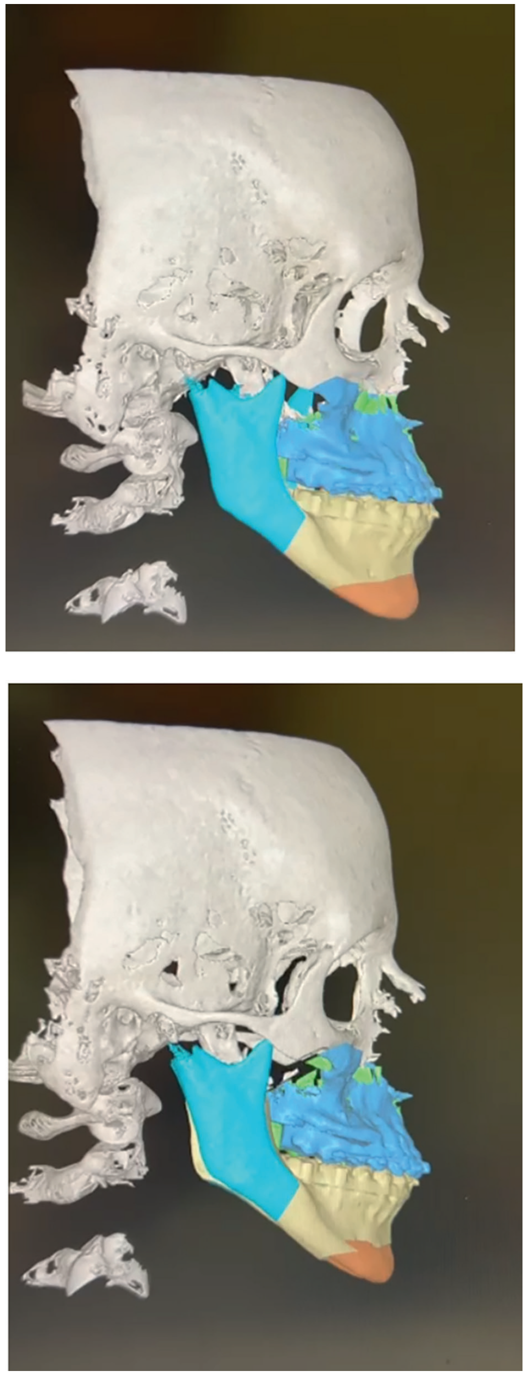


Figure 13.
Pre-surgical preparation.

tissue support, correcting the occlusal relationship, and optimizing facial esthetics. Additionally, lateral cuts extending through the zygomatic process of the maxilla were made to achieve three-dimensional enhancement of the zygomatic region, resulting in volumetric improvement (**Figure 15**).

Figure 14.
Pre-surgical preparation.

8.2 Bilateral sagittal split osteotomy (BSSO). Procedure

The osteotomy was performed along the mandibular ramus, enabling anteroposterior repositioning of the mandible. Stability of the osteotomized segments was ensured with rigid plates and miniscrews, achieving ideal occlusion, maintaining facial symmetry, and ensuring long-term stability. Simultaneous genioplasty involved repositioning the symphysis, secured with plates and screws. The esthetic impact on soft tissues, particularly in the chin and lower lip region, was evaluated during 3D simulations to ensure harmonious outcomes. Following soft tissue healing, the patient underwent a personalized 8-week home physiotherapy program aimed at improving phonation, mastication, and joint mobility. This regimen was complemented by progressive exercises to restore joint function and enhance neuromuscular adaptation (**Figure 16**).

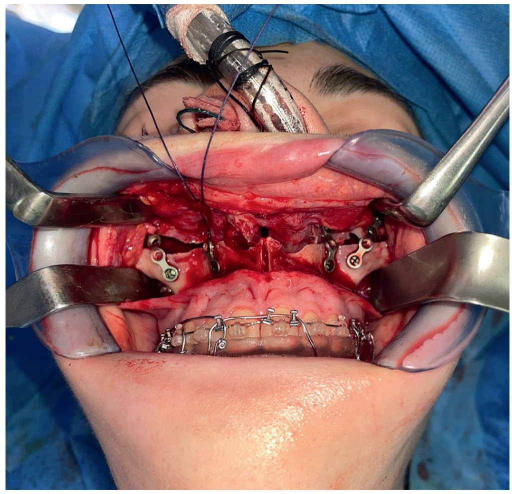


Figure 15.
Lateral cuts extending through the zygomatic process of the maxilla were made to achieve three-dimensional enhancement of the zygomatic region, resulting in volumetric improvement.

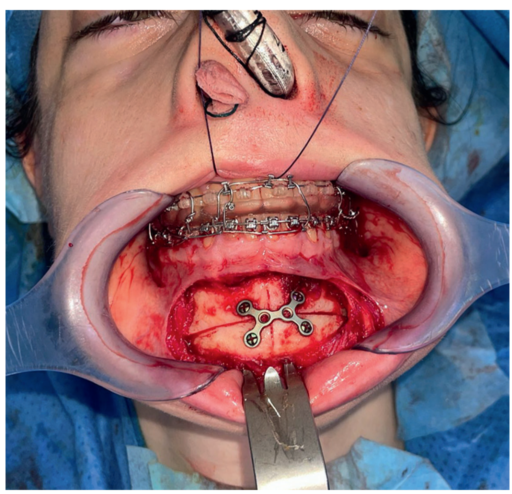


Figure 16.
Bilateral sagittal split osteotomy (BSSO).

9. Post-operative management

- Skin quality and soft tissue retraction were monitored to ensure optimal recovery.
- Complementary esthetic treatments, such as fillers or non-invasive lifting, were considered to optimize outcomes (**Figure 17**).

10. Final phase and retention

Post-treatment records highlighted significant improvements in both skeletal and dentoalveolar parameters. Specifically, facial photographs demonstrated a notable

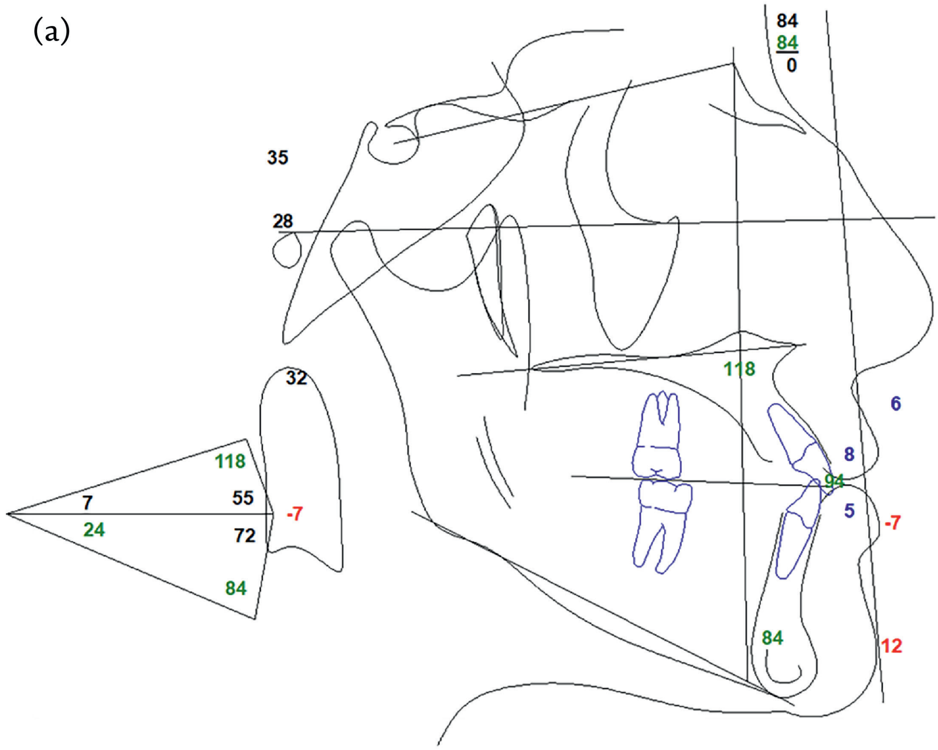
Figure 17.
Post-operative management.

enhancement in the patient's smile and overall facial esthetics (**Figures 11–15**). A comparison between pre- and post-treatment lateral cephalometric radiographs revealed that the hyperdivergent skeletal pattern (long face) was corrected to a normodivergent sagittal plane, with a significant improvement in the ratio of anterior to posterior facial heights. On the frontal plane, facial proportions now adhere to the facial golden ratio (**Figure 16**). Final cephalometric analysis illustrated the treatment's impact through both orthodontic and surgical interventions. Corrections and normalization of previously aberrant cephalometric values were achieved:

- SNA: 83° (82°)
- SNB: 83.7° (85.2°)
- ANB: 0.2° (−3.2°)
- WITS: −7.2 (−9.9)
- FMA (MP-FH): 28.1° (28.1°)
- IMPA: 83.7° (77.2°)
- MP-SN: 31.9° (39.9°)

These improvements extended beyond skeletal components, encompassing esthetic and soft tissue enhancements. Soft tissues are now well proportioned and aligned with current standards. The superimposition of pre- and post-treatment radiographs demonstrates the effectiveness of combining orthognathic surgery and orthodontic treatment in this case (**Figure 17**). Final panoramic radiographs reveal adequate root parallelism and the absence of significant root resorption (**Figure 15**). Final models and intraoral photographs confirm Class I canine relationships with normalized overjet and overbite, achieving proper incisal and canine guidance. The resolution of crowding was accomplished without proclination of incisors or periodontal compromise (**Figure 18A,B**). The new maxillary position improved the frontal exposure of the incisal group and restored muscle tone to the upper lip, which now appears well balanced in both frontal and lateral views, with preserved and enhanced lip competence. Ten months post-surgery, the treatment was concluded with intermaxillary elastics to optimize intercuspation and occlusal harmony, complemented

(a)



(b)

Group/Measurement	Value	Norm	Std Dev	Dev Norm
* HORIZONTAL SKELETAL *				
SNA (°)	83.8	82.0	3.5	0.5
SNB (°)	83.7	80.0	3.0	1.2 *
ANB (°)	0.2	2.0	2.4	-0.8
Maxillary Skeletal (A-Na Perp) (mm)	6.0	1.0	3.1	1.6 *
Mand. Skeletal (Pg-Na Perp) (mm)	12.2	-2.0	5.3	2.7 **
Wits Appraisal (mm)	-7.2	-1.0	1.0	-6.2 ******
* VERTICAL SKELETAL *				
FMA (MP-FH) (°)	28.1	26.0	5.0	0.4
MP - SN (°)	40.1	33.0	6.0	1.2 *
Palatal-Mand Angle (°)	31.9	28.0	6.0	0.7
Palatal-Occ Plane (PP-OP) (°)	7.5	10.0	4.0	-0.6
Mand Plane to Occ Plane (°)	24.4	17.4	5.0	1.4 *
Mx occlusal plane (MxOP-Na Perp) (°)	93.7	95.6	1.8	-1.1 *
* ANTERIOR DENTAL *				
U-Incisor Protrusion (U1-APo) (mm)	7.5	6.0	2.2	0.7
L1 Protrusion (L1-APo) (mm)	5.4	1.0	2.3	1.9 *
U1 - Palatal Plane (°)	118.0	110.0	5.0	1.6 *
U1 - Occ Plane (°)	54.5	57.5	7.0	-0.4
L1 - Occ Plane (°)	71.9	72.0	5.0	-0.0
IMPA (°)	83.7	95.0	7.0	-1.6 *
Subnasale - ST Menton	64.3	N/A	N/A	N/A
Soft tissue A pt to SnV (mm)	5.6	-2.0	N/A	N/A
Soft tissue B pt to SnV (mm)	0.3	-5.0	N/A	N/A
Upper lip anterior (ULA - Sn Vertical) (mm)	3.5	3.0	1.0	0.5
Lower lip anterior (LLA - Sn Vertical) (mm)	3.8	1.0	1.0	2.8 **
Soft tissue Lower lip - Sn-7 (mm)	83.2	N/A	N/A	N/A
Soft tissue Pogonion - Sn-7 (mm)	106.0	N/A	N/A	N/A

Figure 18.
The resolution of crowding was accomplished without proclination of incisors or periodontal compromise.

by finishing arches to refine occlusal details. For retention, permanent splints were placed in both the upper and lower arches, and an Essix® retainer was prescribed for nighttime use to ensure maintenance of the achieved results (**Figure 19**). This combination of traditional and digital approaches enabled predictable, personalized outcomes, significantly enhancing the patient's experience and optimizing clinical results. The comprehensive treatment plan successfully met all objectives, leaving the patient satisfied with the esthetic, functional, and masticatory outcomes. The total treatment duration was 30 months (**Figure 20**). Post-operative monitoring and follow-up are critical phases for the long-term success of orthognathic surgery. Digital technologies not only facilitate outcome evaluation but also provide predictive and corrective tools to further enhance treatment efficacy. Post-surgery, it is essential to monitor healing and evaluate the correspondence between planned and achieved results (**Figure 21**). Outcome verification and any discrepancies between planning workflows and surgical execution are analyzed using post-operative CBCT scans or traditional orthodontic radiographic kits (panoramic radiographs, lateral cephalograms, and posteroanterior (PA) cephalograms), facial scans or photographs, and dental scans [46, 47].

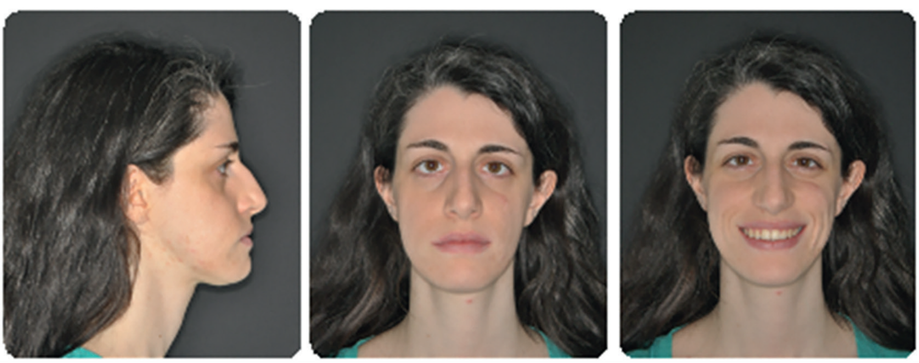


Figure 19.
Retention.

Figure 20.
Treatment duration.

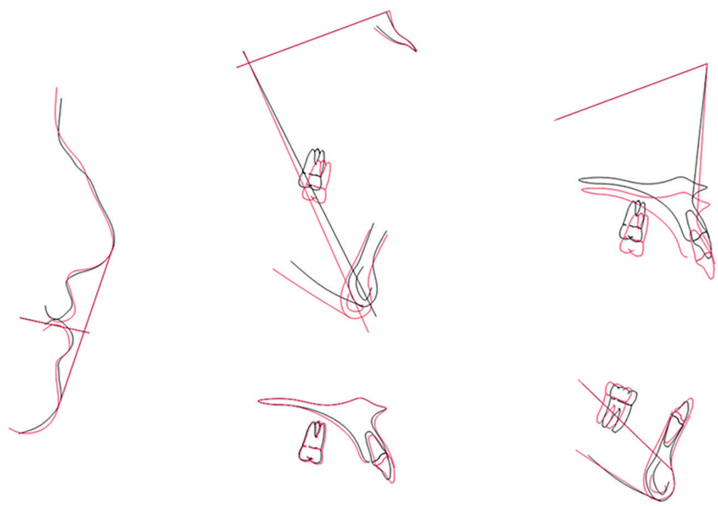


Figure 21.
Monitoring healing.

Our surgical protocols include the following follow-up procedures:

1. Initial follow-up (1–2 weeks post-operatively): Verification of incision healing and initial skeletal stability.

2. Intermediate follow-up (3–6 months): Evaluation of bone consolidation and adaptation of soft tissues.

3. Long-term assessment (1 year or more): Monitoring of skeletal stability and final esthetic results.

Surgical outcome stability is influenced by biomechanical, biological, and behavioral factors. Digital planning provides significant advantages in predicting and managing long-term stability.

11. Stability analysis

- Skeletal movements: Monitoring potential relapses through comparative analysis of pre- and post-operative 3D models.

- Soft tissue adaptation: Evaluation of soft tissue response relative to the new skeletal morphology.

- Dental occlusion: Occlusal control plays a vital role in overall stability.

11.1 Clinical studies

Numerous studies demonstrate that digital planning reduces relapse risk in patients with skeletal Class III malocclusion. Authors have highlighted that the use of customized surgical guides improves mandibular positioning accuracy, enhancing long-term stability [48, 49].

12. Conclusions

The application of a digitized workflow represents a true revolution in cranio-maxillofacial surgery, enabling precise planning and safe execution of complex procedures. Through the use of customized guides and advanced digital tools, predictable and optimized outcomes tailored to individual patient needs are ensured.

12.1 Enhancing treatment quality

- Operational precision: Planning and simulating each procedural phase minimizes errors and improves surgical outcomes.

- Reduced timelines: Digital processes, such as the production of customized surgical guides via 3D printing, shorten preparation and operative times.

- Minimized invasiveness: Detailed planning allows for more conservative approaches, limiting the impact on both soft and skeletal tissues.

- Lower complication rates: Advanced technologies enable more effective management of intra- and post-operative risks.

- Personalized treatment: Patients benefit from a highly tailored approach that accounts for their specific anatomical characteristics and esthetic expectations, increasing satisfaction and trust in the surgeon.

The landscape of cranio-maxillofacial surgery is undergoing dynamic evolution, driven by the integration of digital technologies. Innovations in diagnostics, planning, and clinical application provide new opportunities to enhance accuracy, efficiency, and safety in surgical interventions, paving the way for increasingly predictable and individualized outcomes.

12.2 Future perspectives

- Artificial intelligence (AI): AI applications promise to optimize surgical planning, providing more accurate simulations through machine learning algorithms.

- Augmented reality (AR) and virtual reality (VR): Emerging tools enable surgeons to visualize and interact with 3D models in real time during procedures.

- Robotic assistance: Robotic surgery, already used in some fields, could be further implemented to enhance precision and reduce invasiveness.

- Advanced imaging technologies: High-resolution imaging systems and dynamic scanning technologies may offer even more detailed visualization of craniofacial structures and soft tissues.

The future of cranio-maxillofacial surgery lies in the continued integration of digital technologies, with the potential to redefine standards of care. Advances toward more interactive, personalized, and precise approaches will not only improve clinical efficacy but also strengthen the surgeon's role as a guide in an increasingly patient-centered process.

Acknowledgements

True success is never achieved in isolation; it is the result of unwavering determination, the pursuit of excellence, and the support of a strong foundation. To my family, whose steadfast encouragement and belief in my journey have been my anchor, I owe my deepest gratitude. Your presence has been the silent force behind every milestone. As Aristotle wisely said, "*We are what we repeatedly do. Excellence, then, is not an act but a habit.*" This work is a testament to the relentless dedication to that principle, guided by a vision of continuous improvement and an unyielding commitment to progress. To my mentors, colleagues, and collaborators, who have inspired and challenged me to refine my skills and expand my horizons, thank you for sharing in this journey of growth and discovery. Together, we create not just success, but a legacy of excellence.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

SARPE	surgically assisted rapid palatal expansion
VTO	virtual treatment objectives
CBCT	cone beam computed tomography
BSSO	bilateral sagittal split osteotomy
3D	three-dimensional
CAD-CAM	computer-aided drafting-computer-aided manufacturing
FOV	field of view
AP	anteroposterior
SS	stainless steel
MARPE	microimplant-assisted rapid palatal expansion.

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