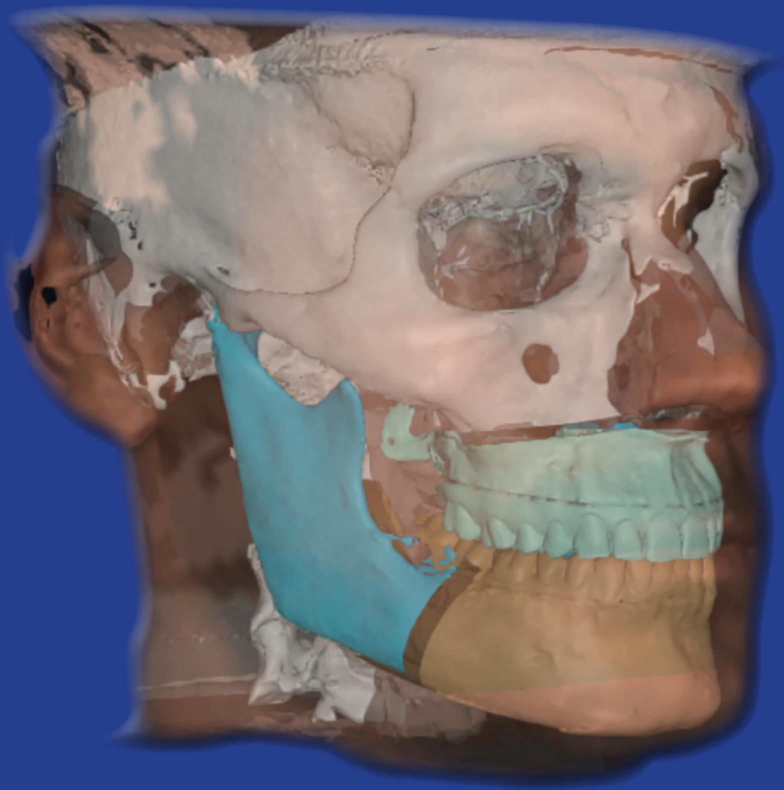
3D SURGICAL PLANNING IN ORTHOGNATHIC SURGERY



JEROEN LIEBREGTS

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Jeroen Henricus Franciscus Liebregts

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Jeroen Henricus Franciscus Liebregts
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Promotoren:
Prof. dr. T.J.J. Maal
Prof. dr. S.J. Bergé

Copromotor:
Dr. T. Xi

Manuscriptcommissie:
Prof. dr. D.J.O. Ulrich
Prof. dr. H. De Bruyn
Prof. dr. A.G. Becking (Amsterdam UMC)

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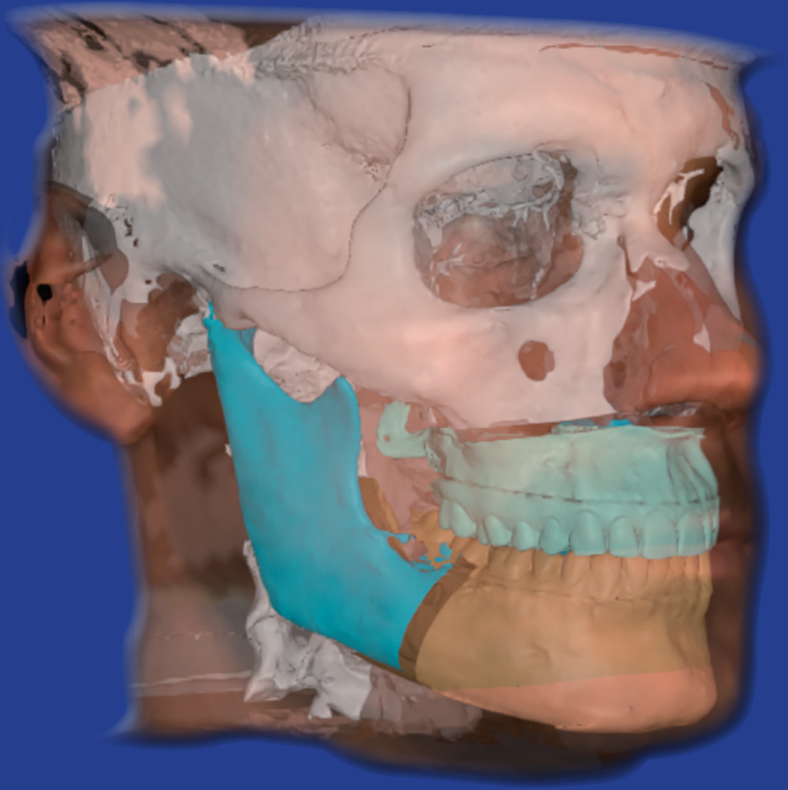

Chapter 1

General introduction

General introduction

Patients with severe malocclusion and malposition of teeth commonly have an underlying maxillofacial deformity (1). In order to achieve a sustainable treatment result, a jaw correction (orthognathic surgery) should be performed, mostly in combination with an orthodontic treatment (2-5). Such combined orthodontic-orthognathic treatment aims to achieve two interdigitating dental arches with an optimal occlusion and a harmonious facial profile.

In the second half of the past century, combined tooth and jaw corrections were performed primarily based on the findings of a cephalometric analysis (6-10). Obtaining a Class I occlusion has been the focus of treatment for many decades. In cases where a Class I occlusion could not be achieved by tooth displacements alone, orthognathic surgery was considered as a means of achieving this occlusion at the end of the treatment process. Clinicians and patients often experienced changes in the facial profile following orthognathic surgery as a positive side effect (1, 11-13).

In recent decades, the emphasis of a combined orthodontic and orthognathic treatment has increasingly moved to combining improved function and optimized aesthetics, in addition to achieving a stable dental occlusion (12, 14, 15). A paradigm shift in treatment philosophy has taken place, from a monodisciplinary orthodontic treatment (correction of teeth) to a multidisciplinary orthofacial correction (correction of facial relationship). Hereby, the treatment team not only focuses on the occlusion, but also examines the bony structures and the soft tissues of the face (15-21). An optimal functional and aesthetic result can only be achieved when the triad of bone structures (e.g., bone and cartilage), soft tissue (e.g., skin, connective tissues, fat, and muscles), and teeth are in harmony with each other. Thus, a thorough understanding of the interactions between these different structures is of great importance in planning and implementing an orthodontic-orthognathic treatment plan. After all, the correction of teeth and jaws has a major influence on the facial soft tissues and subsequently on the facial appearance of the patient (12, 19, 21).

Orthognathic surgery

Hypoplasia of the mandible (underdevelopment of the lower jaw) is the most common developmental disorder of the facial skeleton in the Netherlands (22). People with mandibular hypoplasia generally have a convex facial profile, retruded chin, enlarged overjet, and Class II cuspidate and molar occlusion. For this group of patients, bilateral sagittal split osteotomy (BSSO) advancement surgery can move the tooth-bearing part of the lower jaw anteriorly to reduce the overjet and to move the retruded chin anteriorly.

Over the past decade, fewer monomaxillary osteotomies (BSSO or Le Fort I osteotomy) and more bimaxillary osteotomies (combined upper jaw and lower jaw osteotomy, i.e., BSSO and Le Fort I osteotomy) have been performed (23-26). This trend is associated with the following factors:

- Patients have become more critical and demanding with regard to the aesthetics of the face. In monomaxillary osteotomy, the repositioning of the jaw is dictated by the occlusion, and the subsequent changes of the soft tissue facial profile are therefore limited. In bimaxillary osteotomy, both jaws can be moved more freely to accommodate the desired facial changes, beside obtaining an optimal occlusion (27). Hence, a bimaxillary osteotomy allows more freedom than a monomaxillary osteotomy to optimize facial aesthetics to meet the demands of the patient.
- The aesthetic preference in western society has evolved over the past decades from a straight (neutral) profile to a slight ante face with accentuated jaw lines (28). Creating a slight ante face makes the face look more youthful and provides a rejuvenating effect (29). To accomplish this, both maxillary and mandibular transposition is necessary.
- The postoperative result after a bimaxillary osteotomy is described to be more stable than after a monomaxillary osteotomy. In particular, among patients with an anterior open bite, bimaxillary osteotomies are less prone to postoperative skeletal relapse (30-32).
- In western society, an increasing number of patients are being diagnosed with obstructive sleep apnea syndrome (OSAS). One of the main causes of OSAS is a narrowed upper airway or a lack of space behind the palate, the base of the tongue, and/or in the oro- and hypopharynx. By moving both the maxilla and mandible anteriorly, more space is created in the upper airway to improve the airflow. A bimaxillary osteotomy is the treatment of choice for severe OSAS in the most recent Dutch national guideline for the management of OSAS (33, 34).

In summary, a bimaxillary osteotomy offers more functional and aesthetical options to achieve a sustainable postoperative result. However, more than in monomaxillary procedures, the success of a bimaxillary osteotomy depends on a meticulous preoperative planning and an accurate transfer of the planned jaw movements to the patient in the operation theater (25, 26).

Furthermore, there is an ongoing debate on the sequence of the osteotomies in bimaxillary surgery. It may seem logical to have the maxilla as a stable reference to position the movable and unstable mandible in the case of maxilla-first sequencing. However, in some cases, such as where counterclockwise (CCW) rotation of the occlusal plane is mandatory, mandible-first surgery may be preferred to avoid an anterior open bite (35). Despite several publications, most of which are retrospective case series, little scientific evidence and clinical consensus exist regarding the sequencing of bimaxillary surgery (36).

3D virtual fusion model of the face

In the 20th century, the diagnosis, planning, and postoperative follow-up of surgical procedures were mainly based on clinical investigation, 2D cephalometric analysis, and try-outs with dental plaster models. Although these methods provide helpful information, it is difficult to precisely predict 3D movements of bony jaw segments and the subsequent facial soft tissue changes.

Conventional cephalometric planning primarily focuses on establishing a proper occlusion and is fairly accurate in predicting the soft tissue projection in the midsagittal plane. However, no paramedian or lateral soft tissue information can be derived from lateral skull X-rays, which is a major drawback of conventional 2D cephalometry in the soft tissue planning of bimaxillary osteotomies (7, 10).

Since contemporary orthognathic surgery is increasingly focusing on the creation of a 3D harmonious soft tissue face profile, rather than just on a stable occlusion, clinicians are increasingly facing the limitations of 2D cephalometric planning.

In 2005, a 3D Lab was established at the Department of Oral & Maxillofacial Surgery in the Radboud University Nijmegen Medical Center (Radboudumc). Its main aim is to enhance the accuracy of 3D imaging and its implementation in the daily practice of orthodontics and maxillofacial surgery. An infrastructure has been created to establish a close collaboration between clinicians and technicians, which has enabled strong and efficient interaction between the technical and medical researchers of the 3D Lab and professionals both from the orthodontic and the oral maxillofacial surgery departments.

In the past decade, the imaging of skeletal maxillofacial structures, facial soft tissue, and dentition has undergone major developments. 3D imaging techniques such as cone beam computed tomography (CBCT), stereophotogrammetry (3D photo), and intra-oral scans have increasingly become the gold standard in diagnosing maxillofacial abnormalities (37-39). Using imaging fusion techniques, datasets derived from CBCT, stereophotogrammetry, and intra-oral scans can be combined to create a detailed 3D augmented virtual model of the viscerocranium (Figure 1).

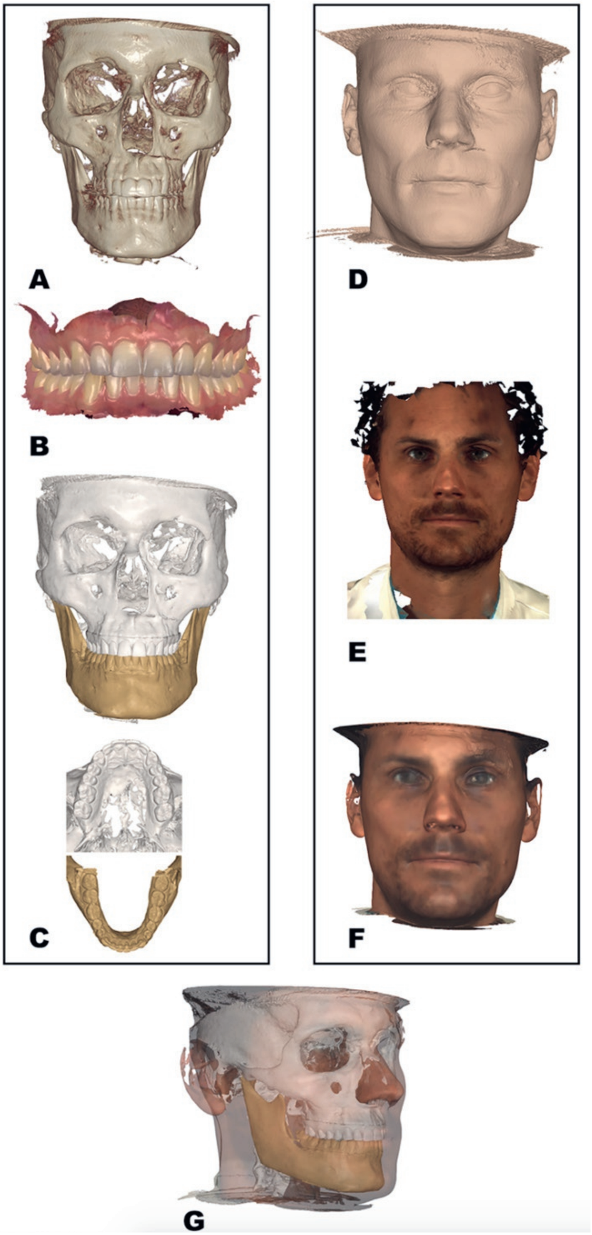

Figure 1: Overview of the construction of an augmented model.

A: The first CBCT scan of the complete skull: the ‘extended height CBCT’.
B: The intra-oral scan of the dentition.
C: The extended height CBCT containing the accurate dentition from the intra-oral scan.
D: 3D reconstruction of the soft tissue from the extended height CBCT.
E: 3D stereophotogrammetry photo.
F: Fusing 3D stereophotogrammetry with correct skin color and texture with the CBCT.
G: 3D fusion model created for the patient with lifelike characteristics of bone structures, soft tissue, and dentition.

The CBCT serves as the basis for the 3D augmented head model. It contains information on the bone structures, the thickness of the overlying soft tissue, and the position of teeth. Due to the scattering of X-rays by orthodontic brackets and metal dental restorative materials, detailed dental surfaces and occlusion are poorly represented on the CBCT. Accurate 3D digitized information of the dentition can be obtained by scanning conventional dental impressions or by making an intra-oral scan. This information can be registered on the CBCT with an arithmetic algorithm to replace the artifacts with accurate dental information (40). By subsequently fusing an acquired 3D stereophotogrammetry containing the color and texture of the skin with the CBCT, a photo-realistic 3D augmented head model is created with lifelike characteristics of bone structures, soft tissue, and dentition (Figure 1).

This virtual 3D augmented head model can be enlarged, reduced, rotated, and moved to visualize dentofacial deformities and to facilitate surgical planning. In addition, it is possible to create 2D cross-sections in any desired direction on the 3D model to identify important anatomical structures such as nerves and blood vessels. Most important for orthognathic surgery, the 3D augmented head model enables the surgeon to create virtual osteotomy lines, establish a virtual occlusion, and move the different jaw segments to change the overlying soft tissue profile with specialized surgical planning software. In this way, a 3D simulation of the postoperative face can be simulated prior to surgery, based on the intended movement of the jaws and the final occlusion. This means that a soft tissue oriented orthognathic planning can be performed. This simulation tool is helpful in the process of shared decision-making as it can provide the clinicians and patients with better insight into the anticipated outcomes of various treatment options.

3D virtual surgical planning

The fundamentals for accomplishing an accurate 3D virtual surgical planning and simulation are the creation of an accurate 3D fusion model of the head with information on bony structures, soft tissue, and dentition, and an accurate soft tissue simulation algorithm.

Several companies have developed dedicated software in which a virtual 3D planning for orthognathic surgery can be performed, such as Maxilim® (Medicim NV, Mechelen, Belgium), SurgiCase®, MiMics®, PROPLAN CMF® (Materialize NV, Leuven, Belgium), IPS Gate® (KLS Martin, Tüttlingen, Germany), SIMPLANT® (Dentsply, Mannheim, Germany), 3dMD vultus® (3dMD, Atlanta, USA), and Dolphin® (Dolphin Imaging & Management Solutions, CA, USA) (20, 41-49).

Such software enables the creation of a 3D augmented head model using 3D image data from different imaging modalities. However, the various software packages differ in the degree of automation, and thus the experienced user-friendliness. Virtual osteotomies can be performed on the patient's 3D model. Jaw movements can then be performed in the virtual environment. Typically, jaw movements can be categorized into translations (forward/backward, cranial/caudal, and left/right) and rotations (pitch, roll, and yaw) (Figure 2).

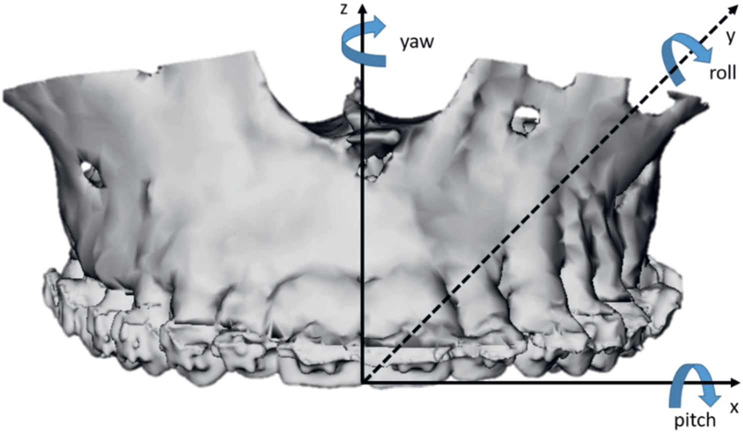

Figure 2: Overview of the rotations used in the virtual 3D planning software.

Most 3D planning software packages for orthognathic surgery automatically calculate the movements of the soft tissues in response to the transformed bone segments. According to the soft tissue oriented orthognathic planning, the final displacement of each jaw segment is determined based on the simulated 3D soft tissue facial profile. Thus, the reliability of the virtual 3D soft tissue planning and the surgical outcome depends on the ability of the software program to make an accurate soft tissue prediction.

Simulation of the facial profile

Developments in 3D visualization techniques in the late 1980s led to the creation of software programs that could reconstruct anatomical models in 3D (50). At the end of the 1990s, various algorithms were introduced to predict 3D facial soft tissue changes based on the displacement of the underlying bone structures (20). These algorithms are based on two types of models: a biomechanical model (51), and a statistical model (52, 53).

Biomechanical simulation models

The biomechanical model consists of applying physical mechanics to the movement of the soft tissue. The first biomechanical simulation model was developed based on an extensive study of movements of living organisms, after which it was translated into a mathematical

simulation model (54). By using different tissue-dependent conversion factors (of skin, fat, muscle, and connective tissue), a prediction can be made as to how a bone displacement can lead to changes in the shape of the soft tissues. The most commonly used biomechanical models are the following four models:
- linear finite element model (FEM)
- non-linear finite element model (NFEM)
- mass-spring model (MSM)
- mass-tensor model (MTM)

The FEM and NFEM models are based on the arithmetic properties of different tissue types. This involves clinical investigations into how different types of tissues react under stress and tension. The link between bone and soft tissue movement is also included in these models. Although the FEM is quite laborious and time-consuming to develop, the simulations correspond well with the actual situation (55). Because of the complicated calculations required to model the changes, the application of this model requires large computing power. Soft tissue simulation using the FEM and the NFEM, therefore, takes a relatively long time (56).

In the MSM model, it is assumed that every piece of tissue has its own mass. These points are linked using small virtual rubber bands so that one large surface is created. When the jaw parts are moved, the computer calculates the movement of the soft parts utilizing the different mass points and the mutual connections (57). The advantage of the MSM is that it is much faster than the FEM, because the calculations are less complex. On the other hand, the MSM is far less accurate than the FEM, as it is not linked to a biomechanical origin.

Finally, the MTM was introduced, which can be seen as an intermediate form of the FEM and the MSM. The MTM has the advantage of the FEM (accurate simulation) combined with that of the MSM (fast calculation). With the MSM, the surgeon can immediately see a 3D soft simulation after the jaw segments have been moved, without the need to wait for computer calculations. The MTM makes a real-time simulation of soft tissue changes possible in the 3D planning of orthognathic surgery (58).

Statistical simulation models

The statistical model is based on principal component analysis (PCA). Karl Pearson, an English mathematician and statistician, introduced PCA in 1901. PCA is a multi-variation analysis method in statistics to group and distill a large amount of data into a smaller number of relevant quantities. This is mainly referred to as data reduction and data organization. PCA is a widely used tool in modern data analysis in various disciplines, such as neuroscience, metrology, oceanography, and graphic design (59). The large amounts of data (big data) with multiple variables are arranged and reduced to the main components (principal components), each of which has a certain characteristic and meaning. An essential condition for achieving a reliable prediction with the statistical model is that there is a large amount of data available to set up and validate the statistical model (55).

To summarize, the main challenge in contemporary 3D virtual planning of orthognathic surgery is establishing an accurate and clinically-validated algorithm to simulate the postoperative soft tissue facial profile based on the jaw movements and final occlusion.

Objective of this thesis

The main objective of this thesis is to investigate how 3D planning in orthognathic surgery can be optimized and fully utilized. The thesis consists of two parts. Part one relates to the evaluation of the soft tissue prediction accuracy in 3D virtual surgical planning. Part two focuses on the surgical achievability of 3D planned jaw movements.

The following research questions are addressed in this thesis:
Part 1: Accuracy in 3D soft tissue simulation prediction

1. What is the accuracy of the MTM-based 3D facial soft tissue simulation in BSSO mandibular advancement and bimaxillary osteotomies?
2. Can PCA be applied to evaluate the 3D changes in soft tissue facial profile following orthognathic surgery?

Part 2: Surgical achievability of 3D virtual surgical planning

1. Is it possible to quantify surgical jaw movements without the use of conventional landmark-based cephalometric analysis?
2. How does the sequencing of bimaxillary osteotomies affect the achievability and stability of the 3D planned bimaxillary surgeries?

Thesis outline

Since 2007, 3D virtual surgical planning (VSP) has been an important cornerstone in orthognathic surgery within the Department of Oral & Maxillofacial Surgery at Radboudumc. The establishment of the 3D Lab in conjunction with the installation of a stereophotogrammetrical camera setup (3dMDface™ System, 3dMD Ltd, Atlanta, USA) and CBCT facilitated the transition of the conventional 2D occlusion-centered planning to the 3D soft tissue centered planning of orthognathic surgery (60, 61). A prospective, clinical-based research protocol has been set up to document the orthognathic patients prior to surgery and to evaluate the surgical results. In this way, 3D data of the soft tissue, bone tissue, and dentition of orthognathic patients can be systematically obtained to enable the evaluation of surgical results and to optimize 3D VSP, forming the basis of this thesis.

To determine the influences of jaw displacements on the postoperative soft tissue profile following orthognathic surgery, an accurate simulation of the soft tissue changes in 3D VSP is required. Maxilim® software has been adopted as a tool for 3D VSP. In Maxilim®, the aforementioned MTM is used to create a 3D simulation in real-time of the final facial soft tissue profile based on the planned jaw movements. In addition, Maxilim® allows the setup of the final occlusion using a virtual occlusion tool. To attain a satisfactory postoperative result, it is desirable that the actual soft tissue facial profile is in accordance with the soft tissue simulation in 3D VSP. The predictability of the postoperative soft tissue changes that accompany the planned skeletal movements are evaluated in **Chapter 2** for BSSO mandibular advancement surgery and in **Chapter 3** for bimaxillary surgery. The influences of patient-related and surgery-related factors on the accuracy of 3D soft tissue simulations of nasal width changes in bimaxillary osteotomies are evaluated in **Chapter 4**.

To evaluate the surgery-related facial soft tissue changes, 2D landmark-based cephalometric measurements have been used as a standard in the clinic and research. **Chapter 5** presents a new 3D photogrammetry-based automated method for the quantification and evaluation of variations in soft tissue facial profiles using PCA.

Besides the accuracy of the 3D soft tissue simulation, another important issue in obtaining a favorable postoperative facial outcome is the accuracy of transferring the 3D planned bony movements to the patient. Despite the emergence of real-time intra-operative navigation tools, the interocclusal wafer remains the most commonly used device to transfer the 3D VSP to the patient in the operating theater. Likewise, interocclusal splints have been used as a standard in orthognathic procedures at the Radboudumc.

To assess the surgical accuracy in transferring the 3D planned jaw displacements to patients, conventional approaches require the use of cephalometric landmarks to quantify differences between the preoperative planning and the actual surgical result. An inherent shortcoming of the landmark-based analysis is the summation of landmark identification errors as a result of the need to identify the same landmarks multiple times on different sets of image data. This increasing error impedes a correct interpretation of the cephalometric analysis, particularly when the surgical error is in the range of the landmark identification error. To optimize the current method of assessing the accuracy of orthognathic surgery, **Chapter 6** presents a new approach (the OrthoGnathicAnalyser) to quantify the surgical accuracy, eliminating the need to identify cephalometric landmarks multiple times.

As said earlier, the surgical approach used during bimaxillary surgery, either the maxillary-first or the mandibular-first sequence, has been a controversial topic in the field of orthognathic surgery. Theoretically, the sequencing of bimaxillary surgeries also affects surgical accuracy. By using the clinically-validated OrthoGnathicAnalyser, **Chapter 7** evaluates the effects of sequencing in bimaxillary osteotomies on the achievability of the 3D virtually planned repositioning of the maxilla and mandible in bimaxillary osteotomies. **Chapter 8** focuses on the influence of sequencing in bimaxillary osteotomies on the postoperative stability of 3D virtually planned repositioning of the maxilla and mandible. By pooling similar data from the Oral and Maxillofacial Surgery Research Unit at the University of Southern Denmark in Odense, **Chapter 9** describes the effects of sequencing in bimaxillary osteotomies on the achievability of the 3D planned jaw movements in a larger multi-center study population.

Finally, the related developments and clinical implications derived from the aforementioned studies and future perspectives are appraised in **Chapter 10**.

References

1. Bell R, Kiyak HA, Joondeph DR, McNeill RW, Wallen TR. Perceptions of facial profile and their influence on the decision to undergo orthognathic surgery. American journal of orthodontics. 1985;88(4):323-32.
2. Schendel SA, Epker BN. Results after mandibular advancement surgery: an analysis of 87 cases. J Oral Surg. 1980;38(4):265-82.
3. Proffit WR, Phillips C, Turvey TA. Stability following superior repositioning of the maxilla by LeFort I osteotomy. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 1987;92(2):151-61.
4. Proffit WR, Phillips C, Dann Ct, Turvey TA. Stability after surgical-orthodontic correction of skeletal Class III malocclusion. I. Mandibular setback. The International journal of adult orthodontics and orthognathic surgery. 1991;6(1):7-18.
5. Arnett GW. A redefinition of bilateral sagittal osteotomy (BSO) advancement relapse. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 1993;104(5):506-15.
6. Holdaway RA. A soft-tissue cephalometric analysis and its use in orthodontic treatment planning. Part I. American journal of orthodontics. 1983;84(1):1-28.
7. Lundstrom A, Lundstrom F, Lebret LM, Moorrees CF. Natural head position and natural head orientation: basic considerations in cephalometric analysis and research. European journal of orthodontics. 1995;17(2):111-20.
8. Donatsky O, Bjorn-Jorgensen J, Holmqvist-Larsen M, Hillerup S. Computerized cephalometric evaluation of orthognathic surgical precision and stability in relation to maxillary superior repositioning combined with mandibular advancement or setback. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 1997;55(10):1071-9; discussion 9-80.
9. Hilgers ML, Scarfe WC, Scheetz JP, Farman AG. Accuracy of linear temporomandibular joint measurements with cone beam computed tomography and digital cephalometric radiography. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2005;128(6):803-11.
10. Gateno J, Xia JJ, Teichgraeber JF. New 3-dimensional cephalometric analysis for orthognathic surgery. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2011;69(3):606-22.
11. Heldt L, Haffke EA, Davis LF. The psychological and social aspects of orthognathic treatment. American journal of orthodontics. 1982;82(4):318-28.

12. Joss CU, Joss-Vassalli IM, Kiliaridis S, Kuijpers-Jagtman AM. Soft tissue profile changes after bilateral sagittal split osteotomy for mandibular advancement: a systematic review. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2010;68(6):1260-9.
13. Iizuka T, Eggensperger N, Smolka W, Thüer U. Analysis of soft tissue profile changes after mandibular advancement surgery. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology. 2004;98(1):16-22.
14. Eggensperger NM, Lieger O, Thuer U, Iizuka T. Soft tissue profile changes following mandibular advancement and setback surgery an average of 12 years postoperatively. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2007;65(11):2301-10.
15. Nadjmi N, Tehranchi A, Azami N, Saedi B, Mollemans W. Comparison of soft-tissue profiles in Le Fort I osteotomy patients with Dolphin and Maxilim softwares. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2013;144(5):654-62.
16. Liebregts JH, Timmermans M, De Koning MJ, Berge SJ, Maal TJ. Three-dimensional facial simulation in bilateral sagittal split osteotomy: a validation study of 100 patients. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2015;73(5):961-70.
17. Lee HJ, Park HS, Kyung HM, Kwon TG. Soft tissue changes and skeletal stability after modified quadrangular Le Fort I osteotomy. International journal of oral and maxillofacial surgery. 2015;44(3):356-61.
18. Khamashta-Ledezma L, Naini FB. Prospective assessment of maxillary advancement effects: maxillary incisor exposure, and upper lip and nasal changes. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics. 2015;147(4):454-64.
19. San Miguel Moragas J, Van Cauteren W, Mommaerts MY. A systematic review on soft-to-hard tissue ratios in orthognathic surgery part I: Maxillary repositioning osteotomy. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery. 2014.
20. Plooij JM, Maal TJ, Haers P, Borstlap WA, Kuijpers-Jagtman AM, Berge SJ. Digital three-dimensional image fusion processes for planning and evaluating orthodontics and orthognathic surgery. A systematic review. International journal of oral and maxillofacial surgery. 2011;40(4):341-52.
21. Alves PV, Mazucheli J, Vogel CJ, Bolognese AM. How the lower face soft tissue changes after mandibular advancement or setback. The Journal of craniofacial surgery. 2008;19(3):593-8.
22. Stoelinga PJ, Kuijpers-Jagtman AM. [Orthodontic-surgical treatment of patients with mandibular hypoplasia]. Ned Tijdschr Tandheelkd. 2002;109(5):172-7.

23. Liebregts J, Xi T, Timmermans M, de Koning M, Berge S, Hoppenreijs T, et al. Accuracy of three-dimensional soft tissue simulation in bimaxillary osteotomies. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery. 2015;43(3):329-35.
24. Schwartz HC. Does computer-aided surgical simulation improve efficiency in bimaxillary orthognathic surgery? International journal of oral and maxillofacial surgery. 2014;43(5):572-6.
25. Sun Y, Luebbers HT, Agbaje JO, Lambrichts I, Politis C. The accuracy of image-guided navigation for maxillary positioning in bimaxillary surgery. The Journal of craniofacial surgery. 2014;25(3):1095-9.
26. Jones RM, Khambay BS, McHugh S, Ayoub AF. The validity of a computer-assisted simulation system for orthognathic surgery (CASSOS) for planning the surgical correction of class III skeletal deformities: single-jaw versus bimaxillary surgery. International journal of oral and maxillofacial surgery. 2007;36(10):900-8.
27. Haas Jr OL, Becker OE, de Oliveira RB. Computer-aided planning in orthognathic surgery-systematic review. International journal of oral and maxillofacial surgery. 2014.
28. Hernandez-Alfaro F. Upper incisor to Soft Tissue Plane (UI-STP): a new reference for diagnosis and planning in dentofacial deformities. Med Oral Patol Oral Cir Bucal. 2010;15(5):e779-81.
29. Lorente C, Hernandez-Alfaro F, Perez-Vela M, Lorente P, Lorente T. Surgical-orthodontic approach for facial rejuvenation based on a reverse facelift. Progress in orthodontics. 2019;20(1):34.
30. Liebregts J, Baan F, van Lierop P, de Koning M, Berge S, Maal T, et al. One-year postoperative skeletal stability of 3D planned bimaxillary osteotomies: maxilla-first versus mandible-first surgery. Sci Rep. 2019;9(1):3000.
31. Joss CU, Vassalli IM. Stability after bilateral sagittal split osteotomy advancement surgery with rigid internal fixation: a systematic review. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2009;67(2):301-13.
32. Hoppenreijs TJ, Freihofer HP, Stoelinga PJ, Tuinzing DB, van't Hof MA, van der Linden FP, et al. Skeletal and dento-alveolar stability of Le Fort I intrusion osteotomies and bimaxillary osteotomies in anterior open bite deformities. A retrospective three-centre study. International journal of oral and maxillofacial surgery. 1997;26(3):161-75.
33. Bettega G, Pepin JL, Orliaguet O, Levy P, Raphael B. [Surgery and obstructive sleep apnea syndrome: indications and precautions]. Rev Stomatol Chir Maxillofac. 2002;103(3):181-7.
34. Specialisten FM. Richtlijn: Obstructief slaapapneu (OSA) bij volwassenen. 06-2018.
35. Perez D, Ellis E, 3rd. Sequencing bimaxillary surgery: mandible first. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2011;69(8):2217-24.
36. Borba AM, Borges AH, Ce PS, Venturi BA, Naclerio-Homem MG, Miloro M. Mandible-first sequence in bimaxillary orthognathic surgery: a systematic review. International journal of oral and maxillofacial surgery. 2016;45(4):472-5.
37. Abduo J, Elseyoufi M. Accuracy of Intraoral Scanners: A Systematic Review of Influencing Factors. Eur J Prosthodont Restor Dent. 2018;26(3):101-21.

38. Wen YF, Wong HM, McGrath CP. Longitudinal Photogrammetric Analysis of Soft Tissue Facial Changes: A Systematic Review of the Literature and a Summary of Recommendations. The Journal of craniofacial surgery. 2015;26(6):1830-4.
39. Weiss R, 2nd, Read-Fuller A. Cone Beam Computed Tomography in Oral and Maxillofacial Surgery: An Evidence-Based Review. Dent J (Basel). 2019;7(2).
40. Baan F, Bruggink R, Nijsink J, Maal TJJ, Ongkosuwito EM. Fusion of intra-oral scans in cone-beam computed tomography scans. Clinical oral investigations. 2020.
41. Shafi MI, Ayoub A, Ju X, Khambay B. The accuracy of three-dimensional prediction planning for the surgical correction of facial deformities using Maxilim. International journal of oral and maxillofacial surgery. 2013;42(7):801-6.
42. Yang J, Hou M, Song D, Chen W, Han D, Yu T, et al. [The research of SurgiCase CMF software in surgical simulation and prediction for mandibular asymmetry]. Zhonghua Zheng Xing Wai Ke Za Zhi. 2015;31(2):118-22.
43. Asif MK, Nambiar P, Ibrahim N, Al-Amery SM, Khan IM. Three-dimensional image analysis of developing mandibular third molars apices for age estimation: A study using CBCT data enhanced with Mimics & 3-Matics software. Leg Med (Tokyo). 2019;39:9-14.
44. Knoops PGM, Borghi A, Breakey RWF, Ong J, Jeelani NUO, Bruun R, et al. Three-dimensional soft tissue prediction in orthognathic surgery: a clinical comparison of Dolphin, ProPlan CMF, and probabilistic finite element modelling. International journal of oral and maxillofacial surgery. 2019;48(4):511-8.
45. Tang TH, Song M, Niu XY, Pan JS. [Preliminary study of Simplant software in mandibular molar implantation]. Shanghai Kou Qiang Yi Xue. 2016;25(4):484-6.
46. Nord F, Ferjencik R, Seifert B, Lanzer M, Gander T, Matthews F, et al. The 3dMD photogrammetric photo system in cranio-maxillofacial surgery: Validation of interexaminer variations and perceptions. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery. 2015;43(9):1798-803.
47. Van den Bempt M, Liebregts J, Maal T, Berge S, Xi T. Toward a higher accuracy in orthognathic surgery by using intraoperative computer navigation, 3D surgical guides, and/or customized osteosynthesis plates: A systematic review. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery. 2018;46(12):2108-19.
48. Olate S, Zaror C, Mommaerts MY. A systematic review of soft-to-hard tissue ratios in orthognathic surgery. Part IV: 3D analysis - Is there evidence? Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery. 2017;45(8):1278-86.
49. Lin HH, Lo LJ. Three-dimensional computer-assisted surgical simulation and intraoperative navigation in orthognathic surgery: a literature review. J Formos Med Assoc. 2015;114(4):300-7.
50. Vannier MW, Gado MH, Marsh JL. Three-dimensional display of intracranial soft-tissue structures. AJNR Am J Neuroradiol. 1983;4(3):520-1.
51. Koch RM, Gross, M.H, Carls, F.R., von Buren, D.F., Fankhauser, G., Parish, Y.I.H. . Simulating facial surgery using finite element models. Proc of SIGGRAPH 1996:421-8.

52. Claes P, Vandermeulen D, De Greef S, Willems G, Suetens P. Craniofacial reconstruction using a combined statistical model of face shape and soft tissue depths: methodology and validation. Forensic science international. 2006;159 Suppl 1:S147-58.
53. Claes P, Liberton DK, Daniels K, Rosana KM, Quillen EE, Pearson LN, et al. Modeling 3D facial shape from DNA. PLoS Genet. 2014;10(3):e1004224.
54. Payan Y, Chabanas M, Pelorson X, Vilain C, Levy P, Luboz V, et al. Biomechanical models to simulate consequences of maxillofacial surgery. C R Biol. 2002;325(4):407-17.
55. Mollemans W, Schutyser F, Nadjmi N, Maes F, Suetens P. Predicting soft tissue deformations for a maxillofacial surgery planning system: from computational strategies to a complete clinical validation. Medical image analysis. 2007;11(3):282-301.
56. Maki K, Inou N, Takanishi A, Miller AJ. Computer-assisted simulations in orthodontic diagnosis and the application of a new cone beam X-ray computed tomography. Orthodontics & craniofacial research. 2003;6 Suppl 1:95-101; discussion 79-82.
57. Ulusoy I, Akagunduz E, Sabuncuoglu F, Gorgulu S, Ucok O. Use of the dynamic volume spline method to predict facial soft tissue changes associated with orthognathic surgery. Oral surgery, oral medicine, oral pathology, oral radiology, and endodontics. 2010;110(5):e17-23.
58. Mollemans W, Schutyser F, Nadjmi N, Suetens P. Very fast soft tissue predictions with mass tensor model for maxillofacial surgery planning systems. Int Congr Ser. 2005;1281:491-6.
59. Jolliffe IT, Cadima J. Principal component analysis: a review and recent developments. Philos Trans A Math Phys Eng Sci. 2016;374(2065):20150202.
60. Rangel FA, Maal TJJ, de Koning MJJ, Bronkhorst EM, Berge SJ, Kuijpers-Jagtman AM. Integration of digital dental casts in cone beam computed tomography scans-a clinical validation study. Clinical oral investigations. 2018;22(3):1215-22.
61. Rangel FA, Maal TJ, Berge SJ, Kuijpers-Jagtman AM. Integration of digital dental casts in cone-beam computed tomography scans. ISRN Dent. 2012;2012:949086.

Chapter 2

Three-dimensional facial simulation in bilateral sagittal split osteotomy, a validation study of 100 patients.

Liebregts JHF, Timmermans M, De Koning MJ, Bergé SJ, Maal TJ.

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Abstract

Purpose: Three-dimensional (3D) virtual planning of orthognathic surgery in combination with 3D soft tissue simulation allows the surgeon and the patient to assess the 3D soft tissue simulation. This study was conducted to validate the predictability of the mass tensor model soft tissue simulation algorithm combined with cone-beam computed tomographic (CBCT) imaging for patients who underwent mandibular advancement using a bilateral sagittal split osteotomy (BSSO).

Materials and Methods: One hundred patients were treated with a BSSO according to the Hunsuck modification. The pre- and postoperative CBCT scans were matched and the mandible was segmented and aligned. The 3D distance maps and 3D cephalometric analyses were used to calculate the differences between the soft tissue simulation and the actual postoperative results. Other study variables were age, gender, and amount of mandibular advancement or rotation.

Results: For the entire face, the mean absolute error was 0.9 ± 0.3 mm, the mean absolute 90th percentile was 1.9 mm, and for all 100 patients the absolute mean error was less than or equal to 2 mm. The subarea with the least accuracy was the lower lip area, with a mean absolute error of 1.2 ± 0.5 mm. No correlation could be found between the error of prediction and the amount of advancement or rotation of the mandible or age or gender of the patient.

Conclusion: Overall, the soft tissue prediction algorithm combined with CBCT imaging is an accurate model for predicting soft tissue changes after mandibular advancement. Future studies will focus on validating the mass tensor model soft tissue algorithm for bimaxillary surgery.

Introduction

The predictability of soft-tissue simulation became one of the most important research items concerning orthognathic surgery since surgeons and orthodontists have shifted their attention from occlusion-based planning to soft-tissue-based planning [1,2]. The recent introduction of 3D virtual planning of orthognathic surgery in combination with 3D soft-tissue simulation has been a major step forward towards real-time planning. For the surgeon, orthodontist and patient, 3D soft-tissue simulation makes it possible to assess 3D changes in a real-time environment allowing quick adaptations to the treatment planning when presented with an unfavorable soft-tissue simulation. Changes in the frontal view due to surgical corrections of the mandible and/or maxilla in the midline can now be an integrated part of the decision making process.

Up till today, no long-term validation study for soft-tissue simulation predictability using CBCT imaging has been published with a large number of patients undergoing a single type of orthognathic operation.

The aim of this study was to assess the accuracy of the Mass Tensor Model algorithm used in Maxilim® software (Medicim NV, Mechelen, Belgium) for simulation of surgery on CBCT images. The influence of patients' age and sex, the amount of mandibular advancement and rotation were independently assessed in order to explain the possible discrepancies.

Material and Methods

Patients

One hundred patients (35 male and 65 female) were included in this study. All patients underwent a mandibular advancement using a bilateral sagittal split osteotomy (BSSO) according to the Hunsuck Modification [3] between January 2007 and December 2010 at the department of Oral and Maxillofacial surgery, Radboud University Medical Centre. This study was conducted under the ethics committee approval (study protocol (181/2005)). All patients were older than 13 years with an average age of 31,6 years at the time of surgery (range 13-68 years). Two weeks prior to surgery a CBCT-scan was acquired. Furthermore, for all patients a postoperative CBCT scan was acquired at least six months after surgical correction (mean period: 13,4 months after surgery); thus, skeletal relapse was not a factor.

Inclusion criteria were a non-syndromic mandibular hypoplasia, patients undergo orthognathic surgery at het author's center, a signed informed consent and the availability of an extended height CBCT scan before and at least six months after surgery.

The exclusion criteria were a chin support used during CBCT-scanning, previous history of orthognathic surgery, simultaneously performed other orthognathic procedures including chin osteotomy, presence of orthodontic appliances when the postoperative CBCT-scan was made, patients who were edentulous, the absence of upper incisors and/or lower incisors and extensive restorative dental work after surgery.

Image acquisition

The extended height CBCT scan was acquired using the i-CAT™3D imaging System (Imaging Sciences International, Hatfield, PA, USA). All patients were scanned while seated, in natural head position using the same i-CAT machine. They were asked to swallow, relax their lips and keep their eyes open. All patients were scanned with a wax bite to ensure proper condylar seating.

The acquired data from the CBCT scans was exported in Digital Imaging and Communications in Medicine (DICOM) format to Maxilim® software (Medicim, Mechelen, Belgium). In Maxilim® the skull and skin tissue of the pre- and postoperative scans were segmented using thresholding resulting in an accurate 3D reconstruction.

Voxel based registration

After reconstruction, the pre- and postoperative CBCT scans were matched using voxel-based registrations on an unaltered sub volume [4]. This sub volume consisted of the cranial base, forehead and the zygomatic arches. After matching the images, the mandible was segmented, as describes by Swennen et al. [32], in the pre-operative scan and the bone cuts were made for the BSSO on the pre-operative scan according to the postoperative result.

Simulation of soft tissues

After the registration of the preoperative and postoperative CBCT scans, the simulation of the soft tissues could be computed. A Mass Tensor Model soft tissue simulation algorithm was applied to the preoperative soft tissue surface. Finally, the preoperative mandible was optimally aligned with the postoperative mandible representing exactly the transformation reached during surgery using the surface based registration method described earlier by Besl et al [5]. Based on the transformation of the mandible a simulation of the soft tissues was computed. The result of the soft tissue simulation could now be compared with the actual postoperative soft tissue result.

Validation of soft tissue simulation

Validation of the soft tissue simulation was performed using two different methods, a cephalometric analysis (method A) and a 3D volume measurement using distance mapping (method B)

3D Cephalometric Analysis (method A)

To investigate the differences between the actual postoperative result and the soft tissue simulation, a cephalometric soft-tissue analysis was performed. The first step was to set up a hard tissue reference frame (fig. 1). The pre- and postoperative 3D reconstructions were marked with cephalometric points for subnasale, labiale superius, stomion, labiale inferius, sublabiale and soft tissue pogonion. To be able to compute the actual hard tissue movements additional hard tissue landmarks were indicated for the upper incisor landmark, lower incisor landmark, the mesial buccal cusp of the 16 and 26 and pogonion. After the cephalometric analysis was performed, the Euclidean distances were computed for all corresponding cephalometric landmarks between the pre-operative simulation and the actual postoperative result. This Euclidean distance represented the degree of deviation and gives an indication of the accuracy of the simulation. The changes of the soft- and hard tissue points following the surgical movement were measured.

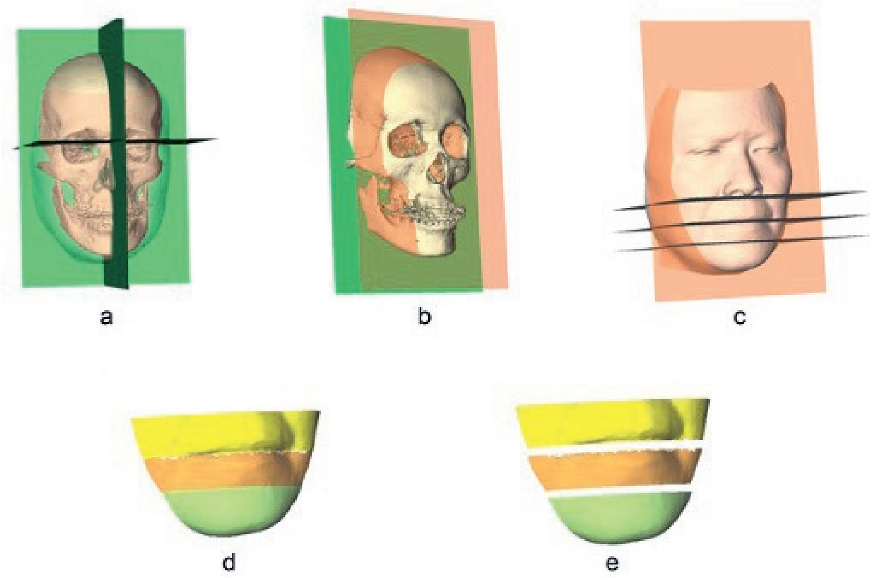


Figure 1. Setting up a hard tissue reference frame (a) and selecting the regions of interest (upper lip area, lower lip area and chin area) limited to specific regions based on specific anatomical landmarks (b – e)

3D Distance Map (method B)

In this second method the soft tissue simulation was validated using a distance map. This distance map was calculated using the inter-surface distance algorithm for surface based registration between the soft tissue surface simulation and the actual postoperative soft tissue surface. The differences can be illustrated by using a color scale image indicating the amount of difference. From this color scale image an absolute mean difference could be calculated.

In order to improve the validation, scattered radiation artifacts were omitted. Furthermore, the soft tissue located in the neck area and surrounding the nasal tip were also omitted, since the neck area is highly influenced by the head position and the segmentation for the nose region is poor due to the fact that the nasal bone is very thin. After computing these results for the complete face, the region of interest was limited to specific regions based on specific anatomical landmarks (fig 1). Both mental foramina were indicated and represented the left and right borders parallel to the vertical plane of the reference frame. These landmarks were defined as the most anterior part of the mental foramen.

The subnasal landmark was indicated and a horizontal plane through this landmark represented the upper border of the upper lip sub region. A plane through stomion parallel to the horizontal plane was used as a separation between the upper and lower lip. A plane parallel to the horizontal plane through soft tissue point sublabiale indicated the separation between the lower lip area and the chin area. The distance maps for these specific areas were used to calculate the differences between the simulation and the actual postoperative result (absolute mean difference) in the upper lip area, the lower lip area and the chin area.

Statistical analysis

Statistical data analyses were performed with the SPSS software program, version 20.0.0.1 (SPSS Inc., Chicago, USA). The cephalometric analysis was used to compute the mean amount of advancement, rotation and translation of the mandible as a result of the BSSO. The mean Euclidean distance and standard deviation between the soft-tissue landmarks (subnasale, labiale superius, stomion, labiale inferius, sublabiale and soft tissue pogonion) were calculated. For the 3D-volume measurements, the mean absolute error, standard deviation and 90th percentile were computed using the measurements derived from the distance maps for each patient and for the sample as a whole. To be able to compare our results with previous validation studies, the percentage ratio between the number of simulations with a high degree of accuracy (error level less or equal to 2 mm) and the total number of scans was calculated.

The Pearson product-moment correlation coefficient was calculated between the absolute mean distance and dependent variables: age, amount of advancement, amount of rotation and the amount of translation for detecting statistical significance at the .05 level of significance ($p \leq 0.05$). Using a student t-test the influence of sex on the simulation accuracy was calculated.

Results

A total of 100 patients were enrolled in this study. No patients were omitted and no data was missing for analysis. A summary of the patients' characteristics at surgery is presented in Table 1.

Table 1: Table showing the patients' characteristics

	Mean	Min	Max
Sex (*n*)	M=35, F=65		
Age (*years*)	31.6 ±13.4	13	68
Follow-up (*months*)	13.4 ± 4.7	6	28
Previous SARPE (*n*)	14		
Brackets per-op (*n*)	98		
Advancement Pogonion (*mm*)	4.2 ± 2.1	0.3	10.2
Rotation Pogonion (*mm*)	1.4 ± 1.1	0.0	5.8

There were more women (n = 65) enrolled in the study than men (n = 35). The mean age at surgery was 31.6 years (range 13 to 68 years) and the mean follow-up time after surgery was 13.4 months (range 6 to 28 months). The average mandibular advancement and rotation were 4.2 mm (range 0.3 to 10.2 mm) and 1.4 mm (range 0.0 to 5.8 mm), respectively.

3D Cephalometric results

The cephalometric analysis (Table 2) showed a mean absolute error comparing the simulation and the postoperative results at subnasale of 1.1 mm (± 0.5 mm), at labiale superius of 1.5 mm (± 0.7 mm), at labiale inferius of 2.0 mm (± 1.0 mm), at sublabiale of 1.7 mm (± 1.1 mm) and at soft tissue pogonion of 1.5 mm (± 0.9 mm).

Table 2: Table showing the mean absolute difference (*Dmean*), the minimum absolute difference (Dmin), the maximum absolute difference (Dmax), the -95% confidence interval for the difference (D-95%), the inter-quartile range (Diqr) and the +95% confidence interval for the difference (D+95%) for the individual landmarks on the 3D cephalometric analysis

Landmark	D_{mean} (*mm*)	D_{min} (*mm*)	D_{max} (*mm*)	$D_{-95\%}$ (*mm*)	D_{iqr} (*mm*)	$D_{+95\%}$ (*mm*)
Subnasale	1.1 ± 0.5	0.0	3.2	1.1	0.7	1.3
labiale superius	1.5 ± 0.7	0.1	4.1	1.4	0.8	1.7
labiale inferius	2.0 ± 1.0	0.4	5.7	1.8	1.3	2.2
Sublabiale	1.7 ± 1.1	0.1	5.4	1.5	1.2	2.0
Pog'	1.5 ± 0.9	0.1	4.1	1.4	1.0	1.7

3D Volumetric results

Table 3 presents the 3D volumetric measurements comparing the simulation and the postoperative results. The mean absolute error was 0.9 mm (± 0.3 mm) for the whole face and 100 percent of the cases had an average absolute error level less or equal to 2 mm. Furthermore, 78% of the patients had an average absolute error level less or equal to 1 mm. For the limited regions of interest, the mean absolute error was 0.9 mm (± 0.5 mm), 1.2 (± 0.5 mm) and 0.8 (± 0.5 mm) for the upper lip area, the lower lip area and the chin area respectively. 98 percent of the cases had an average absolute error level less or equal to 2 mm for the upper lip area, 94 percent for the lower lip area and 97 percent for the chin area. The mean values of the $T_{90\%}$ percentile are 1.9 mm for the whole face, 1.8 mm for the upper lip area, 2.5 mm for the lower lip area and 1.6 mm for the chin area (Fig. 2).

Table 3: Table showing the mean absolute difference (T_{mean}), the percentage of simulations within the 1 mm ($T \leq 1$ mm) and 2 mm ($T_{\leq 2\,mm}$) absolute minimal level of difference and the mean absolute 90% percentile ($T_{90\%}$) for the whole face and the three individual subarea's using the 3D distance maps.

Area	T_{mean} (mm)	$T_{\leq 1\,mm}$ (%)	$T_{\leq 2\,mm}$ (%)	$T_{90\%}$ (mm)
The whole face	0.9 ± 0.3	78	100	1.9
Upper lip area	0.9 ± 0.5	65	98	1.8
Lower lip area	1.2 ± 0.5	45	94	2.5
Chin area	0.8 ± 0.5	72	97	1.6

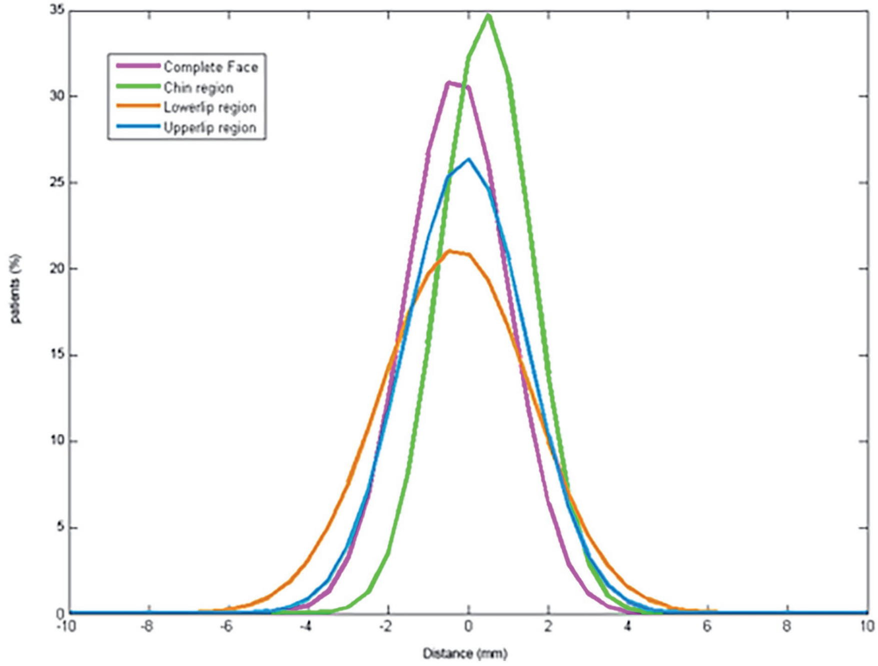


Figure 2. Error distribution for the whole face and the limited regions of interest

Correlation analysis

No significant correlation was found between the mean absolute error for the whole face or the limited regions of interest and the independent variables: age, amount of advancement of the mandible or the amount of rotation of the mandible (Table 4). Sex did not significantly affect mean whole face, upper lip, lower lip or chin area error (t-test p=0.73, p=0.06, p=0.21 and p=0.71 respectively).

Table 4: Table showing the Pearson correlation between absolute mean distance (accuracy of the soft tissue simulation) and dependent variables age, mandibular advancement and mandibular rotation. Advancement and rotation were measured at the level of pogonion.

Correlation	*Whole Face*	*Upper lip*	*Lower Lip*	*Chin*
Age (years)	-0.005	0.382	0.256	0.045
Mandibular advancement (mm)	-0.184	0.094	0.271	0.381
Mandibular rotation (mm)	-0.016	-0.012	-0.098	0.035

Discussion

The goal of this study was to assess the accuracy of the three-dimensional soft-tissue prediction produced by Maxillim® software with CBCT imaging, for 100 consecutive patients who underwent a bilateral sagittal split osteotomy (BSSO). Swennen et al [6] stated that conventional planning with lateral cephalograms is prone to analysis bias due to the difficulty of determining soft-tissue and hard-tissue landmarks with high accuracy because of superimposition of anatomic structures in a two-dimensional environment. The introduction and widespread availability of Cone Beam computed tomography (CBCT) scanning made 3D cephalometric hard tissue en soft tissue analysis possible with high degree of accuracy and reproducibility based on a CT-based reference frame [7].

Recently, quantifying the soft tissue profile changes using 3D evaluation has become more popular [8]. There are different types of soft-tissue simulation algorithms available to match the viscoelastic behaviour of the soft tissues. These models are based on the biomechanical properties of living tissue described by Fung et al [9]. The most frequently used computing algorithms for soft tissue simulations are the mass spring model (MSM) [13, 33], the finite element model (FEM) [11, 34, 35] and the mass tensor model MTM [13, 36, 37]. These algorithms were applied by several commercial software applications for 3D soft tissue simulation. Until now, a limited number of validation studies had been conducted on the accuracy of 3D soft tissue simulation of these software packages.

Bianchi et al. [10] and Marchetti et al. [11] reported a reliable simulation outcome for the whole face with an average absolute error of 0.94 mm and 0.75 mm, respectively. Both reported a high accuracy with an error less than the 2-mm tolerance level, 86.8% and 91%, respectively. Both studies used SurgiCase-CMF software using either CBCT-scanning or multi-slice CT imaging with a volumetric Finite Element Model for soft-tissue simulation according to Sarti et al [12]. It uses the modified linear elasticity equations system and each region (bone, soft tissue and embedded material) received its own equation to obtain a simulation algorithm. In both studies, the research population was small (n=10) and consisted of patients with mixed types of dentoskeletal deformities receiving different types of surgical correction, including genioplasty. Mollemans et al [13] validated the Mass Tensor Model algorithm in a 10 patient series with mixed dentoskeletal deformities using CT data processed by Maxillim® software. He reported an average median distance measuring 0.60 mm and the 90% percentile was smaller than 1.5 mm. They noticed that the areas with the greatest deviation were the area of the lips and the chin area. It was suggested that separating the lips from each other during the simulation, adding sliding contacts between the teeth and the lips and preventing mental straining during imaging would largely improve the simulation. Schendel et al. also performed a study to investigate the accuracy of soft tissue simulation in orthognathic patients. They used 3dMD Vultus software in 23 patients (monomaxillary cases as well as bimaxillary) and found an overall accuracy of 0.27 mm [33]. Conform the study of Mollemans et al. they also found the largest deviation in the peri-oral region, the dynamic parts of the face[13].

Accuracy of data acquisition

The accuracy of data acquisition (i.e. systemic error) is negatively influenced by CBCT-scanning, segmentation of tissues using thresholding, the voxel based and surface based registration method and the reproducibility of the 3D cephalometric analysis.

With CBCT-scanning, an image of the patients’ bone and soft tissue can be acquired with an accuracy of 0.28 mm compared to the gold standard, laser surface scanning [14]. CBCT imaging has advantages and disadvantages compared to Multi-slice CT imaging. Advantages include a lower radiation dose, lower costs and the possibility of scanning while seated. The direct availability and scanning while seated enables the possibility for direct instructions from the maxillofacial surgeon to ensure a correct natural head position and relaxed lips with the proper occlusion. The limitations of these types of studies relate mainly to position of the patient at the time of scanning. A natural head position is very important, because an excessive head tilt or flexion can distort the tissue. The most important is that patients relax the lips to avoid muscle hyperfunction of grimacing during scanning. A standardized scanning protocol is very important to avoid variables. Other disadvantages include radiation artifacts from the cone radiation beam, the absence of comparable Hounsfield units and different soft tissue densities. The poor boundary conditions for thresholding makes adding specific embedded boundary conditions for skin and muscles with only CBCT imaging computationally demanding and this negatively influences the systemic error during segmentation [15]. In this study, it was necessary to manually remove the radiation artifacts at the edges of the images. Also, due to the low radiation dose of the CBCT scan, the nasal tip had to be excluded from the simulation due to poor boundary conditions.

Other factors of influence are the accuracy of the voxel based registration algorithm with an accuracy of 0.5 x the largest voxel size of the largest data set [16], i.e., 0.2 mm for the present setup, and the surface based matching method using the iterative closest point algorithm [17]. Calculating the mean absolute error with the iterative closest point algorithm leads to an underestimation of the real error since the distance between the simulation and the iterative closest point on the postoperative skin surface is measured instead of the actual distance between corresponding points.

Plooij et al. [7] reported an average error of reproducibility of 0.97 mm for soft tissue points in the facial midline using 3D cephalometry. In the present setup, comparable results were found is this study. Subnasale was predicted with a mean absolute difference of 1.1 mm. Due to the fact that position of Subnasale is most likely not influenced by the mandibular advancement or the removal of the orthodontic appliances, this error represents the reproducibility of the 3D cephalometric soft tissue points marked on the pre-operative and postoperative scan.

Other factors influencing the accuracy of the prediction are the reproducibility of the patients' position during pre- and postoperative scanning (mental straining, condylar seating and eye position), weight gain or loss during the evaluation period [18. 19], soft tissue swelling after surgery [20], postoperative orthodontic changes and the removal of the orthodontic appliances [21, 22]. In order to limit these influences, all the postoperative scans were made after the postoperative swelling was resolved and after removal of the orthodontic appliances, in order to be able to compare the postoperative scans among the individual patients.

Predictability of the 3D soft-tissue simulation

If, conform previous studies, the minimum level of difference which would be both clinically important and negate the effect of systemic errors is arbitrarily set at 2mm [23], the accuracy of the prediction for the face as a whole and for the subareas: upper lip, lower lip and chin is high, 100 percent, 98 percent, 94 percent and 97 percent, respectively. These results are higher compared to the results form previous studies. The differences are likely to be caused by the relatively small overall facial changes caused by solely a bilateral sagittal split mandibular advancement, compared to the facial changes as a result of bimaxillary surgery with or without a genioplasty used in the studies mentioned before. Also, the upright scanning method in combination with direct instructions during data acquisition could be contributable factors to the more favorable results.

The mean absolute error found in our study for the face as a whole (0.9 mm) is comparable with previous studies. This means that the predicted skin surface for the whole face on average differs less then 1 mm from the actual postoperative skin surface. The mean 90% percentile is an important factor to evaluate the maximum absolute error for the simulation. The mean absolute 90% percentile for the whole face is 1.9 mm and this is comparable with the 1.6 mm found by Mollemans et al [13]. When calculating the distances of every triangle corner in the whole face to evaluate the accuracy of the simulation against the post-operative result, the error level is lower compared to the calculation in a limited region of interest. This is caused by the large amount of unchanged facial tissue when comparing the face as a whole, contributing to a lower mean difference between the (unchanged) simulation and the postoperative result. To minimize this effect, limited regions of interest for the upper lip, lower lip and chin area were set up between fixed boundaries, described earlier by Maal et al [24]. The Subarea with the least accuracy is the lower lip area (Fig. 3 and 4). The mean absolute error was 1.2 mm and 95 percent had an accuracy with an error less than the 2 mm tolerance level. The mean absolute 90% percentile of 2.5 for the lower lip area also reflects this. In order to further differentiate the differences found using the distances between the simulation and the postoperative skin surfaces, a 3D cephalometric analysis was performed. For all soft tissue points, subnasale was predicted with the most accuracy (mean absolute difference of 1.1 mm). Labiale inferius was predicted with the least accuracy (median absolute difference of 2.0 mm). Multiple studies have shown that the lips are the most difficult to predict [13, 20, 25,26] and that the simulation is most accurate when the surgical movements are moderate and the patients have competent lips with little eversion [27].

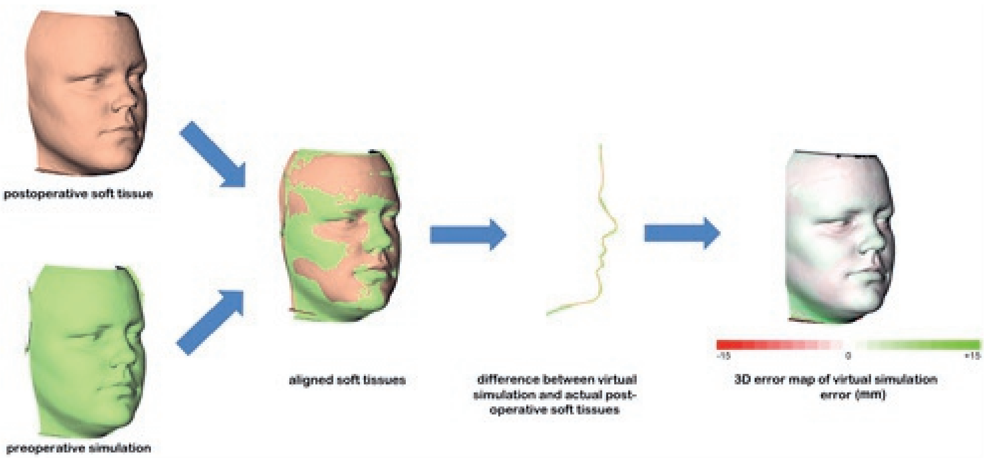


Figure 3. Example of a good match between the postoperative soft-tissue and the soft-tissue simulation.

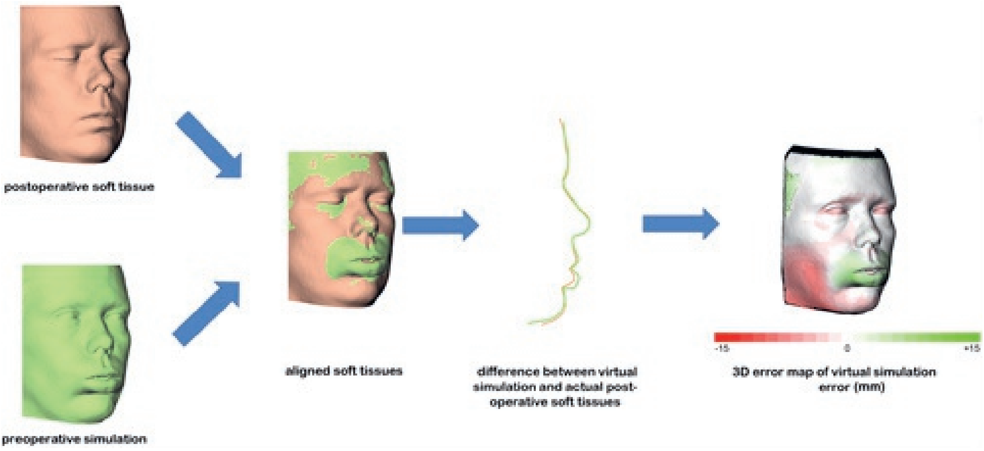


Figure 4. Example of a bad match between the postoperative soft-tissue and the soft-tissue simulation

The presence of the orthodontic appliances during the pre-operative scan could also have an effect on the more ventrally simulated upper and lower lip compared to the postoperative position. Abed et al{Abed, 2009 #32}{Abed, 2009 #32} [8] reported no lip posture differences directly after removal of orthodontic appliances using conventional profile photographs. Late effects of removal of these labial appliances on the position of the upper and lower lip are unknown. Other possible influencing factors previously described are variation in the thickness of the soft tissues [28,29], soft-tissue swelling after surgery [20,30], weight gain or loss in the post-operative period, the presence of rigid orthodontic appliances preoperatively and dental changes due to orthodontic treatment after surgery.

There was no correlation found between the error of simulation and age, sex, amount of mandibular advancement or amount of mandibular rotation, both for the 3D distance maps and the 3D cephalometric analysis. This is most likely due to the fact that the overall error of prediction is small in combination with the various possible influencing factors.

Clinical relevance

3D virtual planning of orthognathic surgery in combination with 3D soft-tissue simulation makes assessment of the 3D soft-tissue simulation possible for both surgeon and patient.

Sarver et al [31] have found that 89% of patients thought simulations were realistic, 83% of patients said the simulation helped them to make a treatment decision and 72% felt that the simulation allowed them to be an integral part of the treatment process. For use in a clinical setting, the mean absolute 90% percentile is an important factor to contemplate. It represents the maximum error for 90 percent of the measurements and it reflects the possible discrepancies of the simulation. Only the lower lip area has a mean absolute

90% percentile above the arbitrarily set minimal level of difference of 2.0 mm. On visual inspection, the largest errors were caused by patients with a difference in lip posturing of the lower lip between the pre-operative and post-operative scan. As a result, the lower lip is simulated more ventrally compared to the actual post-operative result. Correctly positioning of the lower lip during the pre-operative scan is the key to a predictable simulation.

Conclusion

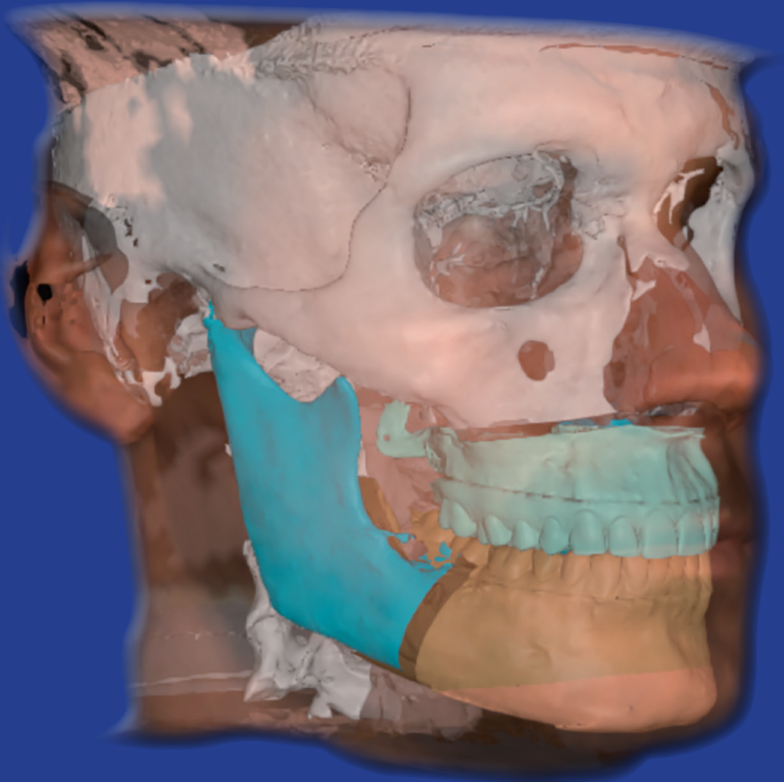
The 3D soft-tissue simulation predictability for facial changes after advancement of the mandible using the Mass Tensor Model algorithm with CBCT imaging was found to be high. The accuracy of the prediction (average absolute error level ≤ 2 mm) for the face as a whole and for the subareas: upper lip, lower lip and chin, are, 100 percent, 98 percent, 94 percent and 97 percent, respectively. For the face as a whole, the mean absolute 90% percentile stays below the 2 mm. The subarea with the least accuracy is the lower lip with a mean absolute error of 1.2 mm for the 3D distance map analysis and 2.0 mm for the 3D cephalometric analysis. No correlation could be found between the error of prediction and the amount of advancement or rotation of the mandible, age and sex of the patient. This is most likely due to different patient factors influencing the reproducibility for the position of the lower lip and the small mean absolute errors found in this study. Visual inspection of the differences between the simulations and the actual postoperative results showed better results when the patient was scanned with relaxed lips with little eversion. Overall, the Mass Tensor Model algorithm combined with CBCT imaging is an accurate method for predicting soft tissue changes after mandibular advancement and can readily be used to confront patients, surgeons and orthodontists with the postoperative soft tissue prediction. Future studies will focus on validating the Mass Tensor Model algorithm for bimaxillary surgery.

References

1. Holdaway RA. A soft-tissue cephalometric analysis and its use in orthodontic treatment planning. Part I. American journal of orthodontics 1983;84:1-28.
2. Alves PV, Mazucheli J, Vogel CJ, Bolognese AM. How the lower face soft tissue changes after mandibular advancement or setback. The Journal of craniofacial surgery 2008;19:593-8.
3. Hunsuck EE. A modified intraoral sagittal splitting technic for correction of mandibular prognathism. J Oral Surg 1968;26:250-3.
4. Nada RM, Maal TJ, Breuning KH, Berge SJ, Mostafa YA, Kuijpers-Jagtman AM. Accuracy and reproducibility of voxel based superimposition of cone beam computed tomography models on the anterior cranial base and the zygomatic arches. PLoS One 2011;6:0016520.
5. Besl PJ, McKay ND. A Method for Registration of 3-D Shapes. IEEE Trans Pattern Anal Mach Intell 1992;14:239-56.
6. Swennen GR, Schutyser F, Barth EL, De Groeve P, De Mey A. A new method of 3-D cephalometry Part I: the anatomic Cartesian 3-D reference system. The Journal of craniofacial surgery 2006;17:314-25.
7. Plooij JM, Swennen GR, Rangel FA, et al. Evaluation of reproducibility and reliability of 3D soft tissue analysis using 3D stereophotogrammetry. International journal of oral and maxillofacial surgery 2009;38:267-73.
8. Abed Y, Har-Zion G, Redlich M. Lip posture following debonding of labial appliances based on conventional profile photographs. The Angle orthodontist 2009;79:235-9.
9. Fung YC. Biomechanics : mechanical properties of living tissues. 2nd ed. New York: Springer-Verlag; 1993.
10. Bianchi A, Muyldermans L, Di Martino M, et al. Facial soft tissue esthetic predictions: validation in craniomaxillofacial surgery with cone beam computed tomography data. J Oral Maxillofac Surg 2010;68:1471-9.
11. Marchetti C, Bianchi A, Muyldermans L, Di Martino M, Lancellotti L, Sarti A. Validation of new soft tissue software in orthognathic surgery planning. International journal of oral and maxillofacial surgery 2011;40:26-32.
12. Sarti A, Gori R, Lamberti C. A physically based model to simulate maxillo-facial surgery from 3D CT images. Future Gener Comput Syst 1999;15:217-301.
13. Mollemans W, Schutyser F, Nadjmi N, Maes F, Suetens P. Predicting soft tissue deformations for a maxillofacial surgery planning system: from computational strategies to a complete clinical validation. Med Image Anal 2007;11:282-301.
14. Liang X, Lambrichts I, Sun Y, et al. A comparative evaluation of Cone Beam Computed Tomography (CBCT) and Multi-Slice CT (MSCT). Part II: On 3D model accuracy. European journal of radiology 2010;75:270-4.
15. Loubele M, Maes F, Schutyser F, Marchal G, Jacobs R, Suetens P. Assessment of bone segmentation quality of cone-beam CT versus multislice spiral CT: a pilot study. Oral surgery, oral medicine, oral pathology, oral radiology, and endodontics 2006;102:225-34.

16. Maes F, Collignon A, Vandermeulen D, Marchal G, Suetens P. Multimodality image registration by maximization of mutual information. IEEE Trans Med Imaging 1997;16:187-98.
17. Chabanas M, Payan Y, Marécaux C, Swider P, Boutault F. Comparison of linear and Non-linear Soft Tissue Models with Post-operative CT scan in Maxillofacial Surgery. In: Cotin S, Metaxas D, eds. Medical Simulation. Heidelberg: Springer Berlin; 2004:19-27.
18. Kuvat SV, Guven E, Hocaoglu E, et al. Body fat composition and weight changes after double-jaw osteotomy. The Journal of craniofacial surgery 2010;21:1516-8.
19. Worrall SF. Changes in weight and body composition after orthognathic surgery and jaw fractures: a comparison of miniplates and intermaxillary fixation. The British journal of oral & maxillofacial surgery 1994;32:289-92.
20. Kau CH, Cronin AJ, Richmond S. A three-dimensional evaluation of postoperative swelling following orthognathic surgery at 6 months. Plast Reconstr Surg 2007;119:2192-9.
21. Chew MT. Soft and hard tissue changes after bimaxillary surgery in Chinese Class III patients. The Angle orthodontist 2005;75:959-63.
22. Joss CU, Joss-Vassalli IM, Kiliaridis S, Kuijpers-Jagtman AM. Soft tissue profile changes after bilateral sagittal split osteotomy for mandibular advancement: a systematic review. J Oral Maxillofac Surg 2010;68:1260-9.
23. Proffit WR, Phillips C, Turvey TA. Stability following superior repositioning of the maxilla by LeFort I osteotomy. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics 1987;92:151-61.
24. Maal TJ, de Koning MJ, Plooij JM, et al. One year postoperative hard and soft tissue volumetric changes after a BSSO mandibular advancement. International journal of oral and maxillofacial surgery 2012;41:1137-45.
25. Jones RM, Khambay BS, McHugh S, Ayoub AF. The validity of a computer-assisted simulation system for orthognathic surgery (CASSOS) for planning the surgical correction of class III skeletal deformities: single-jaw versus bimaxillary surgery. International journal of oral and maxillofacial surgery 2007;36:900-8.
26. Smith JD, Thomas PM, Proffit WR. A comparison of current prediction imaging programs. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics 2004;125:527-36.
27. Hernandez-Orsini R, Jacobson A, Sarver DM, Bartolucci A. Short-term and long-term soft tissue profile changes after mandibular advancements using rigid fixation techniques. Int J Adult Orthodon Orthognath Surg 1989;4:209-18.
28. Eckhardt CE, Cunningham SJ. How predictable is orthognathic surgery? Eur J Orthod 2004;26:303-9.
29. Mobarak KA, Espeland L, Krogstad O, Lyberg T. Soft tissue profile changes following mandibular advancement surgery: predictability and long-term outcome. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics 2001;119:353-67.

30. Dolce C, Hatch JP, Van Sickels JE, Rugh JD. Five-year outcome and predictability of soft tissue profiles when wire or rigid fixation is used in mandibular advancement surgery. American journal of orthodontics and dentofacial orthopedics : official publication of the American Association of Orthodontists, its constituent societies, and the American Board of Orthodontics 2003;124:249-56.
31. Sarver DM, Johnston MW, Matukas VJ. Video imaging for planning and counseling in orthognathic surgery. J Oral Maxillofac Surg 1988;46:939-45.
32. Swennen GR, Mollemans W, Schutyser F. Three-dimensional treatment planning of orthognatihic surgery in the era of virtual imaging. J Oral Maxillofac Surg 2009;67:2080-2092
33. Schendel SA, Jacobson R, Khalessi S: 3-dimensional facial simulation in orthognathic surgery: is it accurate? *J Oral Maxillofac Surg* 2013;71:1406-14
34. Marchetti C, Bianchi A, Bassi M et al.: Mathematical modeling and numerical simulation in maxillofacial virtual surgery. *J Craniofac Surg* 2007;18:826-32
35. Marchetti C, Bianchi A, Bassi M et al.: Mathematical modeling and numerical simulation in maxillo-facial virtual surgery (VISU). *J Craniofac Surg* 2006;17:661-7; discussion 8
36. Shafi MI, Ayoub A, Ju X, Khambay B: The accuracy of three-dimensional prediction planning for the surgical correction of facial deformities using Maxilim. *Int J Oral Maxillofac Surg* 2013;42:801-6
37. Nadjmi N, Tehranchi A, Azami N et al.: Comparison of soft-tissue profiles in Le Fort I osteotomy patients with Dolphin and Maxilim softwares. *Am J Orthod Dentofacial Orthop* 2013;144:654-62



Chapter 3

Accuracy of three-dimensional soft tissue simulation in bimaxillary osteotomies.

Liebregts JHF*, Xi T*, Timmermans M, de Koning M, Bergé SJ, Hoppenreijs T, Maal TJ.

* Both authors contributed equally

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Abstract

Purpose: The purpose of this study was to evaluate the accuracy of a mass tensor model (MTM) based algorithm for computerized 3D simulation of soft-tissue changes following bimaxillary osteotomy, and to identify patient and surgery related factors that may affect the accuracy of the simulation.

Materials and methods: Sixty patients (mean age of 26.0 years) who had undergone bimaxillary osteotomy participated in this prospective study. Cone beam CT scans were acquired pre- and one year postoperatively. The 3D rendered pre- and postoperative scans were matched. Maxilla and mandible were segmented and aligned to the postoperative position. 3D distance maps and cephalometric analyses were used to quantify the simulation error.

Results: The mean absolute error between the 3D simulation and the actual postoperative facial profile was 0.81 ± 0.22 mm for the face as a whole. The accuracy of the simulation (average absolute error ≤ 2 mm) for the whole face and for the subregions upper lip, lower lip and chin were 100%, 93%, 90% and 95%, respectively. The predictability was correlated with the magnitude of the maxillary and mandibular advancement, age and V-Y closure.

Conclusion: The MTM based soft tissue simulation for bimaxillary surgery was accurate for clinical use, though patients should be informed of possible variations in the predicted lip position.

Introduction

The introduction of three-dimensional (3D) virtual surgery planning software in the field of orthognathic surgery has provided orthodontist and surgeons with an opportunity to perform virtual osteotomies in order to obtain a favourable facial appearance [1, 2]. Since the final aesthetic result is reflected by the postoperative soft tissue facial profile, the predictability of the soft tissue changes that accompany the planned bony tissue movements has become the key issue in surgical simulations[2-4]. An accurate 3D simulation of the desired surgical result is essential in treatment planning and (shared) decision making [1, 5-7].

Various computational strategies have been adopted to perform 3D virtual soft tissue simulations [1, 4, 6]. Mollemans et al. found that the highest accuracy was obtained by using a finite element model (FEM) or a mass tensor model (MTM), with a mean median error of 0.60 mm (90 percentile < 1.5 mm) [4]. Considering significant time gain in simulation time compared to the two traditionally used models (FEM and mass spring model), MTM seemed to be the more favourable one for clinical use.

The importance of an accurate 3D soft tissue simulation increases with the complexity of the planned orthognathic surgery [1, 8]. From a theoretical point of view, however, an increased complexity of the surgical intervention (bimaxillary surgery) is technically more challenging to manage compared to single jaw surgery. It can be expected that the induced error in soft tissue simulation would be higher as both the complexity of jaw movements and the number of jaw segments are increased in bimaxillary surgery. Up till today, no study on the predictability of computerized simulation of 3D soft tissue facial profile with a large number of homogeneous patients undergoing bimaxillary surgery has been published.

The aim of this prospective study was to evaluate the accuracy of a MTM algorithm for computerized 3D simulation of soft-tissue changes following bimaxillary surgery and to identify patient and surgery related factors that may explain possible discrepancies between the initial 3D soft tissue simulation and the postoperative soft tissue profile.

Material and Methods

The inclusion criteria were a non-syndromatic dysgnathia requiring bimaxillary osteotomy, and the availability of a CBCT scan before and at least six months after surgery. The exclusion criteria were non-native Dutch patients, the usage of a chin support during CBCT-scanning, previous history of Le Fort I osteotomy or BSSO, a chin osteotomy performed during bimaxillary surgery, presence of orthodontic labial appliances in the postoperative CBCT-scan, the absence of upper and/or lower incisors and extensive restorative dental treatment during the postoperative follow-up period.

This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research ethics. The approval of the regional medical ethics review board (CMO Arnhem-Nijmegen) was obtained for this study. All patient data were anonymized and de-identified prior to analysis.

Data acquisition

CBCT imaging data were obtained two weeks prior to and at least six months following bimaxillary surgery using a standard CBCT scanning protocol (i-CAT, 3D Imaging System, Imaging Sciences International Inc, Hatfield, PA, USA) in “Extended Field” modus (field of view: 16 cm diameter/22 cm height; scan time: 2x20 seconds; voxel size: 0.4 mm). Patients were scanned while seated in a natural head position. Patients were asked to swallow and to relax their lips and facial muscles and to keep their eyes open. The acquired CBCT data were stored in DICOM format and exported into Maxilim® software (Medicim NV, Mechelen, Belgium). In Maxilim, a 3D virtual augmented head model was rendered [9].

Simulation of soft tissue profile

The pre- and postoperative 3D virtual head models were superimposed using voxel based registration on an unaltered subvolume that consisted of the cranial base, forehead and zygomatic arches [10]. Virtual Le Fort I and BSSO osteotomies were made on the preoperative 3D virtual head model according to the actual osteotomies performed during surgery (postoperative scan).

In order to eliminate discrepancies between the planned skeletal movement and the actual displacement of the bimaxillary complex at surgery, the virtually osteotomized maxilla and mandible were aligned with the position of the maxilla and mandibula in the postoperative scan using surface based registration [11]. In this way, the simulated skeletal movements duplicated the actual jaw displacements during surgery. In Maxilim, a soft tissue simulation was carried out based on the simulated skeletal movements using a MTM soft tissue simulation algorithm. The result of the soft tissue simulation could subsequently be compared with the actual postoperative soft tissue profile (figure 1).

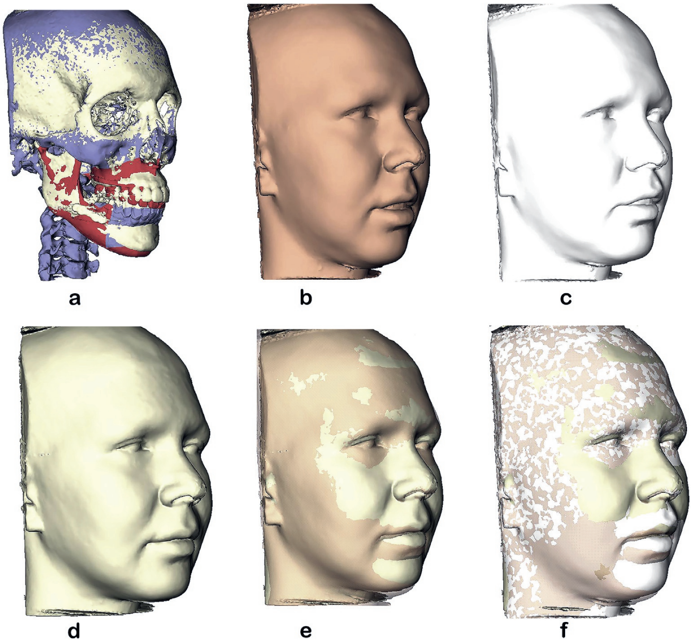

Figure 1. The registration procedure of the preoperative, postoperative and simulated facial profiles.

(a) Voxel based registration of the preoperative (blue/red) and postoperative (white) CBCT scans. (b) Preoperative soft tissue facial profile. (c) Simulated soft tissue outcome by Maxilim according to the performed bimaxillary osteotomy. (d) Postoperative soft tissue facial profile. (e) The preoperative soft tissue facial profile is compared with the postoperative result. (f) The simulated facial profile is compared with the preoperative and postoperative situation. It can be seen that the simulation has overestimated the position of the upper lip and chin regions.

Analysis of soft tissue simulation

The accuracy of the soft tissue simulation was evaluated by cephalometric analysis (method A) and 3D distance mapping (method B).

A) Cephalometric Analysis

Differences between the soft tissue simulation and actual soft tissue changes were calculated using 11 3D cephalometric landmarks. Following the set-up of a 3D hard tissue reference frame, 6 midline soft tissue landmarks (subnasale, labrale superius, stomion, labrale inferius, sublabiale, and soft tissue pogonion), 3 midline hard tissue landmarks (upper incisor landmark, lower incisor landmark, and pogonion) and 1 bilateral hard tissue landmark (mental foramen) were identified through the validated method described by Swennen et al [12]. The Euclidean distances were computed for all corresponding landmarks between the soft tissue simulation and the actual postoperative result as a measure for the accuracy of soft tissue simulation. The Euclidean distances between the corresponding landmarks in the pre- and postoperative scans were also calculated, to assess the actual surgical movements.

B) 3D Distance Mapping

The overall differences between the soft tissue simulation and actual postoperative soft tissue profile were calculated using 3D distance mapping, generated by the application of an inter-surface distance algorithm. Differences between the 3D soft tissue profiles were visualized by using colour scaled distance maps. From these distance maps the absolute mean difference between the simulation and surgical result was calculated. Scattered radiation artifacts were removed to prevent bias. The soft tissue located in the neck area and around the nasal tip were also omitted. The soft tissue outline in the neck area is highly influenced by the position of the head and cervical spine and was considered to be poorly reproducible. The exclusion of the nasal region is due to the poor segmentation and 3D rendering of the soft tissue nasal tip.

The absolute mean differences were computed for the face as a whole, and for three specific regions of interest, the upper lip, lower lip and chin region, defined by the aforementioned cephalometric landmarks (figure 2). For each specific region, a distance map was generated to calculate the mean absolute difference between the simulation and the actual postoperative result.

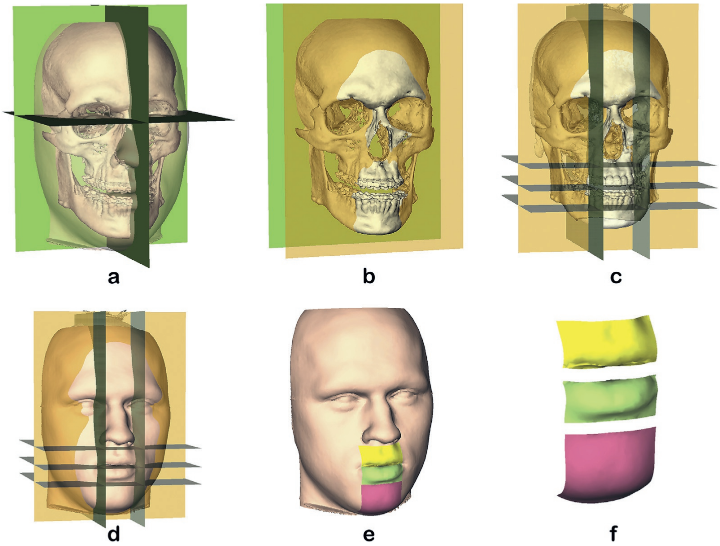

Figure 2. The set up and definition of facial regions.

A reference frame is set up according to the method described by Swennen et al. (a). Two vertical planes through the left and right mental foramen running parallel to the median plane were constructed. Three horizontal planes through the landmarks subnasale, stomion and sublabiale running parallel to the horizontal plane were also constructed (b and c). These planes are used to define the borders of the facial subregions (d). Subsequently, the soft tissue profile is divided into different subregions (e). The upper lip region (yellow), lower lip region (green) and chin region (purple) are depicted in (f). Upper lip region: area between horizontal planes through stomion and subnasale, bordered by two vertical planes through the left and right mental foramen. Lower lip region: area between the horizontal planes through stomion and sublabiale, bordered by two vertical planes through the left and right mental foramen. Chin region: area located below the horizontal plane through sublabiale and between the two vertical planes through the left and right mental foramen.

Statistical analysis

IBM SPSS software, version 20.0.1 (IBM Corp., Armonk, NY, USA) was used to perform the statistical data analysis. The 3D cephalometric data were used to compute the mean amount of advancement and jaw of the bimaxillary complex at I_{sup} and I_{inf} as the result of surgery. The Euclidean distances between the corresponding soft tissue landmarks subnasale, labrale superius, labrale inferius, sublabiale and soft tissue pogonion on the simulated soft tissue profiles and actual postoperative soft tissue profiles were calculated as a parameter for the accuracy of simulation. The mean absolute error, standard deviation, range and 95th percentile were computed for the soft tissue profile face as a whole and for the three subregions of interest using the distance maps derived from the 3D virtual head models. To be able to compare our results with previous studies, the percentage ratio between the number of simulations with a high and medium degree of accuracy (error level less or equal to 1 mm and 2 mm, respectively) and the total number of scans was calculated.

Multivariate linear regression analysis with backward regression (5% level of significance) was used to investigate the correlation between the dependent variables (prediction of the soft tissue profile for the whole face and in each of the three subregions) and independent variables (age at surgery, sex, amount of surgical advancement and jaw at I_{sup} and I_{inf}, SARME prior to surgery, alar cinch suture and V-Y closure). Adjusted r square values were calculated to describe the explained variance of dependant variables.

Results

60 patients were enrolled in this study, 45 females (75%) and 15 males (25%). The mean age at surgery was 26 (range 15-58) years. The mean follow-up time was 14,0 months (range 6-35 months). 26 patients underwent a surgically assisted maxillary expansion prior to the bimaxillary surgery. The alar cinch suturing technique was applied on 22 patients; an upper lip augmentation with V-Y closure on 14 patients.

3D cephalometric analysis

The mean surgical advancement of the maxilla (measured at I_{sup}) and mandible (measured at I_{inf}) was 2.7 ± 1,9 mm and 4.1 ± 4,2 mm, respectively. The chin (pogonion) was advanced by an average of 3.5 ± 4,5 mm.

The mean absolute error between the simulation and postoperative result at soft tissue landmarks subnasale, labrale superius, labrale inferius, sublabiale and soft tissue pogonion are presented in table 1. The maximum absolute error was at the labrale inferius (3.1 ± 1.4 mm) whereas the smallest absolute error appeared at the subnasale (1.5 ± 0.6 mm).

Table 1 Soft tissue simulation error (mm) at five cephalometric soft tissue landmarks.

Landmark	$Error_{m}$ (mm)	SD (mm)	$Error_{min}$ (mm)	$Error_{max}$ (mm)	$Error_{95\%\text{-}CI}$ (mm)
Subnasale	1.48	0.6	0.4	3.1	1.32 – 1.64
Labrale superius	2.55	1.0	0.7	4.9	2.29 – 2.80
Labrale inferius	3.12	1.4	0.5	7.5	2.76 – 3.48
Sublabiale	2.48	1.2	0.8	6.3	2.19 – 2.79
Pogonion	2.75	1.4	0.2	6.6	2.39 – 3.10

$Error_{m}$: mean absolute error. SD: standard deviation of mean absolute error. $Error_{min}$: the minimum absolute error. $Error_{max}$: the maximum absolute error. $Error_{95\%\text{-}CI}$: 95% confidence interval of the absolute error.

3D distance mapping

The mean absolute differences of the soft tissue profile between simulation and postoperative result of the face as a whole and in the three subregions are summarized in table 3. For the face as a whole, the mean absolute error was 0.81 ± 0.22 mm. The percentage ratio with a high degree of accuracy (error ≤ 1 mm) and with a medium degree of accuracy (error ≤ 2 mm) was 83.3% and 100%, respectively. The accuracy of the soft tissue simulation in the upper lip region was the highest (1.2 ± 0.6 mm), whereas the lower lip region was the least predictable (1.4 ± 0.5 mm). Figures 3 and 4 depict respectively a good and a poor match (distance map) between the postoperative and simulated soft tissue facial profile.

Table 2 The mean absolute error in soft tissue simulation (mm and percentage) for the whole face and in the three subregions of the face based on the 3D distance maps.

Area	T_{mean} (mm)	$T_{\leq 1mm}$ (%)	$T_{\leq 2mm}$ (%)	$T_{90\%}$ (mm)
The whole face	0.8 ± 0.2	83	100	2.0
The upper lip region	1.2 ± 0.6	47	93	2.2
The lower lip region	1.4 ± 0.5	20	90	2.9
The chin region	1.1 ± 0.6	57	95	2.3

T_{mean}: the mean absolute surface error. $T_{\leq 1mm}$: the percentage of simulations within an error margin of 1 mm. $T_{\leq 2mm}$: the percentage of simulations within an error margin of 2 mm. $T_{90\%}$: 90% percentile of the mean absolute error.

Correlation analysis

The accuracy of soft tissue simulation for the face as a whole was correlated to the magnitude of the skeletal advancement of the maxilla ($p=0.001$) and mandible ($p=0.009$), as well to the use of alar cinch suture ($p=0.03$) and V-Y closure ($p<0.001$). Multivariate regression analysis involving these four factors gave an explained variance of 26%. The mean error in soft tissue simulation among patients who had a V-Y closure (0.7 mm) was statistically significantly smaller than those without a V-Y closure (0.8). However, this difference was not present with regard to the alar cinch suture.

The soft tissue simulation error of the upper and lower lip region was significantly correlated to the magnitude of the maxillary and mandibular advancement, respectively resulting in an explained variance of 5% and 15% ($p<0.05$). The age of the patients was found to be correlated to the accuracy of soft tissue simulation in the lower lip region ($p=0.002$). The soft tissue simulation became slightly less accurate as the age of the patient increased. The error in simulation of the soft tissue chin was best explained by the age of patient and the surgical advancement of the maxilla and mandible ($r^2=0.35$). In general, the accuracy of the soft tissue simulation decreased in patients with a larger surgical advancement.

Discussion

The introduction of CBCT had provided the surgeons with a powerful imaging tool to depict the facial soft tissue and hard tissue in 3D, while exposing patients to a much lower radiation dose than conventional CT [13, 14]. Upon the rendered virtual 3D head models, virtual surgery could be performed. By adopting a specific type of algorithm, the soft tissue profile of the virtual osteotomy could be simulated. The accuracy of the computerized 3D soft tissue simulation relied, therefore, on the ability of the computing algorithm to predict the soft tissue movements [4, 6, 15]. Several computing algorithms have been adopted for soft tissue simulations. The most frequently used are the mass spring model (MSM) [1, 4], the finite element model (FEM) [3, 6, 16] and the mass tensor model MTM [4, 17, 18]. These algorithms were applied by several commercial software applications for 3D soft tissue simulation. Up till now, a limited number of validation studies had been conducted on the accuracy of the soft tissue simulation of these software packages.

The present study evaluated the accuracy of 3D soft tissue simulation of bimaxillary osteotomies using Maxilim software (MTM algorithm). The mean simulation error for the face as a whole and for the subregions upper lip, lower lip and chin were 0.8 mm, 1.2 mm, 1.4 mm and 1.1 mm, respectively. The 90% percentile of the mean absolute error stayed below the 2 mm. These errors were much lower than those reported by Shafi et al. (mean error in the upper lip region of 2.73 mm), who also investigated the predictability of the Maxilim software, but for isolated Le Fort I advancements [17]. It needs to be underlined that average maxillary advancement in the study of Shafi et al. was larger than in this study (5.5 mm vs. 2.7 mm), which might have induced more inaccuracies in the soft tissue simulation. The recent study performed by Nadjmi et al. used 15 midline soft tissue landmarks on the midfacial plane to assess the soft tissue simulation error of Maxilim software [18]. Based on the findings of 13 patients who had undergone Le Fort I or bimaxillary surgery, the mean error in the horizontal direction for the landmarks subnasale, labrale superior and pogonion were respectively 0.05 mm, 0.062 mm and 0.16 mm. The errors on the transverse plane were not reported because only the simulation error on the midfacial plane was investigated. The true simulation error is, in fact, the sum of error on the horizontal, vertical and transverse planes. Thus, the combined error as reported in this study is expected to be larger than the error on each plane.

The mean absolute error for the whole face of 0.8 mm found in the present study coincided well with the studies of Bianchi et al [19] and Marchetti et al [3], since they found an average absolute error of 0.94 mm and 0.75 mm, respectively. Both studies used the volumetric FEM based SurgiCase-CMF software, that had difficulties of predicting the lip position and the chin region. The outcome from both abovementioned studies should be interpreted with caution. Not only was the population size limited, it also comprised different types of maxillofacial deformities. The patients received different types of osteotomies, including genioplasty. In addition, the reported mean absolute error for the whole face included large areas that were not affected by surgery. By the inclusion of facial areas that were not affected by surgery in the analysis, the reported error tended to be an underestimation of the actual prediction error caused by surgery. This statement is highlighted by the findings of the present study, in which the simulation accuracy for the whole face is higher than in the regions of interest (lip and chin regions).

In the present study, the prediction error at five cephalometric landmarks pointed out that subnasale was the most predictable landmark (mean error of 1.48 ± 0.60 mm) whereas labrale superius was the least predictable (mean error of 3.12 ± 1.40 mm). The relative low predictability of the effect of orthognathic surgery on the upper and lower lip position and the large variability in predicted lip positions were also found in the previous studies [1, 3, 5, 8, 17-19]. It is remarkable that the most predictable and the least predictable landmarks are located so closely to each other. Several factors could have influenced the precision of the lip position simulation. Firstly, the positional changes of the upper and lower incisors during the pre- and postoperative orthodontic treatment might have affected the final lip position. Although the magnitude of this effect has not been quantified in the present study, a previous 3D CBCT study on the soft tissue response to mandibular advancement showed that only 30% of the variability of the postoperative lower lip displacement was explained by changes in the lower incisor position [20]. The effect of incisor position on the simulation error in the lip regions is thus considered to be limited. Secondly, the presence of labial brackets on the preoperative scan and their absence on the one-year postoperative scan had probably influenced the final lip position. Jeon et al reported in their 3D soft tissue study that debonding of the labial brackets caused positional changes of the vermilion border up to 1.4 mm [21]. In addition, difficulties in reproducing a relaxed lip position during CBCT scans might have also increased the variations in the simulation of lip position [7, 22]. From the technical point of view, the large errors in the lip regions can also be caused by the fact that the software moves the CT data of the upper and lower lip as a continuous area, instead of considering them as two separate anatomical structures that move separately [3].

Soft tissue changes in response to bimaxillary surgery are multifactorial, depending on surgical related factors as well as patient related factors. With regard to the surgical related factors, the correlation analysis showed that the simulation error is positively correlated to the magnitude of the surgical advancement. The proposed theories to explain the low predictability are either that the fraction of the maxilla bone advancement is partially absorbed by the thickness of the upper lip, or that there may be space present between the upper maxillary dentoalveolar structures and the labial mucosa of the upper lip, so that the upper lip only moves once the maxillary advancement has bridged this space and made contact with the labial lip surface [16]. This would explain the non-linear nature of the hard-tissue to soft-tissue ratio for prediction of the soft tissue results, especially in the lip regions [3, 17, 19]. The use of V-Y closure after Le Fort I osteotomy seemed to be able to improve the simulation slightly, in contrast to the use of alar cinch sutures. This finding confirmed that MTM algorithm was able to give an acceptable prediction of the vermillion show [18], as a V-Y closure was carried out to counteract the tendency for the shortening of the upper lip and to allow some eversion of the vermillion border [22]. The alar cinch suture was primarily used to stabilize the alar width after surgery. Therefore, its presence was not expected to influence the soft tissue profile of the upper lip region significantly, regardless whether the V-Y closure was used [23].

Concerning the patient related factors, such as age and gender, it could be concluded that the prediction of soft tissue response in older patients was less accurate, and that no gender difference could be identified. Because the age of a patient is an influential factor of the soft tissue elasticity, fat distribution and oro-facial muscle tone [24], the incorporation of the aging related effects in the Maxilim software may provide more accurate simulation among elderly patients, an increasing subgroup among the orthognathic patients. It is worth to note that the current study is based solely on native Dutch (Caucasian) patients. As patients of different origins exhibit different anthropometric facial features [25], a slightly different prediction model may be required to achieve a similar accuracy for those groups of patients.

Although not fully quantified, the design of this study limited the influence of several other factors affecting the accuracy of the prediction. By scanning patients sitting upright in the natural head position with relaxed lips and facial muscles, the influences of the patients' position during the CBCT scans were kept to a minimum [26]. As all postoperative scans were made one year after the surgery, the effects of postoperative soft tissue edema on the facial profile were limited [27]. Also the effect of postoperative skeletal relapse on soft tissue changes was eliminated by the surface based matching of the virtually osteotomized maxilla and mandibular segments onto the postsurgical position of the jaws. By adopting this meticulous transformation of the actual skeletal movements in the virtual simulation, it could be ensured that the virtual postoperative skeletal position was concordant with the actual bony displacements. It needs to be noted that the influences of weight changes between the moment of pre- and postoperative scans, the thickness of the lips, and the effect of the orthodontics teeth movements were not quantified in this study.

The accuracy of the simulation (average absolute error ≤ 2 mm) for the face as a whole and for the subregions upper lip, lower lip and chin were 100%, 93%, 90% and 95% respectively. Errors below 2 mm were previously reported to be clinically acceptable by orthodontists, surgeons and patients as these errors would not seriously affect treatment planning and patient communication [28-31]. Taking this into account, the accuracy of the MTM based soft tissue simulation of bimaxillary surgery is considered to be accurate enough for clinical use as an aid in treatment planning, communication with the patient and shared decision making. Computer aided surgical simulation also offers great potential for improving the efficiency of surgical planning of bimaxillary surgery, in terms of a reduced total doctor time and an increased compliance to attend the appointments [32]. When using prediction software in the process of shared decision-making, patients should, however, be informed of relatively big variations of the predicted soft tissue profile in the lip regions.

There is certainly room to further enhance the accuracy of the soft tissue simulation. The adaption of computing algorithm to suit specific patient groups (i.e. based on the patient age and origin) and surgery type would be an option. The incorporation of certain clinically validated soft-tissue to hard-tissue ratios as described by the recent review of Moragas et al. [22] may also contribute to a more accurate computing model, especially in terms of the incisal and vermillion show. In order to optimize these ratios, multicenter databases with pre- and postoperative soft tissue and hard tissue data need to be established. More clinical validation studies with a significant sample size are recommended to provide evidence regarding the accuracy of soft tissue simulation used in various commercially software packages.

Conclusion

The MTM based soft tissue simulation is an accurate model for the prediction of soft tissue changes following bimaxillary surgery. The accuracy of the prediction is influenced by the magnitude of the maxillary and mandibular advancement, the age of patient and the usage of V-Y closure. Patients should be informed of possible variations in the predicted lip position.

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References

1. Schendel SA, Jacobson R, Khalessi S: 3-dimensional facial simulation in orthognathic surgery: is it accurate? *J Oral Maxillofac Surg* 2013;71:1406-14
2. Westermark A, Zachow S, Eppley BL: Three-dimensional osteotomy planning in maxillofacial surgery including soft tissue prediction. *J Craniofac Surg* 2005;16:100-4
3. Marchetti C, Bianchi A, Muyldermans L et al.: Validation of new soft tissue software in orthognathic surgery planning. *Int J Oral Maxillofac Surg* 2011;40:26-32
4. Mollemans W, Schutyser F, Nadjmi N et al.: Predicting soft tissue deformations for a maxillofacial surgery planning system: from computational strategies to a complete clinical validation. *Med Image Anal* 2007;11:282-301
5. Kaipatur NR, Flores-Mir C: Accuracy of computer programs in predicting orthognathic surgery soft tissue response. *J Oral Maxillofac Surg* 2009;67:751-9
6. Marchetti C, Bianchi A, Bassi M et al.: Mathematical modeling and numerical simulation in maxillofacial virtual surgery. *J Craniofac Surg* 2007;18:826-32
7. Mobarak KA, Espeland L, Krogstad O, Lyberg T: Soft tissue profile changes following mandibular advancement surgery: predictability and long-term outcome. *Am J Orthod Dentofacial Orthop* 2001;119:353-67
8. Xia JJ, Shevchenko L, Gateno J et al.: Outcome study of computer-aided surgical simulation in the treatment of patients with craniomaxillofacial deformities. *J Oral Maxillofac Surg* 2011;69:2014-24
9. Swennen GR, Mollemans W, De Clercq C et al.: A cone-beam computed tomography triple scan procedure to obtain a three-dimensional augmented virtual skull model appropriate for orthognathic surgery planning. *J Craniofac Surg* 2009;20:297-307
10. Nada RM, Maal TJJ, Breuning KH et al.: Accuracy and Reproducibility of Voxel Based Superimposition of Cone Beam Computed Tomography Models on the Anterior Cranial Base and the Zygomatic Arches. *Plos One* 2011;6:
11. Besl PJ, Mckay ND: A Method for Registration of 3-D Shapes. *Ieee Transactions on Pattern Analysis and Machine Intelligence* 1992;14:239-56
12. Swennen GRJ, Schutyser F, Barth EL et al.: A new method of 3-D cephalometry - Part I: The anatomic cartesian 3-D reference system. *Journal of Craniofacial Surgery* 2006;17:314-25
13. De Vos W, Casselman J, Swennen GR: Cone-beam computerized tomography (CBCT) imaging of the oral and maxillofacial region: a systematic review of the literature. *Int J Oral Maxillofac Surg* 2009;38:609-25
14. Schendel SA, Jacobson R: Three-dimensional imaging and computer simulation for office-based surgery. *J Oral Maxillofac Surg* 2009;67:2107-14
15. Xia J, Samman N, Yeung RW et al.: Computer-assisted three-dimensional surgical planing and simulation. 3D soft tissue planning and prediction. *Int J Oral Maxillofac Surg* 2000;29:250-8
16. Marchetti C, Bianchi A, Bassi M et al.: Mathematical modeling and numerical simulation in maxillo-facial virtual surgery (VISU). *J Craniofac Surg* 2006;17:661-7; discussion 8

17. Shafi MI, Ayoub A, Ju X, Khambay B: The accuracy of three-dimensional prediction planning for the surgical correction of facial deformities using Maxilim. *Int J Oral Maxillofac Surg* 2013;42:801-6
18. Nadjmi N, Tehranchi A, Azami N et al.: Comparison of soft-tissue profiles in Le Fort I osteotomy patients with Dolphin and Maxilim softwares. *Am J Orthod Dentofacial Orthop* 2013;144:654-62
19. Bianchi A, Muyldermans L, Di Martino M et al.: Facial soft tissue esthetic predictions: validation in craniomaxillofacial surgery with cone beam computed tomography data. *J Oral Maxillofac Surg* 2010;68:1471-9
20. Almeida RC, Cevidanes LH, Carvalho FA et al.: Soft tissue response to mandibular advancement using 3D CBCT scanning. *Int J Oral Maxillofac Surg* 2011;40:353-9
21. Jeon H, Lee SJ, Kim TW, Donatelli RE: Three-dimensional analysis of lip and perioral soft tissue changes after debonding of labial brackets. *Orthod Craniofac Res* 2013;16:65-74
22. San Miguel Moragas J, Van Cauteren W, Mommaerts MY: A systematic review on soft-to-hard tissue ratios in orthognathic surgery part I: Maxillary repositioning osteotomy. *J Craniomaxillofac Surg* 2014
23. Peled M, Ardekian L, Krausz AA, Aizenbud D: Comparing the effects of V-Y advancement versus simple closure on upper lip aesthetics after Le Fort I advancement. *J Oral Maxillofac Surg* 2004;62:315-9
24. Coleman S, Saboeiro A, Sengelmann R: A comparison of lipoatrophy and aging: volume deficits in the face. *Aesthetic Plast Surg* 2009;33:14-21
25. Shaweesh AI, Clement JG, Thomas CD, Bankier A: Construction and use of facial archetypes in anthropology and syndrome diagnosis. *Forensic Sci Int* 2006;159 Suppl 1:S175-85
26. Weber DW, Fallis DW, Packer MD: Three-dimensional reproducibility of natural head position. *Am J Orthod Dentofacial Orthop* 2013;143:738-44
27. Kau CH, Cronin A, Durning P et al.: A new method for the 3D measurement of postoperative swelling following orthognathic surgery. *Orthod Craniofac Res* 2006;9:31-7
28. Kazandjian S, Sameshima GT, Champlin T, Sinclair PM: Accuracy of video imaging for predicting the soft tissue profile after mandibular set-back surgery. *Am J Orthod Dentofacial Orthop* 1999;115:382-9
29. Proffit WR, Phillips C, Turvey TA: Stability following superior repositioning of the maxilla by LeFort I osteotomy. *Am J Orthod Dentofacial Orthop* 1987;92:151-61
30. Joss CU, Vassalli IM: Stability after bilateral sagittal split osteotomy advancement surgery with rigid internal fixation: a systematic review. *J Oral Maxillofac Surg* 2009;67:301-13
31. Proffit WR, Phillips C, Dann Ct, Turvey TA: Stability after surgical-orthodontic correction of skeletal Class III malocclusion. I. Mandibular setback. *Int J Adult Orthodon Orthognath Surg* 1991;6:7-18
32. Schwartz HC: Does computer-aided surgical simulation improve efficiency in bimaxillary orthognathic surgery? *Int J Oral Maxillofac Surg* 2014;43:572-6

Chapter 4

Three-dimensional virtual simulation of alar width changes following bimaxillary osteotomies.

Liebregts JHF, Xi T, Schreurs R, van Loon B, Bergé SJ, Maal TJ.

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Abstract

Purpose: The purpose of this study was to evaluate the accuracy of 3D soft tissue simulation of nose width changes following bimaxillary osteotomies and to identify patient and surgery related factors that may affect the accuracy of the simulation.

Materials and methods: Sixty patients (mean 26.0 years) who underwent bimaxillary osteotomies participated in this study. Cone-beam CT scans were acquired pre-operatively and one-year postoperatively. The 3D hard- and soft tissue rendered pre- and postoperative virtual head models were superimposed, after which the maxilla and mandible were segmented and aligned to the postoperative position. The postoperative changes in alar width were simulated using a mass tensor model based algorithm and compared with the postoperative outcome. 3D Cephalometric analyses were used to quantify the simulation error.

Results: The postoperative alar width was increased by 1.6 ± 1.1 mm and the mean error between the 3D simulation and the actual postoperative alar width was 1.0 ± 0.9 mm. The predictability was correlated with the magnitude of maxillary advancement. Factors such as age, gender, alar cinch, VY closure and a history of SARME were not of influence to the accuracy of the simulation.

Conclusion: The MTM based simulation model of postoperative alar width changes was found to be reasonably accurate.

Introduction

The nasolabial region is the central aesthetic unit of the face and is considered to be one of the most important determinants of facial aesthetics [1]. To achieve a good functional as well as aesthetic result, it is important to understand the effects that orthognathic surgery will have on the soft tissue within the nasiolabial region. This is particularly the case when the displacement of maxillary complex is involved, such as in bimaxillary surgery. Various studies [2-4] reported that the alar width is subdued to the most changes postoperatively whereas the nasal tip is the least affected in the nasiolabial region. The frequently reported postoperative widening of the alar base leads to an increased soft tissue nose base width, which may be undesirable and unaesthetic [5]. To counteract this excessive increase in alar width different suturing methods can be applied, such as alar cinch, VY-closure and modified alar cinch [6-8].

3D soft tissue simulation is a useful tool to preview the outcome of orthognathic surgery, both for surgeons as well as patients, especially in an era in which shared decision-making is becoming more and more important in the treatment planning [9, 10]. Several computed-based strategies have been adopted to perform 3D virtual soft tissue simulations [11-13]. Mollemans et al. found that the highest accuracy was obtained by using a finite element model (FEM) or a mass tensor model (MTM). The MTM seemed to be more suitable for clinical use because of a significant time gain in simulation.

Over the years many previous studies have reported the hard and soft tissue changes in simulation and their relation to orthognathic surgery [13-15]. However, none of these simulation studies focused on the nasiolabial region after bimaxillary surgery despite its prominent role in facial aesthetics. It is yet unclear whether the 3D soft tissue simulation is able to predict the most important change of the nose, alar widening.

The aim of this study was to evaluate the accuracy of the 3D soft tissue simulation of changes in alar width following bimaxillary osteotomies.

Material and Methods

Patients

Patients with non-syndromic dysgnathia requiring bimaxillary osteotomy who underwent bimaxillary osteotomies between 2007 and 2011 at the Department of Oral and Maxillofacial Surgery in Radboudumc Nijmegen were enrolled in the present study. Inclusion criteria were the availability of a cone beam computed tomography (CBCT) scan before and at least six months after surgery. The exclusion criteria were a previous history of BSSO or previously bimaxillary surgery, simultaneously performed surgery other than bimaxillary osteotomy, the usage of a chin support during CBCT-scanning, the presence of orthodontic labial appliances in the postoperative CBCT-scan, the absence of upper and/or lower incisors and extensive restorative dental treatment during the postoperative follow-up period.

This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research ethics. The approval of the regional medical ethics review board (CMO Arnhem-Nijmegen) was obtained for this study. All patient data were anonymized and de-identified prior to analysis.

Data acquisition

Preoperative and postoperative CBCT imaging data were obtained two weeks prior to and at least six months after bimaxillary surgery using a standard CBCT scanning protocol (i-CAT, 3D Imaging System, Imaging Sciences International Inc, Hatfield, PA, USA) in “Extended Field” modus (field of view: 16 cm in diameter/22 cm in height; scan time: 2x20 seconds; voxel size: 0.4 mm). All patients were scanned while seated in a natural head position. They were asked to swallow, relax their lips and facial muscles and to keep their eyes open. The acquired CBCT data were saved in DICOM format and exported into Maxilim® software (Medicim NV, Mechelen, Belgium). In Maxilim, a 3D virtual augmented head model was rendered [16].

Simulation of soft tissue profile

The pre- and postoperative 3D virtual head models were matched using voxel-based registration on an unaltered sub volume that consisted of the cranial base, forehead and zygomatic arches [17]. Virtual Le Fort I and BSSO osteotomies were made on the preoperative 3D virtual head model according to the actual osteotomies performed during surgery.

In Maxilim, a soft tissue simulation was carried out based on the simulated skeletal movements using a MTM soft tissue simulation algorithm. In order to exclude discrepancies between the planned skeletal movement and the actual displacement of the bimaxillary complex at surgery, the virtually osteotomized maxilla and mandible were aligned with the position of the maxilla and mandibula in the postoperative scan using surface based registration as described in our previous study [14]. In this way, the simulated skeletal movements duplicated the actual jaw displacements during surgery. Thereafter the result of the soft tissue simulation could be compared with the actual postoperative soft tissue profile (Figure 1).

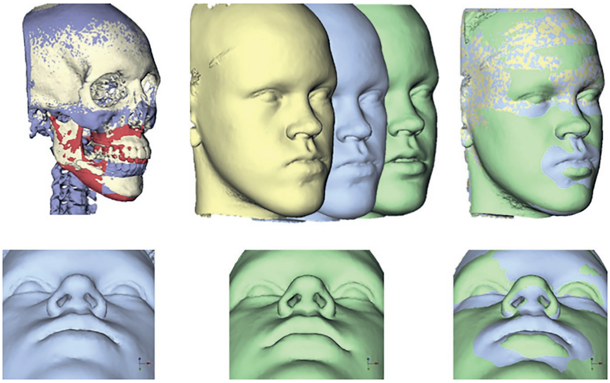


Figure 1. The registration procedure for the preoperative, postoperative, and simulated facial profiles.

(a) Voxel-based registration of the preoperative (blue/red) and postoperative (white) CBCT scans. (b) Preoperative soft tissue facial profile (yellow), simulated soft tissue outcome (Maxilim) according to the bimaxillary osteotomy performed (blue), and postoperative soft tissue facial profile (green). (c) The simulated facial profile is compared with the preoperative and postoperative situation. It can be seen that postoperative soft tissue overestimated the postoperative increase in alar width. (d) A close-up caudal view of the simulated soft tissue outcome according to the bimaxillary osteotomy performed. (e) A close-up caudal view of the postoperative soft tissue outcome according to the bimaxillary osteotomy performed. (f) A close-up caudal view of the simulated soft tissue facial profile compared with the postoperative result.

Analysis of soft tissue simulation

The accuracy of the soft tissue simulation was evaluated by 3D cephalometric analysis using three soft tissue; subnasale, alare left (al_l), alare right (al_r) and two hard tissue landmarks, upper incisor landmark (I_{sup}) and nasion. Euclidean distances were computed for all corresponding landmarks between the soft tissue simulation and the actual postoperative result as a measure for the accuracy of soft tissue simulation (figure 2). The Euclidean distances between the corresponding landmarks (upper incisor and nasion) in the pre- and postoperative scans were also calculated, to assess the actual surgical movements.

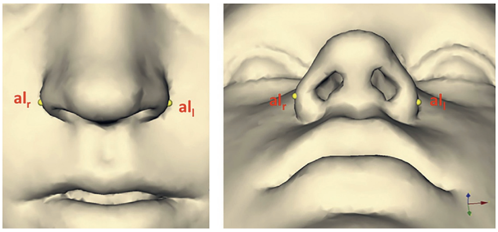


Figure 2. Frontal and inferior view of the nose for the measurement of alar width based on the cephalometric points identified, alr (alare right) and all (alare left), defined as the most lateral point on each alar contour.

Statistical analysis

Statistical data analyses were performed with IBM SPSS software, version 21.0.1 (IBM Corp., Armonk, NY, USA). The 3D cephalometric data were used to compute the mean amount of surgical advancement and simulation error of the postoperative alar width changes, expressed in terms of mean absolute error, standard deviation and range.

The postoperative alar width was compared with the simulated alar width using the student's paired t-test and Pearson correlation. To identify the potential risk factors for large simulation errors and postoperative alar widening, linear regression was performed, involving factors such as age at surgery, sex, amount of surgical advancement at I_{sup}, alar cinch suture and V-Y closure. ANOVA was used to evaluate the role of previously performed surgically assisted rapid maxillary expansion (SARME) and large advancements (I_{sup} > 4mm) on the accuracy of the alar width simulation.

Results

The study population consisted of 60 patients, 45 females (75%) and 15 males (25%). The mean age at surgery was 26 (range 15-58) years. The mean follow-up time was 14 months (range 6-35 months). Twenty-six patients underwent a SARME prior to the bimaxillary surgery. A summary of the patients' characteristics at surgery is presented in table 1. The alar cinch suturing technique was applied on 22 patients and V-Y closure was applied on 14 patients. Twelve patients had V-Y closure and alar cinch as suturing technique.

Table 1 Patients' characteristics

	Mean	SD	Range Min - max
Age (yr)	26	± 9.9	15 - 58
Gender			
- Male	15		
- Female	45		
Follow up (months)	14	± 6	6 - 35
Advancement of I_{sup} (mm)	2.7	± 1.9	-0,7 - 8.7
Alar width preoperative	34.8	± 2.9	27.6 - 42.9
Alar width simulation	35.9	± 3.1	29.0 - 44.6
Alar width postoperative	36.2	36.2	30.0 - 45.1
Maxillary advancement of A point (mm)	-0,31	1,98	-5,90 - 3,70
Maxillary vertical A point displacement (mm)	1,61	1,64	-2,30 - 5,60

Maxillary advancement of A point: A positive value means that the maxilla was positioned more posteriorly than the preoperative position a negative value means that he maxilla was positioned more anteriorly than the preoperative position. Maxillary vertical A point displacement: a positive value means that the maxilla was positioned more caudal compared the preoperative position, a negative value means that the maxilla was positioned more cranial compared to the preoperative position.

Postoperative changes of the alar base

The alar width was increased by a mean of 1.4 mm, from 34.8 ± 2.9 mm prior to surgery to 36.2 ± 3.1 mm and the mean absolute difference between alar width postoperative and preoperative was 1.6 ± 1.1 mm 14 months after surgery. The linear regression analysis demonstrated that the postoperative alar width was positively correlated to the amount of maxilla advancement, whereas variables as age, gender, alar cinch, VY closure and a history of SARME were not correlated with a postoperative increase of alar width (table 2). For every 1 mm of maxillary advancement, the alar width increased with 0.24 mm.

Table 2 Linear regression analyses of different variables in predicting absolute postoperative and preoperative alar with changes.

Predictor	B	(95%-CI)	P value
Age	0.02	(-0.17 – 1.69)	0.16
Gender	-0.06	(-0.65 – 0.53)	0.83
Alar cinch	-0.06	(-0.69 – 0.57)	0.86
VY-closure	-0.33	(-1.05 – 0.40)	0.37
Advancement I_{sup}	0.24	(0.10 – 0.37)	<0.01
SARME in history	-0.45	(-0.96 – 0.07)	0.09

Explained variance (R^2)=0.05

Soft tissue simulation accuracy of the nasal base

3D Cephalometric analysis of the simulation versus the actual postoperative results showed a mean absolute simulation error of 1.0 ± 0.9 mm in alar width (p=0.15). A high correlation was found between the simulation and postoperative result (Pearson's r=0.91; p=<0.01) as seen in figure 3. To identify the potential factors that may affect the accuracy of the alar width simulation, a linear regression analysis was carried out. Table 3 demonstrated that factors such as age, gender, alar cinch, VY closure and a history of SARME were not of influence to the accuracy of the simulation.

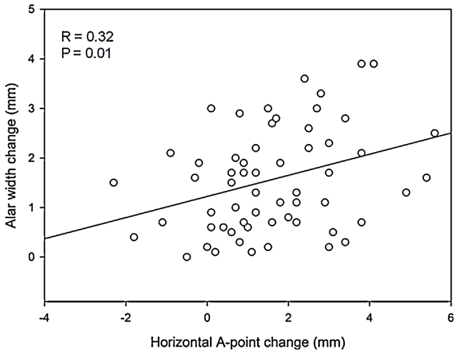


Figure 3. The correlation between alar width change and maxillary advancement at A point (the deepest point on the curve of the maxilla between the anterior nasal spine and the dental alveolus).

To investigate the affect of maxillary advancement on the accuracy of the alar width simulation, 60 patients were divided into 2 groups. Thirteen patients had a maxillary advancement at I_{sup} of greater than 4 mm (mean absolute error alar width of 1.01 ± 0.86 mm) and 47 patients had an advancement at I_{sup} of less than 4 mm (mean absolute error alar width of 1.08 ± 0.94 mm). No significant simulation error was found between the two groups, suggesting that the amount of maxillary advancement did not affect the magnitude of simulation error [F(1, 58) = 3.37, p=0.07].

Twenty-six patients had a SARME prior to the bimaxillary surgery. ANOVA revealed no significant differences between patients with and without a history of SARME with regard to the actual postoperative widening of alar width (p=0.47) and the accuracy of alar width simulation [F(1, 58) = 1.45, p=0.23].

Table 3 Linear regression analyses of different variables in predicting simulation error in alar width changes.

Predictor	B (95%-CI)	P value
Age	-0.00 (-0.03 – 0.02)	0.75
Gender (male vs. female)	0.34 (-0.20 – 0.89)	0.21
Alar cinch (alar cinch vs. no alar cinch)	0.08 (-0.50 – 0.66)	0.79
VY-closure (VY-closure vs. no VY-closure)	-0.10 (-0.77 – 0.57)	0.77
Advancement I_{sup} (mm)	-0.02 (-0.15 – 0.10)	0.71
SARME in history	0.25 (-0.22 – 0.72)	0,29

Explained variance (R^2)=0.05

Discussion

The increase of alar width is a common phenomenon following bimaxillary surgery [18]. As a result of the muscular detachment and translational and rotational movement of the maxilla during bimaxillary surgery, the alar width and nose tip projection tend to change postoperatively [19]. The increase of alar width was reported to vary between 0.79 and 2.45 mm as the result of bimaxillary surgery [2, 3, 20, 21]. This postoperative increase of alar width was believed to be related to the anterior movement of the maxilla, irrespective of additional upward or downward maxillary rotations [22]. However, several other surgical related factors as well as patient related factors were also reported to be related to the increase in alar width, such as the use of alar cinch sutures, age, gender and ethnic background of patients, making it difficult for surgeons to anticipate the postoperative changes [23]. As the postoperative widening of the nose base may be aesthetically undesirable, especially in patients with a wide nose prior to surgery, it would be ideal to be able to predict the alar widths changes during the planning of bimaxillary osteotomy.

With the introduction of CBCT, OMF surgeons have a powerful imaging tool to depict the facial soft and hard tissue in 3D with a lower radiation dose than conventional CTs [9, 13, 24]. Upon the rendered virtual 3D head model, virtual osteotomies and planned surgical movements can be performed. Simultaneously, the accompanied soft tissue changes can be visualized, as an aid to achieve a harmonious postoperative facial profile [25, 26]. The postoperative surgical outcome is, therefore, becoming more and more dependent on the accuracy of the soft tissue simulation.

Several recent studies have been published concerning the accuracy of mass spring model (MSM) based [12, 13], finite element model (FEM) based [10, 11, 27] and mass tensor model (MTM) based [12, 28, 29] soft tissue simulations of postoperative facial profile changes following orthognathic surgery. The FEM and MTM based soft tissue simulations were reported to be accurate in the simulation of postoperative soft tissue changes in the peri-oral and mental regions, with a mean absolute error of 0 to 1.4 mm [13, 14]. However, the accuracy of soft tissue simulation of postoperative changes in the nasal region, the alar width in particular, has not yet been thoroughly investigated despite the widely recognized risk of undesired alar width increase following bimaxillary surgery. It is unclear whether the 3D soft tissue simulation is able to predict the postoperative alar widening. Taking the prominent role that the alar width plays in facial esthetics into account, the current study is thus focused on the predictability of simulated alar width changes following bimaxillary surgery.

The present study reported a mean absolute simulation error of 1.0 mm in postoperative alar width changes using MTM algorithm (Maxilim software). These results are similar to the findings of Schendel et al. [13], who used the MSM algorithm model for the simulation of alar width changes. Simulation errors in the range of 0 to 2 mm were found. This relatively large variance may be related to the fact that patients in this study underwent different types of mono- and bimaxillary osteotomies, whereas patients in the presented study all underwent bimaxillary osteotomy. Although the clinical relevance of this simulation error of 1.0 mm is limited, this error is large with regard to the mean simulated alar widening of 1.6 mm. Therefore, it should be questioned whether the MTM algorithm is able to simulate the postoperative alar width changes following bimaxillary surgery accurately.

The linear regression analysis showed that the error of alar width simulation was neither correlated to patient related factors such as age and gender nor to surgery related factors such as the use of alar cinch suture and maxillary advancement. Previous clinical studies have reported a clear correlation between the magnitude of maxillary advancement and the degree of postoperative alar widening [23, 30, 31]. According to the MTM model, the simulation error is positively correlated to the jaw displacement [12]. Thus, it is expected to increase as the maxillary advancement increases, in contrary to our results. This lack of correlation between the simulation error of alar widening and maxillary advancement seemed to point out that the MTM model is unable to exhibit the correct relationship between postoperative alar changes and maxillary displacement.

Due to the CBCT related truncated view artefact, this study presented only the alar width simulation after bimaxillary surgery. Truncated view artefacts occurs as the result of the fact that the field of view (FOV) used in CBCT is smaller than the size of the object being imaged, leading to “incomplete data” and a limited field of view. Because of the limited size of the detector in CBCT scanners, the most affected regions are situated near the edge of the FOV, at the nose region [32, 33]. Nowadays the majority of CBCT scanners are equipped with specific algorithms to partly solve this issue, which leads to a sharper visualisation of the soft tissue nose. Unfortunately, the nose tip still cannot always be visualized with the correct 3D geometry as demonstrated in figure 4.

The MTM is based on a biomechanical model in which tissue properties such as the tissue elasticity and stiffness are incorporated based on measurements within a clinical control group. These tissue properties can be measured in an accurate manner at the region of the chin, lower lip and upper lip. For the nose, however, the quantification of these properties is not so straightforward because the nose contains relatively large air-filled cavities which impede the accurate computation of soft tissue changes by the MTM model. This underlying shortcoming of the MTM model, leading to the relatively large simulation error of the postoperative alar widening, limits its application in the soft tissue simulation of the nasal region.

A possible solution to enhance the simulation accuracy of surgery related nasal soft tissue changes could be the use of a statistical simulation model. By incorporating the soft tissue data obtained from long-term clinical follow-up of orthognathic patients in statistical models, i.e. principal component analysis and active shape modelling, the 3D simulation software can be trained to simulate the effects of orthognathic surgery on the whole nasal area based on clinically If enough clinical data is incorporated in such a statistical model, it will be possible to predict the postoperative nasal changes more accurately than relying on biomechanical algorithms. This topic is now one of the focus in future research with regard to 3D planning and simulation of orthognathic patients.

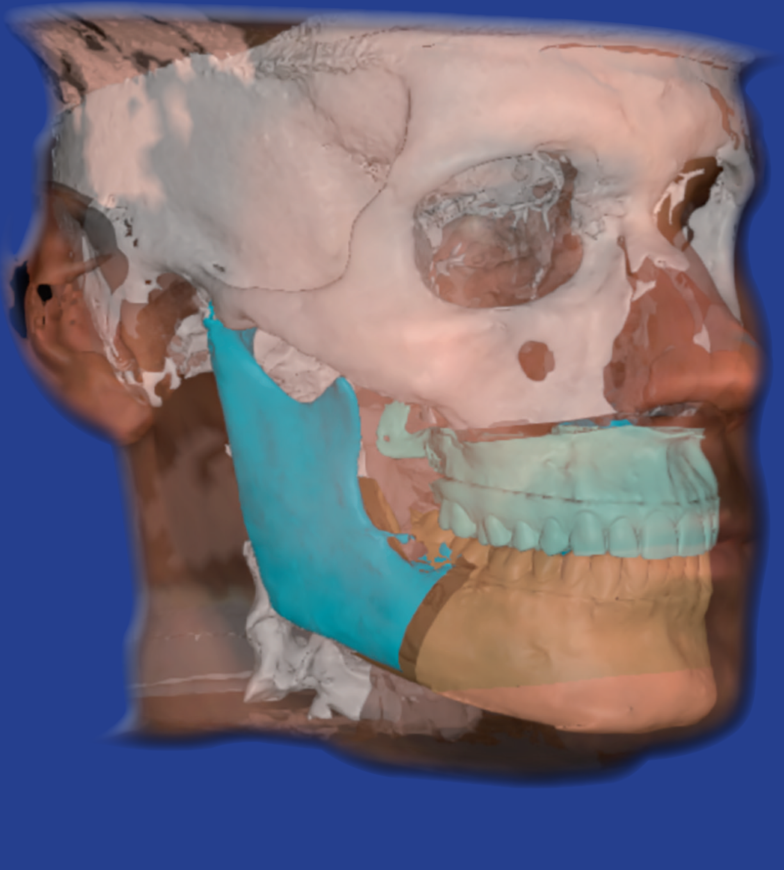
By the result of the current study we believe that further enhancement of the 3D planning and simulation of orthognathic surgery should focus on the surgical related changes of the nasal region. There is undoubtedly room for further enhancement of the accuracy of the alar width soft tissue simulation. The 3D simulation of the changes of the complete nose due to orthognathic surgery is an even bigger challenge, though very clinically relevant regarding the dominant role of the nasal labial region for the facial aesthetics. More clinical validation studies on this topic are recommended to provide evidence regarding the accuracy of soft tissue simulation used in various commercially software packages and using different simulation models. The incorporation of statistical data of previous treated patients can possibly resolve the shortcomings of biomechanical models used in this study.

The MTM based 3D soft tissue simulation of alar width changes after bimaxillary surgery was found to be reasonably accurate for daily clinical use. The accuracy of the simulation is correlated to the amount of maxillary advancement. Age, gender, or the usage of alar cinch or V-Y closure had no influence in the accuracy of the 3D simulation. A more accurate and clinically based model for the 3D soft tissue simulation of the entire nose should be developed, validated and incorporated into the 3D surgical planning software to inform the patients on the undesired effects of bimaxillary surgery in the nasal region.

References

1. Mitchell, C., et al., *Nasolabial aesthetics.* J Craniofac Surg, 2007. **18**(4): p. 756-65.
2. Park, S.B., et al., *The evaluation of the nasal morphologic changes after bimaxillary surgery in skeletal class III maloccusion by using the superimposition of cone-beam computed tomography (CBCT) volumes.* J Craniomaxillofac Surg, 2012. **40**(4): p. e87-92.
3. Soncul, M. and M.A. Bamber, *Evaluation of facial soft tissue changes with optical surface scan after surgical correction of Class III deformities.* J Oral Maxillofac Surg, 2004. **62**(11): p. 1331-40.
4. Ubaya, T., et al., *Soft tissue morphology of the naso-maxillary complex following surgical correction of maxillary hypoplasia.* Int J Oral Maxillofac Surg, 2012. **41**(6): p. 727-32.
5. Liu, X., S. Zhu, and J. Hu, *Modified versus classic alar base sutures after LeFort I osteotomy: a systematic review.* Oral Surg Oral Med Oral Pathol Oral Radiol, 2014. **117**(1): p. 37-44.
6. Millard, D.R., Jr., *The alar cinch in the flat, flaring nose.* Plast Reconstr Surg, 1980. **65**(5): p. 669-72.
7. Chen, C.Y., C.C. Lin, and E.W. Ko, *Effects of two alar base suture techniques suture techniques on nasolabial changes after bimaxillary orthognathic surgery in Taiwanese patients with class III malocclusions.* Int J Oral Maxillofac Surg, 2015. **44**(7): p. 816-22.
8. Muradin, M.S., et al., *The effect of alar cinch sutures and V-Y closure on soft tissue dynamics after Le Fort I intrusion osteotomies.* J Craniomaxillofac Surg, 2009. **37**(6): p. 334-40.
9. Schendel, S.A. and R. Jacobson, *Three-dimensional imaging and computer simulation for office-based surgery.* J Oral Maxillofac Surg, 2009. **67**(10): p. 2107-14.
10. Marchetti, C., et al., *Validation of new soft tissue software in orthognathic surgery planning.* Int J Oral Maxillofac Surg, 2011. **40**(1): p. 26-32.
11. Marchetti, C., et al., *Mathematical modeling and numerical simulation in maxillofacial virtual surgery.* J Craniofac Surg, 2007. **18**(4): p. 826-32.
12. Mollemans, W., et al., *Predicting soft tissue deformations for a maxillofacial surgery planning system: from computational strategies to a complete clinical validation.* Med Image Anal, 2007. **11**(3): p. 282-301.
13. Schendel, S.A., R. Jacobson, and S. Khalessi, *3-dimensional facial simulation in orthognathic surgery: is it accurate?* J Oral Maxillofac Surg, 2013. **71**(8): p. 1406-14.
14. Liebregts, J., et al., *Accuracy of three-dimensional soft tissue simulation in bimaxillary osteotomies.* J Craniomaxillofac Surg, 2015. **43**(3): p. 329-35.
15. Liebregts, J.H., et al., *Three-dimensional facial simulation in bilateral sagittal split osteotomy: a validation study of 100 patients.* J Oral Maxillofac Surg, 2015. **73**(5): p. 961-70.
16. Swennen, G.R., et al., *A cone-beam computed tomography triple scan procedure to obtain a three-dimensional augmented virtual skull model appropriate for orthognathic surgery planning.* J Craniofac Surg, 2009. **20**(2): p. 297-307.
17. Nada, R.M., et al., *Accuracy and reproducibility of voxel based superimposition of cone beam computed tomography models on the anterior cranial base and the zygomatic arches.* PLoS One, 2011. **6**(2): p. e16520.

18. van Loon, B., et al., *Three-dimensional changes in nose and upper lip volume after orthognathic surgery.* Int J Oral Maxillofac Surg, 2015. **44**(1): p. 83-9.
19. Altman, J.I. and J.C. Oeltjen, *Nasal deformities associated with orthognathic surgery: analysis, prevention, and correction.* J Craniofac Surg, 2007. **18**(4): p. 734-9.
20. Vasudavan, S., Y.S. Jayaratne, and B.L. Padwa, *Nasolabial soft tissue changes after Le Fort I advancement.* J Oral Maxillofac Surg, 2012. **70**(4): p. e270-7.
21. Yamada, T., et al., *Nasolabial morphologic changes after a Le Fort I osteotomy: a three-dimensional anthropometric study.* J Craniofac Surg, 2010. **21**(4): p. 1089-95.
22. Honrado, C.P., et al., *Quantitative assessment of nasal changes after maxillomandibular surgery using a 3-dimensional digital imaging system.* Arch Facial Plast Surg, 2006. **8**(1): p. 26-35.
23. Khamashta-Ledezma, L. and F.B. Naini, *Prospective assessment of maxillary advancement effects: maxillary incisor exposure, and upper lip and nasal changes.* Am J Orthod Dentofacial Orthop, 2015. **147**(4): p. 454-64.
24. De Vos, W., J. Casselman, and G.R. Swennen, *Cone-beam computerized tomography (CBCT) imaging of the oral and maxillofacial region: a systematic review of the literature.* Int J Oral Maxillofac Surg, 2009. **38**(6): p. 609-25.
25. Abed, Y., G. Har-Zion, and M. Redlich, *Lip posture following debonding of labial appliances based on conventional profile photographs.* Angle Orthod, 2009. **79**(2): p. 235-9.
26. Haas Jr, O.L., O.E. Becker, and R.B. de Oliveira, *Computer-aided planning in orthognathic surgery-systematic review.* Int J Oral Maxillofac Surg, 2014.
27. Marchetti, C., et al., *Mathematical modeling and numerical simulation in maxillo-facial virtual surgery (VISU).* J Craniofac Surg, 2006. **17**(4): p. 661-7; discussion 668.
28. Nadjmi, N., et al., *Comparison of soft-tissue profiles in Le Fort I osteotomy patients with Dolphin and Maxilim softwares.* Am J Orthod Dentofacial Orthop, 2013. **144**(5): p. 654-62.
29. Shafi, M.I., et al., *The accuracy of three-dimensional prediction planning for the surgical correction of facial deformities using Maxilim.* Int J Oral Maxillofac Surg, 2013. **42**(7): p. 801-6.
30. Howley, C., et al., *Use of the alar base cinch suture in Le Fort I osteotomy: is it effective?* Br J Oral Maxillofac Surg, 2011. **49**(2): p. 127-30.
31. Ryckman, M.S., et al., *Soft-tissue changes after maxillomandibular advancement surgery assessed with cone-beam computed tomography.* Am J Orthod Dentofacial Orthop, 2010. **137**(4 Suppl): p. S86-93.
32. Jaju, P.P., et al., *Artefacts in cone beam CT.* Open Journal of Stomatology, 2013. **Vol.03No.05**: p. 6.
33. Lehr, J.L., *Truncated-view artifacts: clinical importance on CT.* AJR Am J Roentgenol, 1983. **141**(1): p. 183-91.



Chapter 5

A new 3D approach to evaluate facial profile changes following BSSO.

Liebregts JHF*, Meulstee J*, Xi T, Vos F, de Koning M, Bergé SJ, Maal TJ.

* Both authors contributed equally

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Abstract

Purpose: The purpose of this study was to evaluate changes in soft tissue facial profile in patients who underwent bilateral sagittal split osteotomy (BSSO) using 3D stereophotogrammetry and Principal Component Analysis (PCA).

Materials and methods: 25 female patients (mean age of 24 years, range: 18-26) who underwent a BSSO and 70 female controls (mean age 24 years, range: 18-26) participated in this prospective study. 3D photographs of all patients and controls were acquired. PCA was used to determine the morphological variations (UV) between the dysgnathic group and the control group.

Results: The most prominent facial morphologic difference between the dysgnathic group and control group (UV1) was a clockwise rotation of the mandible and shortening of the lower part of the face, followed by a protrusion of the upper lip, retrusion of the mandible and over-accentuation of the labial-mental fold (UV2). The combination of UV1 and UV2 could be used to simulate a typical Class II facial profile and to automatically differentiate between the preoperative patients, postoperative patients and the control group.

Conclusion: Based on the applied PCA method, this study demonstrated that BSSO advancement surgery could only provide a suboptimal improvement of the soft tissue facial profile in the majority of cases.

Introduction

Orthognathic surgery is performed to correct a wide range of dentoskeletal deformities and to provide functional improvements in mastification, speech and breathing. Besides functional improvements, the patient's appearance and facial harmony can be enhanced significantly as a result of surgery. Several studies described the optimal dentofacial profile and the suitable methods to obtain facial harmony by means of orthognathic surgery [1, 2]. This awareness of obtaining facial balance in combination with the introduction of three-dimensional (3D) planning of the soft tissue in the recent years have evolved the treatment philosophy from the conventional occlusion-centred planning to a soft tissue based planning, in order to achieve a more harmonious facial profile [3, 4]. Many two-dimensional (2D) cephalometric analyses have been used to quantify the soft tissue facial profile [5, 6]. However, 2D measurements have limited validity and reliability when used for the evaluation of the 3D face. Therefore, a complete 3D evaluation of the facial profile is preferred in orthognathic surgery [7]. The use of 3D imaging in oral- and maxillofacial surgery and orthodontics has evolved rapidly over the past decade [8]. Although many advances have been made in the 3D virtual planning and evaluation of orthognathic surgery, facial harmony is still difficult to quantify in an objective manner [9].

The aim of this study was to present a new 3D photogrammetry based automatic method for the quantification of variations in facial profile. This novel method was applied to evaluate the effect of BSSO advancement surgery on the facial profile of Class II patients in comparison to a sample of the Dutch population with a class I facial profile.

Patients and Methods

Patients

Female patients with dentofacial deformities who underwent a Bilateral Sagittal Split Osteotomy (BSSO) in the Department of Oral and Maxillofacial Surgery at the Radboud University Nijmegen Medical Centre were included in this prospective study. Informed consent was obtained from all participants. Approval from the regional medical ethics review board (CMO Arnhem-Nijmegen) was obtained for this study. This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research ethics.

Inclusion criteria were the presence of a preoperative 3D photograph acquired one to four weeks prior to surgery, and a postoperative 3D photograph acquired six to twelve months postoperatively to ensure that oedema was resolved and a full functional recovery was achieved. Exclusion criteria were large quality inconsistencies in the 3D photographs, previous history of orthognathic surgery and simultaneously performed orthognathic surgery other than a BSSO advancement such as genioplasty or Le Fort I osteotomy.

In order to create a normative reference for the soft tissue facial profile, a control group consisted of native Dutch females with Class I facial profile was created. Patients who underwent facial surgery in the past and whose BMI was under 18 or above 25 were excluded from the control group to ensure a representative control population.

Image Analysis

3D photographs of all patients and controls were acquired using the 3DMD stereophotogrammetry Facial system (3dMDFace, 3dMD, Atlanta, USA). All subjects were photographed while seated in natural head position, with relaxed facial musculature, eyes open and loosely closed lips. The acquired 3D photographs were imported into the 3DMDPatient© software (3dMDPatient, 3dMD, Atlanta, USA). Four soft tissue anatomical landmarks, subnasale, pogonion, left and right exocanthia, were identified. All photographs were subsequently exported to Matlab 7.0 (Mathworks, Natick, Massachusetts, USA) for further analysis, as described in the three following steps.

1. Using the previously assigned anatomical landmarks, each subject was automatically superimposed on a pre-existent generic facial template that was developed in our department as described by Zhurov et al. [10].
2. A newly developed iterative closest point (ICP) based algorithm was used for the precise and automatic registration of all 3D faces. This automatic registration reduced the registration errors, ensured the optimal fit and eliminated inconsistencies caused by the superimposition based on the manually indicated landmarks (step 1). Only the parts of the face that were not affected by BSSO (forehead, nose and cheeks) were used for the automatic registration [11].
3. The average face of the control population was computed. This average face replaced the generic facial template that was used in step 1 after which step 1 and 2 were repeated (figure 1).

Finding the unique variations of the face

In order to find the morphological variations in facial appearance among patients and controls, principal component analysis (PCA) was used. PCA is a statistical method, which is able to identify specific morphological variations in the dataset of all superimposed 3D photographs. The specific facial variations were defined as unique variations. The effects of each unique variation (UV) on the soft tissue facial profile were investigated. The UVs that described the variations in the retrusion of the mandible were used to distinguish patients with mandibular hypoplasia from the control population.

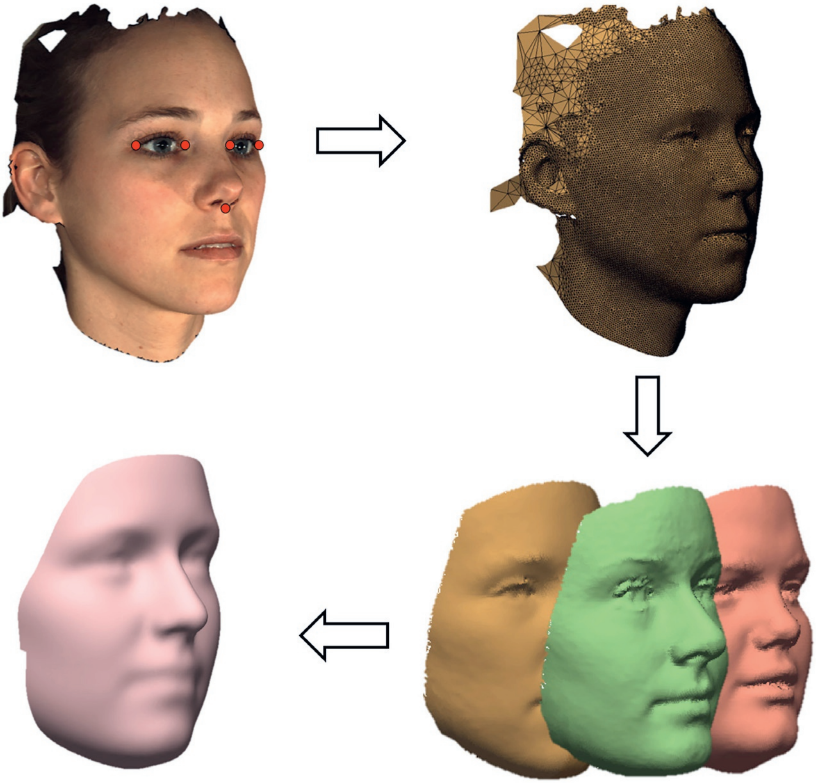

Figure 1: Computing the average face among the control population.

A) A 3D photograph was taken in the facial rest position on which anatomical landmarks were identified manually.
B) The polygon mesh of the 3D photograph was superimposed on a facial template.
C) All controls were superimposed in the same manner.
D) Calculation of the average face from the dataset. This average face was used as a new template and step 2 and 3 are repeated.

Statistical Analysis

IBM SPSS software, version 20.0.1 (IBM corp., Armonk, NY, USA) was used to perform the statistical data analysis. UV1 and UV2 were used to summarize the facial characteristics and to study the preoperative, the postoperative measurements of the patient group and to compare these with controls. The two sample Hotelling's T-test was used to compare the UV1 and UV2 scores between the preoperative situation and control population as well as between the postoperative situation and control population. One sample Hoteling's T test was used for the comparison of the preoperative and postoperative facial profiles in terms of UV1 and UV2. Bonferroni correction for multiple testing was applied.

Results

95 females were enrolled in this study, 25 female patients (mean age 24 years, range 18-26 years) and 70 female controls (mean age 24 years, range 18-26 years). The mean follow-up for the 25 BSSO patients was 7 months (range 6-12 months).

Variations in the soft tissue facial profile between the preoperative BSSO patients and the control group were identified by the automatized PCA based method presented earlier. A clockwise rotation of the mandible and a shortening of the lower part of the face were the most prominent differences between the two groups. This effect, referred to as UV1, is visualized with a color-coded distance map in figure 2. An animation of the variations in facial profile is accessible online.

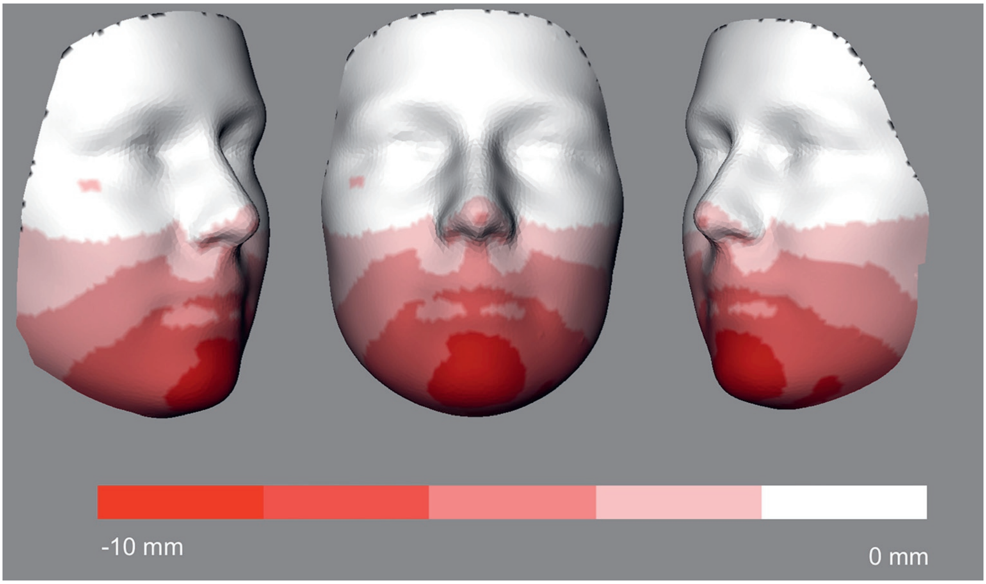

Figure 2 : The 3D coloured distance maps of the morphological effect of the first unique variation (UV1). UV1 described a clockwise rotation of the mandible and lower half of the face compared the average face (red).

Furthermore, a protrusion of the upper lip and a retrusion of the mandible were observed among the preoperative BSSO patients compared to the control group. Consequently, an over-accentuation of the labial-mental fold was present in the preoperative BSSO patient group compared to the control group. This morphological variation was defined as UV2. A typical Class II profile could be visualized when this unique variation was simulated (figure 3).

The aforementioned facial features (UV1 and UV2) were used to discriminate between the control group, the preoperative patient population and the postoperative patient population. For all subjects, the scores for UV1 and UV2 were calculated, grouped and plotted (figure 4). The effect of BSSO advancement surgery was evident. The postoperative group of BSSO patients (green) had shifted towards the control group (blue) compared to the preoperative situation (red). However, the postoperative group did not overlap the control group completely, indicating that many BSSO patients maintained some characteristics of Class II facial profile despite the surgery. Three examples of patients are demonstrated in figure 5.

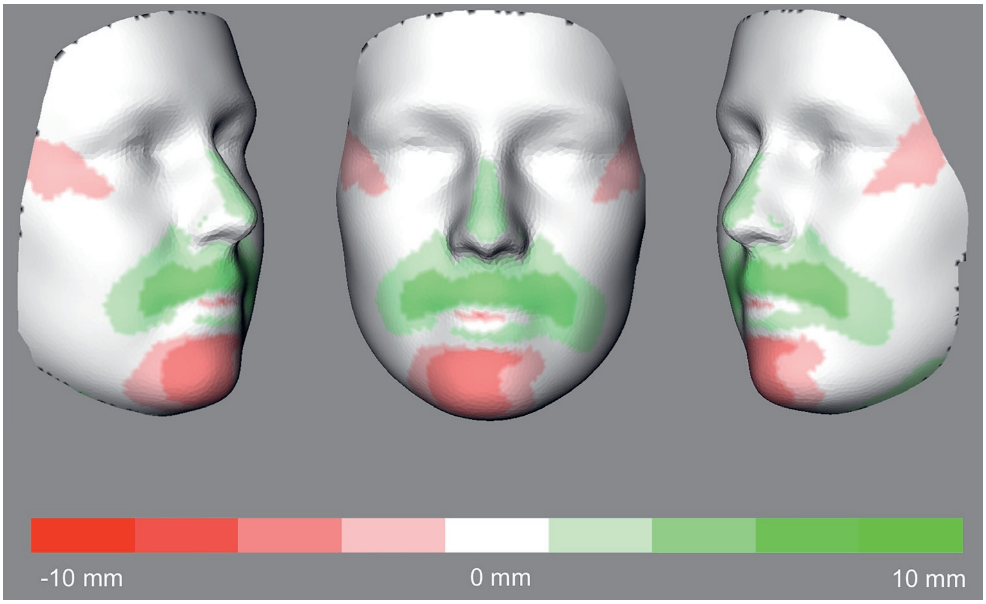

Figure 3: The 3D coloured histogram (distance map) of the second unique variation (UV2).

The green color indicated a volume increase and the red colour a volume loss. UV2 demonstrated a protrusion of the upper lip and a retrusion of the mandible. As a result, the labial-mental fold was over- accentuated and a typical Class-II profile was seen.

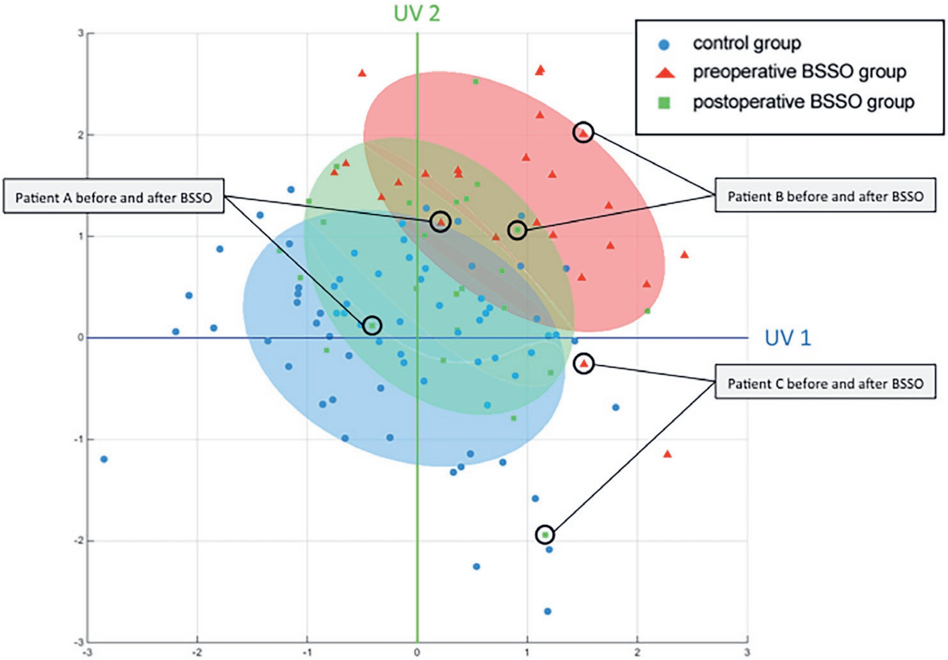

Figure 4: Scatterplot of preoperative patients (red), postoperative patients (green) and control group (blue).

UV1 was represented by the x-axis and UV2 by the y-axis. The ellipses involved 80% of the population in each group. The postoperative group consisted of the same individuals as the preoperative group. Note that the center of the plot (0,0) indicated the average face. For three patients (A, B and C) their preoperative and corresponding postoperative positions for UV1 and UV2 were marked.

Hotelling’s T-test demonstrated a significant difference between the control and the preoperative group: (F value = 46.68 and Pr > F = 0.0001). Also a significant difference between the preoperative and postoperative group was found (F value = 57.28 and Pr > F = 0.0001). A less but still significant difference was found between the control and the postoperative group (F value = 7.26 and Pr > F = 0.0012). This confirmed the observation that dysgnathic patients still possessed some dysgnathic facial characteristics despite the BSSO advancement surgery.

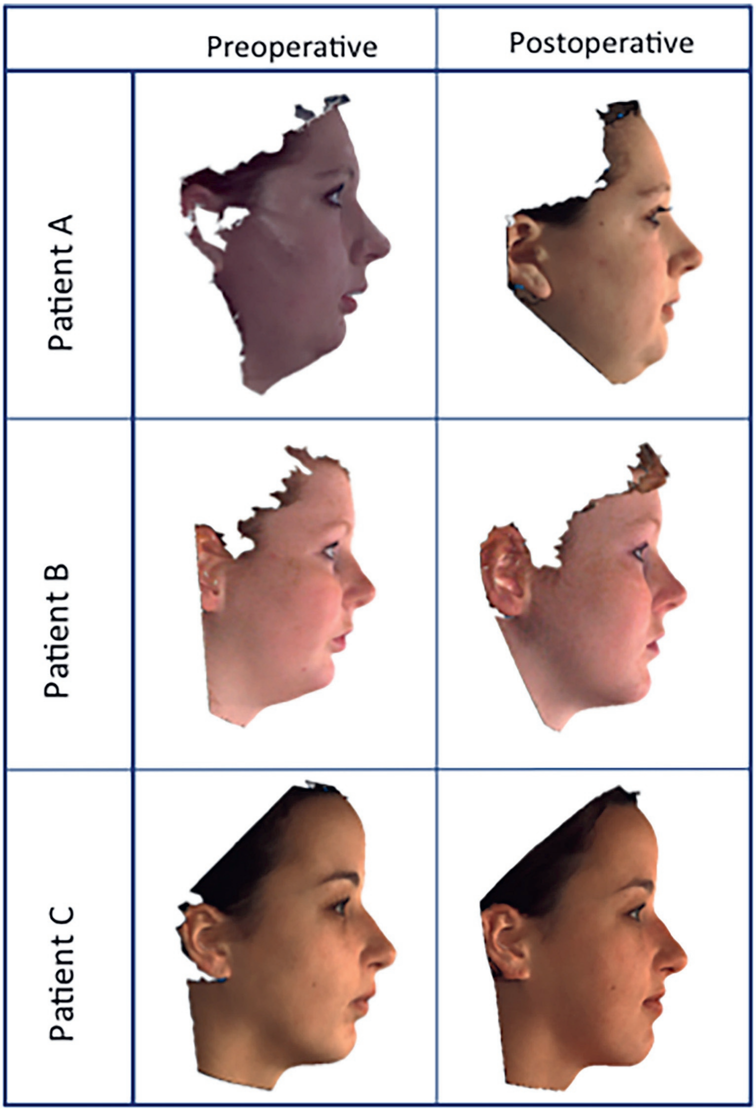

Figure 5: Preoperative and one-year postoperative 3D photographs of three patients (A, B and C).

Discussion

Principal Component Analysis

3D imaging of the face, in combination with a large number of patients, provides a valuable yet immense collection of data. In order to extract and evaluate the clinical relevant data concerning the facial morphology of patients, most studies use anatomical landmarks indicated on the 3D images [2, 12]. Although anatomical landmarks are positioned at relevant locations of the face, the overall appearance of the face is disregarded, making morphological variations of the facial profile between patients difficult to comprehend. To reduce data and yet to preserve the complete 3D facial morphology, PCA can be used for the evaluation of the face. PCA is a commonly used tool in modern data analysis in various disciplines, including neuroscience, meteorology, oceanography and computer graphics (Shlens, 2005). PCA is applied to reduce complex data in simplified structures or patterns. Claes et al. implemented PCA based applications in forensics and also used PCA based methods to correlate facial appearance with genomics [13, 14]. Hammond successfully applied a PCA based method to evaluate patients with a wide range of facial dysmorpholgies [15].

To the best knowledge of the authors, this is the first study using 3D stereophotogrammetry and PCA to evaluate the three-dimensional variations before and after orthognathic surgery.

3D Stereophotogrammetry

3D stereophotogrammetry is a safe and noninvasive imaging modality. It is able to capture high quality 3D photographs of the soft tissue facial profile in less than two milliseconds without the use of radiation [16]. These characteristics make 3D stereophotogrammetry a valuable tool for the collection of large 3D facial data sets, even the faces of young children or newborns.

At this moment, various commercial 3D imaging systems are available, such as3dMDfaceTM System (3dMD LLC, Atlanta, USA), Di3DTM (Dimensional Imaging, Glasgow, UK) and 3D-Sensors FaceSCAN3D (3D Shape GmbH, Erlangen, Germany).

The accuracy and reproducibility of 3D imaging systems have been investigated extensively in previous studies [17-19]. The accuracy of the 3DMD system was reported to be limited to 0.1 mm [17] whereas the reproducibility was 0.4 mm [20]. These results highlighted a good precision and reproducibility of 3D stereophotogrammetry for the evaluation of soft tissue facial profile in a clinical situation. To minimize the acquisition errors, in the present study, all 3D photographs were obtained by a trained and experienced photographer. In addition, all patients were carefully positioned with their head in natural head position and relaxed facial musculature, keeping the reproducibility error to a minimum [21].

Registration

3D photographs are composed of approximately 20,000 3D points resembling the morphological aspects of the face. Superimposition of these point clouds is essential in order to calculate the average face and facial variations between the subjects. Commonly used methods for superimposition are based on the procrustes analysis (PA) [22]. A major drawback of PA is its poor handling of outlier points [23]. In addition, scaling of subjects is not preferred because some morphological characteristics of the face may be omitted. Thus, a rigid transformation algorithm for the superposition is desirable such as the ICP algorithm. The ICP algorithm described by Besl and McKay is able to calculate the most optimal transformation to align two surfaces [24]. This algorithm was adapted by Wilm et al for facial surfaces (Kjer and Wilm, 2010). An optimised version of this ICP algorithm with an improved accuracy, robustness and reduced computation time for the superimposition was adopted in this study. This ICP algorithm was able to deal with unfavourable conditions such as an unequal distribution and unequal number of surface points.

Beside the registration algorithm, the selection of anatomical regions used for the registration might also have affected the accuracy. Only regions what were not affect by BSSO advancement surgery, such as the forehead, nose and exocanthia, were used as the reference region [11]. In this way, the registration error could be reduced further.

Quantification of the facial profile

UV1 and UV2 described respectively 52% and 6% of the total morphologic variations in the facial region. This supported the hypothesis that PCA is able to detect morphological differences between Class II patients and the control population. By changing the scores for UV1 and UV2, a Class II facial profile could be transformed towards the average face of the control group. As described earlier, figure 4 illustrated the preoperative group, postoperative group and control group in terms of UV1 (x-axis) and UV2 (y-axis) variations. A partial overlap between the preoperative group and the control group was observed. At first sight, this might not be expected as this suggested that a small number of Class II patients could already be classified as non-dysgnathic prior to surgery. However, as Class II skeletal relationship is the most prevalent among the Dutch population, the control population might have included a limited number of underdiagnosed mild Class II cases.

The comparison between the preoperative group (red) and the postoperative group (green) in figure 4 clearly illustrated the surgical effect of BSSO among Class II patients. This effect is demonstrated by a shift from the preoperative group (red) towards the control population (blue) on both the x-axis (UV1) and y-axis (UV2). In general, this corresponded with an increase of the lower facial height and an improvement of the over-accentuated labial-mental fold. Nevertheless, the surgical effect of BSSO was suboptimal when the postoperative group was compared to the control group because the postoperative group could still be distinguished from the control population.

Figure 5 showed the different degrees of preoperative Class II facial features prior to and following surgery.

The preoperative position of patient A in the graphical plot suggested that she possessed Class II facial features. As a result of BSSO, her postoperative position in the plot had shifted towards the control group, almost towards the average face of the control group (origin of the plot). These findings were supported by profile view of the 3D photographs (figure 5) of patient A.

By looking at the preoperative position of patient B in the graphical plot of the UVs, this patient was quantified as the most severe class II patient. As a result of BSSO, her postoperative position in the plot clearly shifted towards the control group. However, the fact that she was still located in the overlapping area of the control group and preoperative Class II group indicated that she could still be classified as a minor Class II patient, as demonstrated by the clinical features on preoperative and postoperative 3D photographs (figure 5).

In the same manner, regarding the preoperative position of patient C in the graphical plot, she could be regarded as part of the control group, especially because her UV2 score was within the range of the control population. This suggested that no direct surgery may be required to improve her facial profile. Nevertheless, her postoperative position in the graphical plot demonstrated an improvement for both UV1 and UV2, which should indicate more prominence of the chin region. The clinical photographs of patient C supported these findings.

Patient Selection

It can be questioned whether the selected control population used in this study is the optimal reference group for benchmarking dysgnathic patients. The majority of orthognathic patients wish to achieve more facial harmony and/or balance, rather than match anthropometric averages. This might suggest that it would be better to use generally perceived beautiful faces as a control group. These beautiful faces could for example be selected using laymen panels [25]. The difference between a control population and a beautiful population may also be an interesting topic for further research.

Clinical Relevance

The present study illustrated that the facial profile of a large number of the Class II patients differed from the average facial profile of an age and gender matched control group. By the incorporation of the PCA image analysis technique into the 3D virtual planning software, it has the potential to detect and quantify facial dysgnathia automatically. It provides us a new possibility for a patient specific estimation of the postoperative result based on a single preoperative 3D photograph.

The virtual simulation based on mass-tensor prediction models used in 3D orthognathic planning software lacks accuracy in the prediction of the lip region after BSSO or BIMAX surgery [26]. The model in this new study demonstrated excellent simulation of the lip region and labial-mental fold as can be seen in the animation which is available online. An incorporation of the statistical model in combination with the prediction models has the potential to improve the soft tissue simulation and complete orthognathic planning.

All patients included in this study underwent a BSSO advancement in order to correct the mandibular hypoplasia. During a BSSO advancement, however, the position of the distal segment is mainly dictated by the occlusion. This means that the influence of the surgeon on the final aesthetical outcome is limited. In bimaxillary surgery, the surgeon has more freedom to optimize the soft tissue facial profile. Therefore, it is expected that extrapolation of the proposed study model to a patients undergoing bimaxillary surgery (with or without a genioplasty) may illustrate an even greater shift of the soft tissue facial profile towards the control population after surgery. This will be subject of future research.

Conclusion

The automatic PCA based method of facial analysis was able to quantify and evaluate the effect of BSSO surgery on the facial profile and was able to differentiate between patients with mandibular hypoplasia from an age and gender matched control group. Patients who underwent BSSO surgery had a suboptimal improvement of their soft tissue facial profile.

References

1. Arnett, G.W. and R.T. Bergman, *Facial keys to orthodontic diagnosis and treatment planning. Part I.* Am J Orthod Dentofacial Orthop, 1993. **103**(4): p. 299-312.
2. Mommaerts, M.Y. and H. Marxer, *A cephalometric analysis of the long-term, soft tissue profile changes which accompany the advancement of the mandible by sagittal split ramus osteotomies.* J Craniomaxillofac Surg, 1987. **15**(3): p. 127-31.
3. Ackerman, J.L., W.R. Proffit, and D.M. Sarver, *The emerging soft tissue paradigm in orthodontic diagnosis and treatment planning.* Clin Orthod Res, 1999. **2**(2): p. 49-52.
4. Kau, C.H., et al., *Three-dimensional surface acquisition systems for the study of facial morphology and their application to maxillofacial surgery.* Int J Med Robot, 2007. **3**(2): p. 97-110.
5. Paiva, J.B., et al., *Facial harmony in orthodontic diagnosis and planning.* Braz Oral Res, 2010. **24**(1): p. 52-7.
6. Mees, S., et al., *Preferences of AP position of the straight Caucasian facial profile.* J Craniomaxillofac Surg, 2013. **41**(8): p. 755-63.
7. Schendel, S.A., R. Jacobson, and S. Khalessi, *3-dimensional facial simulation in orthognathic surgery: is it accurate?* J Oral Maxillofac Surg, 2013. **71**(8): p. 1406-14.
8. Liebregts, J.H., et al., *Three-dimensional facial simulation in bilateral sagittal split osteotomy: a validation study of 100 patients.* J Oral Maxillofac Surg, 2015. **73**(5): p. 961-70.
9. Farkas, L.G., *Accuracy of anthropometric measurements: past, present, and future.* Cleft Palate Craniofac J, 1996. **33**(1): p. 10-8; discussion 19-22.
10. Zhurov AI, Kau CH, and R. S., *Computer methods for measuring 3D facial morphology*, in *Proceedings of the 6th International Symposium on Computer Methods in Bomechanics & Biomedical Engineering*, Middleton J, Shrive MG, and J. ML., Editors. 2005, First Numerics Ltd.: Cardiff.
11. Maal, T.J., et al., *Registration of 3-dimensional facial photographs for clinical use.* J Oral Maxillofac Surg, 2010. **68**(10): p. 2391-401.
12. Soncul, M. and M.A. Bamber, *Evaluation of facial soft tissue changes with optical surface scan after surgical correction of Class III deformities.* J Oral Maxillofac Surg, 2004. **62**(11): p. 1331-40.
13. Claes, P., et al., *Craniofacial reconstruction using a combined statistical model of face shape and soft tissue depths: Methodology and validation.* Forensic Science International, 2006. **159**: p. S147-S158.
14. Claes, P., et al., *Modeling 3D Facial Shape from DNA.* Plos Genetics, 2014. **10**(3).
15. Hammond, P., *The use of 3D face shape modelling in dysmorphology.* Archives of Disease in Childhood, 2007. **92**(12): p. 1120-1126.
16. Lane, C. and W. Harrell, *Completing the 3-dimensional picture.* American Journal of Orthodontics and Dentofacial Orthopedics, 2008. **133**(4): p. 612-620.
17. Boehnen, C. and P. Flynn, *Accuracy of 3D scanning technologies in a face scanning scenario* IEEE, 2005: p. 310-317.

18. Weber, D.W., D.W. Fallis, and M.D. Packer, *Three-dimensional reproducibility of natural head position.* Am J Orthod Dentofacial Orthop, 2013. **143**(5): p. 738-44.
19. Coombes, A.M., et al., *A mathematical method for the comparison of three-dimensional changes in the facial surface.* Eur J Orthod, 1991. **13**(2): p. 95-110.
20. Maal, T.J., et al., *Variation of the face in rest using 3D stereophotogrammetry.* Int J Oral Maxillofac Surg, 2011. **40**(11): p. 1252-7.
21. Cooke, M.S. and S.H. Wei, *The reproducibility of natural head posture: a methodological study.* Am J Orthod Dentofacial Orthop, 1988. **93**(4): p. 280-8.
22. Gower, J.C., *Generalized Procrustes Analysis.* Psychometrika, 1975. **40**(1): p. 33-51.
23. Heimann, T. and H.P. Meinzer, *Statistical shape models for 3D medical image segmentation: A review.* Medical Image Analysis, 2009. **13**(4): p. 543-563.
24. Besl, P.J. and N.D. Mckay, *A Method for Registration of 3-D Shapes.* Ieee Transactions on Pattern Analysis and Machine Intelligence, 1992. **14**(2): p. 239-256.
25. Kiekens, R.M.A., et al., *Panel perception of change in facial aesthetics following orthodontic treatment in adolescents.* European Journal of Orthodontics, 2008. **30**(2): p. 141-146.
26. Liebregts, J., et al., *Accuracy of three-dimensional soft tissue simulation in bimaxillary osteotomies.* Journal of Cranio-Maxillofacial Surgery, 2015. **43**(3): p. 329-335.

Chapter 6

A New 3D Tool for Assessing the Accuracy of Bimaxillary Surgery: The OrthoGnathicAnalyser

Liebregts JHF*, Baan HF*, Xi T, Schreurs R, de Koning M, Bergé SJ, Maal TJ.

* Both authors contributed equally

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Abstract

Purpose: The purpose of this study was to present and validate an innovative semi-automatic approach to quantify the accuracy of the surgical outcome in relation to 3D virtual orthognathic planning among patients who underwent bimaxillary surgery.

Materials and methods: For the validation of this new semi-automatic approach, CBCT scans of ten patients who underwent bimaxillary surgery were acquired pre-operatively. Individualized 3D virtual operation plans were made for all patients prior to surgery. During surgery, the maxillary and mandibular segments were positioned as planned by using 3D milled interocclusal wafers. Consequently, post-operative CBCT scan were acquired. The 3D rendered pre- and postoperative virtual head models were aligned by voxel-based registration upon the anterior cranial base. To calculate the discrepancies between the 3D planning and the actual surgical outcome, the 3D planned maxillary and mandibular segments were segmented and superimposed upon the postoperative maxillary and mandibular segments. The translation matrices obtained from this registration process were translated into translational and rotational discrepancies between the 3D planning and the surgical outcome, by using the newly developed tool, the OrthoGnathicAnalyser. To evaluate the reproducibility of this method, the process was performed by two independent observers multiple times.

Results: Low intra-observer and inter-observer variations in measurement error (mean error < 0.25 mm) and high intraclass correlation coefficients (> 0.97) were found, supportive of the observer independent character of the OrthoGnathicAnalyser. The pitch of the maxilla and mandible showed the highest discrepancy between the 3D planning and the postoperative results, 2.72° and 2.75° respectively.

Conclusion: This novel method provides a reproducible tool for the evaluation of bimaxillary surgery, making it possible to compare larger patient groups in an objective and time-efficient manner in order to optimize the current workflow in orthognathic surgery.

Introduction

Three-dimensional (3D) treatment planning in orthognathic surgery provides surgeons with an opportunity to perform virtual osteotomies prior to surgery in order to correct dysgnathia in a predictable way and to obtain a favorable surgical outcome [1-3]. One of the key issues in obtaining a favorable postoperative outcome is an accurate transfer of the 3D planned bony movements to the patient in the operating theatre. Despite the emergence of intra-operative navigation tools, the interocclusal wafer remains the most commonly used device to transfer the 3D orthognathic planning to the patient in the operating theatre [4, 5]. The interocclusal wafer contains information concerning the positioning of maxillary and mandibular segments and guides the sagittal and transverse displacements of the maxilla and mandible during surgery. In combination with the use of a nasion pin and observing changes in dental show, vertical control of the maxilla can also be obtained intra-operatively [6, 7].

For assessing the accuracy of the postoperative outcome with regard to the 3D surgical planning, several methods have been proposed in previous studies [8, 9]. All these methods are based on the use of cephalometric landmarks to quantify differences between the virtual planning and the actual result. An inherent shortcoming of the landmark based analysis is the summation of landmark identification errors as a result of the need to identify the same landmarks multiple times. This increasing error impedes a correct interpretation of the cephalometric analysis and the actual difference between the 3D planning and the postoperative outcome.

To optimize the current way of assessing the accuracy of orthognathic surgery, this study presents a new approach to quantify the accuracy of the 3D virtual orthognathic planning, eliminating the need to identify cephalometric landmarks multiple times. The aim of this article is to validate this innovative tool, the OrthoGnathicAnalyser, in patients who underwent bimaxillary osteotomies.

Materials and methods

The first ten patients in 2012 with dentofacial deformities who underwent a bimaxillary surgery at the Department of Oral and Maxillofacial Surgery at the Radboud University Nijmegen Medical Centre were enrolled in this study. The inclusion criteria were a non-syndromatic dysgnathia requiring bimaxillary osteotomy and the availability of preoperative and postoperative CBCT data. Exclusion criteria were previous history of Le Fort I osteotomy or bilateral sagittal split osteotomy (BSSO), cleft palate and syndromic patients. This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research. All patient data were anonymized and de-identified prior to analysis.

Image acquisition

Two CBCT scans were acquired for each patient: four weeks prior to surgery and one to three weeks after surgery. Preoperative scanning was performed according to the triple scan protocol as proposed by Swennen et al. [10]. CBCT scans were acquired in the natural head position (NHP) in extended field modus (FOV: 16x22cm, scanning time 2x20s, voxel size 0,4 mm, 3D Imaging System, Imaging Sciences International Inc, Hatfield, PA, USA). Maxilim® software (Medicim NV, Mechelen, Belgium) was used to render an augmented 3D virtual head model.

Surgery planning

The preoperative 3D augmented virtual head model was placed in the natural head position using six validated cephalometric landmarks as described by Swennen et al. [10] (table 1). Virtual Le Fort I and BSSO osteotomies were subsequently performed on the preoperative 3D virtual head model. The maxillary and mandibular segments were moved to the desired positions in order to create 3D facial harmonization as simulated in all three dimensions by the Maxilim software (mass tensor model based soft tissue simulation). Based on the virtual planning, an interocclusal wafer was milled to transfer the virtual planning to the patient in the operating theatre.

The Le Fort I osteotomy and BSSO were performed in general anesthesia according to Obwegeser-- Dal Pont, including the Hunsuck modification. The maxilla was first positioned using the intermediate wafer and fixated with four Synthes Orthognatic 0.5 mm (DePuy Synthes Inc, West Chester, USA). Vertical control was achieved based on the intraoperative dental and gingival show. After the BSSO, the distal segment of the mandible was positioned using a second interocclusal wafer and fixed with one Champy 2.0 mm osteosynthesis plate (KLS Martin, Tuttlingen, Germany) on each side. Patients were instructed to wear tight elastics during the first week following surgery.

To evaluate the accuracy of the postoperative outcome compared to the virtual planning the following steps were carried out.

Step 1: Registration of the postoperative 3D head model to the 3D planned model

The postoperative 3D virtual head model was rendered and registered to the preoperative 3D planned virtual head model using voxel-based matching (VBM) [11]. A subvolume that was unaffected by surgery, consisted of the anterior cranial base, zygomatic arches and forehead, was used for the registration [12].

Step 2: Construction of a virtual triangle on each bone segment

To determine the position of the maxilla, distal mandibular segment and both proximal segments, three previously validated cephalometric landmarks were placed on each bone segment (Table 1) [13-15]. The landmarks formed the vertices of a virtual triangle, which contained information on the 3D position and orientation of the bone segment (Figure 1). Triangles were constructed on the preoperative jaw segments.

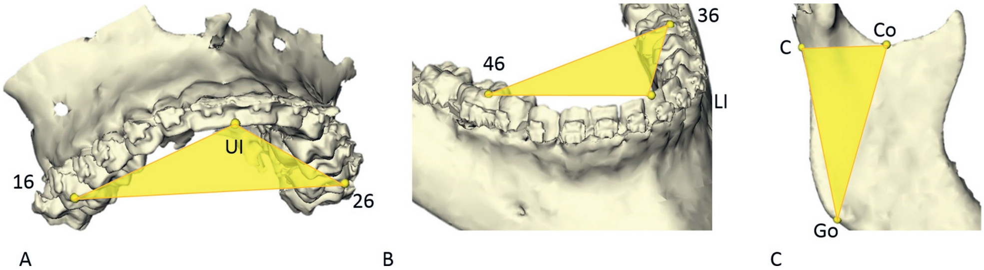


Figure 1: Landmarks used to create a triangle in order to obtain the 3D position and orientation.

A: on the maxilla, the mesial cusp 16 (16), upper incisor (UI) and mesial cusp 26 (26). B: on the mandible, the mesial cusp 36 (36), lower incisor (LI) and mesial cusp 46 (46). C: on the proximal segment, the condor (Co), C-point (C) and gonion (Go) were identified. Virtual triangles were created based on these landmarks.

Table 1: Definitions of the 3D cephalometric landmarks.

Reference landmarks	Description of landmarks	Bilateral
Nasion (N)	The midpoint of the frontonasale suture.	
Sella (S)	The center of the hypophyseal fossa.	
Porion (Por)	The most superior point of the meatus acusticus externus.	X
Orbitale (Or)	The most inferior point of the orbital rim.	X
Landmarks maxilla		
Upper incisor (UI)	The most mesial point of the incisor edge of the right upper central incisor.	
Mesial cusp 16	The most inferior point of mesial cusp of the crown of the right first upper molar.	
Mesial cusp 26	The most inferior point of mesial cusp of the crown of the left first upper molar.	
Landmarks mandible		
Lower incisor (LI)	The most mesial point of the incisor edge of the left lower central incisor.	
Mesial cusp 36	The most superior point of mesial cusp of the crown of the left first lower molar.	
Mesial cusp 46	The most superior point of mesial cusp of the crown of the right first lower molar.	
Landmarks rami		
Condor (Con)	The most posterior point of the mandibular ramus at the intersection with C-plane. C-plane is a plane that runs through the C-point and is parallel to the Frankfurter plane.	X
C-point (C)	The most caudal point of the sigmoid notch.	X
Gonion (Go)	The most caudal and most posterior point of the mandibular angle.	X

Step 3: Registration of the preoperative, 3D planned & postoperative maxillary and mandibular segments

The preoperative virtually osteotomized maxilla and distal mandibular segment were translated to the 3D planned position by Maxilim. The landmarks placed on the preoperative maxilla and mandible, and thus the previously constructed triangles, were translated along with the maxilla and mandible to the 3D planned position [16] (figure 2A-2C). Consequently, the maxilla and mandibular segments were again translated from the 3D planned position to the postoperative position through voxel-based registration of the maxilla and distal segment of the mandible and surface-based registration of the proximal segments (figure 2D-2F). In this way, the virtual triangle of each jaw segment was translated from the 3D planned position to the postoperative position.

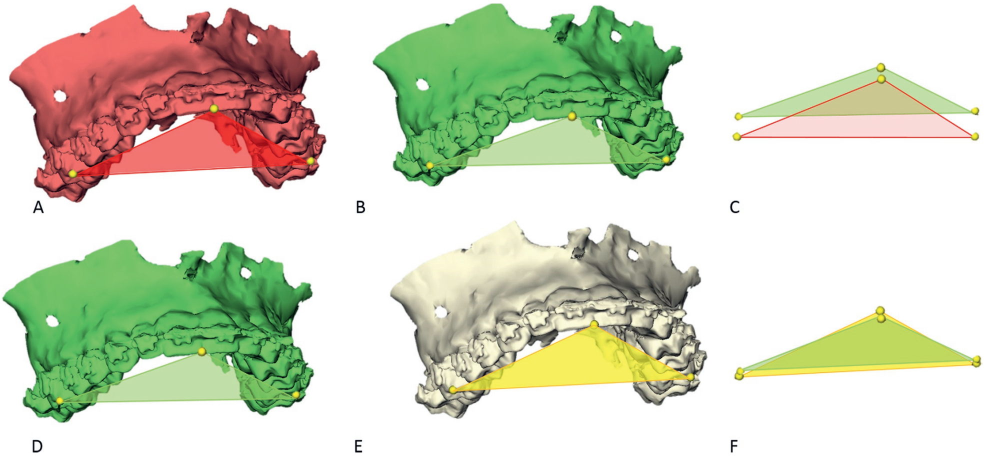
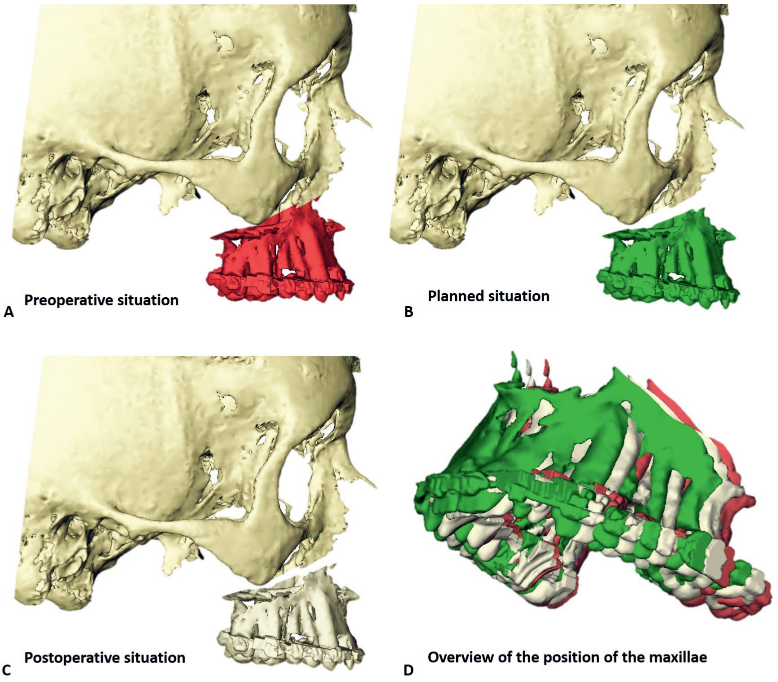


Figure 2: The landmarks and virtual triangle on the preoperative virtually osteotomized maxilla (A) were translated to the 3D planned position of the maxilla (B) by Maxilim. Differences between the preoperative (red) and planned (green) position of the maxilla could be seen (C). Using voxel-based registration, the 3D planned maxilla (D) was then registered to the postoperative maxilla (E). Differences between planned (green) and postoperative (yellow) position of the maxilla is displayed in (F).

Step 4: Calculation of rotational and translational movements

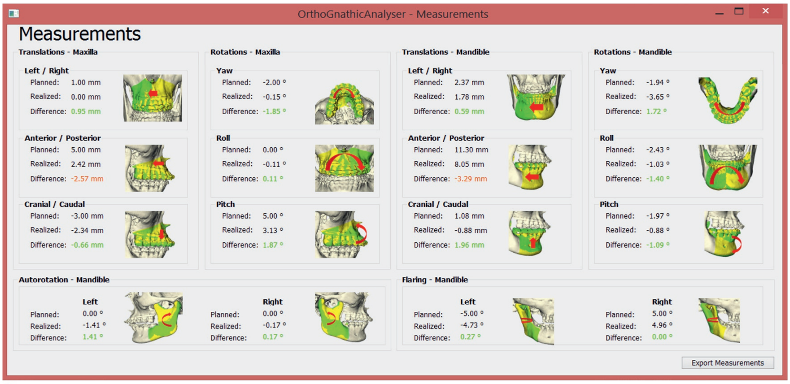
The coordinates of the triangles containing information on the preoperative, 3D planned and postoperative position of each jaw segment were imported into the OrthoGnathicAnalyser (figure 3). The OrthoGnathicAnalyser was developed with C++ in Microsoft Visual Studio 2008 (Microsoft Corporation, Redmond, WA, USA) as a user-friendly interface to assess and visualize the accuracy of the translation of the 3D planning to the patient. Procrustes transformation was used [17] to match the preoperative and planned dataset towards the postoperative dataset and to calculate the translations and rotations of the virtual triangles from one dataset to another. Two transformation matrices were obtained which contained information on the translations and rotations of the maxillary and mandibular segments from preoperative position to postoperative position (surgical displacement) and from 3D planned position to postoperative position (surgical accuracy according to the 3D planning). Subsequently, the OrthoGnathicAnalyser translated these transformation matrices into clinically relevant information, such as the anterior/posterior, left/right and up/down translations as well as the pitch, roll and yaw, in a way that the discrepancies could also be visualized in a 3D viewer.


A Preoperative situation

B Planned situation

C Postoperative situation

D Overview of the position of the maxillae



Measurements

Translations - Maxilla

Left / Right
Planned: 1.00 mm
Realized: 0.00 mm
Difference: 0.95 mm

Anterior / Posterior
Planned: 5.00 mm
Realized: 2.42 mm
Difference: -2.57 mm

Cranial / Caudal
Planned: -3.00 mm
Realized: -2.34 mm
Difference: -0.66 mm

Rotations - Maxilla

Yaw
Planned: -2.00 °
Realized: -0.15 °
Difference: -1.85 °

Roll
Planned: 0.00 °
Realized: -0.11 °
Difference: 0.11 °

Pitch
Planned: 5.00 °
Realized: 3.13 °
Difference: 1.87 °

Translations - Mandible

Left / Right
Planned: 2.37 mm
Realized: 1.78 mm
Difference: 0.59 mm

Anterior / Posterior
Planned: 11.30 mm
Realized: 8.05 mm
Difference: -3.29 mm

Cranial / Caudal
Planned: 1.08 mm
Realized: -0.88 mm
Difference: 1.96 mm

Rotations - Mandible

Yaw
Planned: -1.94 °
Realized: -3.65 °
Difference: 1.72 °

Roll
Planned: -2.43 °
Realized: -1.03 °
Difference: -1.40 °

Pitch
Planned: -1.97 °
Realized: -0.88 °
Difference: -1.09 °

Autorotation - Mandible

Left
Planned: 0.00 °
Realized: -1.41 °
Difference: 1.41 °

Right
Planned: 0.00 °
Realized: -0.17 °
Difference: 0.17 °

Flaring - Mandible

Left
Planned: -5.00 °
Realized: -4.73 °
Difference: 0.27 °

Right
Planned: 5.00 °
Realized: 4.96 °
Difference: 0.00 °

E

Figure 3: Example of a patient who underwent bimaxillary surgery. Only the maxilla is displayed.

A: maxilla in the preoperative position. B: maxilla in the planned position. C: maxilla in the postoperative position. D: overview of the position of the maxillae after voxel-based registration of the head models on the anterior cranial base. E: differences between the planned surgical movement and the achieved surgical movement of the maxilla, distal and proximal mandibular segments were calculated and displayed by the OrthoGnathicAnalyser.

Step 5: Clinical validation and evaluation

To validate the currently presented method and to evaluate the accuracy of the translation of 3D planning to the patients, two independent observers analyzed the CBCT data sets of ten clinical patients. Both observers performed the steps 2 to 4 independently to determine the inter-observer variability. One observer performed the steps 2 to 4 again after an interval of four weeks to assess the intra-observer variability. The mean and absolute mean differences of the surgical displacement for the maxillary, proximal and distal mandibular segments were computed. The anterior/posterior, left/right and up/down translations as well as the pitch, roll and yaw were assessed. Concerning the accuracy of the translation of 3D planning to patients, only the movements of the maxilla and distal mandibular segment were evaluated as the position of the proximal segments were not planned in 3D prior to surgery.

Statistical analysis

Statistical data analyses were performed with IBM SPSS software, version 21.0.1 (IBM Corp., Armonk, NY, USA). Intraclass correlation coefficient (ICC) was calculated to evaluate the inter-observer and intra-observer variability for the rotational and translational measurements of the maxilla and mandible. The mean and absolute mean error in the translation of 3D planning to patients using interocclusal wafers were computed.

Results

Six females (mean age 25,8 years, range 17-40 years) and four males (mean age 27,5 years, range 17-45 years) with skeletal Class II profile were enrolled into this study. In nine patients, an additional genioplasty was performed during the bimaxillary procedure.

Validation of the method

The mean intra-observer and inter-observer variations in translational and rotational displacements of the maxillary and mandibular segments are displayed in table 2 and 3 respectively. Transverse translations were subjected to the least observer dependent errors (mean 0.037 mm) whereas vertical movements were subjected to more observer dependent variations (mean 0.24 mm). None of the mean observer dependent variation exceeded 0.25 mm. With regard to the observer dependent variations for pitch, roll and yaw, it was demonstrated that the mean intra-observer and inter-observer variations were all below 0.6°. Rotational movements of the proximal segments, however, exhibited variations up to a maximum of 1.1°. The intra-observer and inter-observer ICCs coincided with the aforementioned variations, demonstrating a very high correlation between the different measurements.

Table 2: The intra-observer and inter-observer variations and intraclass correlations (ICC) for measurements of the maxilla.

	Intra observer variation	95% - CI	Inter observer variation	95% - CI	Intra observer ICC	Inter observer ICC
Translation AP	0.1033 mm	(0.0440 - 0.1606)	0.1070 mm	(0.0691 - 0.1391)	0.9984	0.9983
Translation LR	0.0368 mm	(0.0243 - 0.0510)	0.0374 mm	(0.0231 - 0.0489)	0.9997	0.9997
Translation UD	0.2308 mm	(0.1110 - 0.3278)	0.2398 mm	(0.1602 - 0.2998)	0.9938	0.9934
Pitch	0.5995°	(0.2013 - 0.8923)	0.5995°	(0.4075 - 0.6740)	0.9717	0.9717
Roll	0.1430°	(0.0987 - 0.1818)	0.1614°	(0.0738 - 0.2252)	0.9960	0.9949
Yaw	0.0541°	(0.0366 - 0.0690)	0.0582°	(0.0402 - 0.0701)	0.9980	0.9977

AP: Anterior/Posterior, LR: Left/Right AP, UD: Up/Down. 95%-CI: 95% confidence interval.

Table 3: The intra-observer and inter-observer variations and intraclass correlations (ICC) for measurements of the mandibular segments.

		Intra observer variation	95% - CI	Inter observer variation	95% - CI	Intra observer ICC	Inter observer ICC
Distal segment	**Translation AP**	0.1520 mm	(0.0700 - 0.2235)	0.1520 mm	(0.2013 - 0.8923)	0.9991	0.9991
	Translation LR	0.0871 mm	(0.0840 - 0.1265)	0.1079 mm	(0.0438 - 0.1287)	0.9995	0.9992
	Translation UD	0.2136 mm	(0.1406 - 0.0867)	0.2136 mm	(0.0899 - 0.3063)	0.9930	0.9930
	Pitch	0.6290 °	(0.3004 - 0.7147)	0.6327 °	(0.1988 - 0.9731)	0.9780	0.9777
	Roll	0.3865 °	(0.2983 - 0.6114)	0.4498 °	(0.1993 - 0.5498)	0.9872	0.9827
	Yaw	0.0968 °	(0.1006 - 0.0725)	0.1048 °	(0.0730 - 0.1166)	0.9981	0.9978
Proximal segment	**Autorotation left**	0.7870 °	(0.3428 - 1.2146)	0.8520 °	(0.2402 - 1.1692)	0.9401	0.9306
	Autorotation right	0.9631°	(0.4444 - 1.6757)	1.1343 °	(0.2668 -1.5895)	0.9014	0.8683
	Flair left	0.4983 °	(0.3383 - 1.2101)	0.8374 °	(0.1401 -0.7489)	0.9875	0.9654
	Flair right	0.3346 °	(0.2263 - 0.9709)	0.5989 °	(0.1657 -0.4540)	0.9849	0.9531

AP: Anterior/Posterior, LR: Left/Right AP, UD: Up/Down. 95%-CI: 95% confidence interval.

Accuracy of the translation of 3D planning to patients

For clinical evaluation of the accuracy of bimaxillary surgery, the postoperative result was analyzed with the OrthoGnathicAnalyser with regard to the virtual planning. The results are illustrated in table 4 and table 5. The left/right translation showed the lowest absolute mean difference between the 3D planning and the surgical result for both the maxilla and mandible, 0.49 mm and 0.71 mm respectively. The discrepancy between the 3D planning and the postoperative result was the greatest with regard to the vertical positioning of the maxilla and mandible, suggesting a less accurate intra-operative vertical control of the maxillary and mandibular segment using the interocclusal wafer. Furthermore, it was worth to note that in 7 out of 10 cases, the maxilla was positioned more posteriorly than in the 3D planning, with an absolute mean difference of 1.41 mm. The same tendency was found in the sagittal position of the mandible, where in 8 out of 10 cases the mandible was positioned more posteriorly than planned (absolute mean difference of 1.17 mm). The pitch of the maxilla (2.72°) and mandible (2.75°) showed the highest discrepancy between the 3D planning and postoperative result among all rotational measurements.

Table 4: The mean differences between the 3D planned and the postoperative position of the maxilla.

Patient	Translation AP (mm)	Translation LR (mm)	Translation UD (mm)	Pitch (degree)	Roll (degree)	Yaw (degree)
1	-1.44	0.04	1.19	2.60	-0.73	1.00
2	-0.41	0.17	-1.52	-1.67	-2.23	0
3	-2.63	0.11	-0.68	2.34	-1.75	3.22
4	0.03	-0.16	-2.85	3.82	-0.04	0.22
5	3.71	-0.11	-3.45	5.87	0.79	-0.68
6	1.05	-0.09	-2.33	3.52	1.20	-0.59
7	-0.38	-0.66	2.67	-4.32	0.50	2.20
8	-2.02	1.22	0,26	-0.77	-1.42	-0.58
9	-1.35	1.44	-0.64	1.04	-0.87	-0.49
10	-1.12	0.91	2.88	1.26	-0.82	0.75
Mean	-0.46	0.29	-0.45	1.37	-0.54	0.51
Absolute mean	1.41	0.49	1.85	2.72	1.04	0.97

Translation AP: a positive value means that the maxilla was positioned more anteriorly than planned, a negative value means that the maxilla was positioned more posteriorly than planned. Translation LR: a positive value means that the maxilla was positioned more to the right compared to the planning, a negative value means that the maxilla was positioned more to the left compared to the planning. Translation UD: a positive value means that the maxilla was displaced more cranially compared to the planning, a negative value means that the maxilla was displaced more cranially compared to the planning. Pitch: a positive value means an anti-clockwise rotation compared to the planning, a negative value means a clockwise rotation compared to the planning. Roll: a positive value means an anti-clockwise rotation around the horizontal axis compared to the planning, a negative value means a clockwise rotation around the horizontal axis compared to the planning. Yaw: a positive value means an anti-clockwise rotation around the vertical axis compared to the planning, a negative value means a clockwise rotation around the vertical axis compared to the planning.

Table 5: The mean differences between the 3D planned and the postoperative position of the distal mandibular segment.

Patient	Translation anterior/ posterior (mm)	Translation left/right (mm)	Translation up/ down (mm)	Pitch (degree)	Roll (degree)	Yaw (degree)
1	-1.28	0.23	1.95	3.32	0.61	-0.07
2	-0.71	0.35	-0.45	-1.23	0.11	-3.39
3	-3.03	0.44	0.20	3.51	-0.36	1.54
4	-0.06	-0.84	-0.08	-0.86	0.55	1.59
5	3.61	-0.14	-1.17	5.81	0.81	-1.00
6	0.36	1.17	-0.13	1.27	1.73	-1.06
7	-0.05	1.41	3.92	-6.71	-0.75	-0.29
8	-2.25	1.21	1.06	0.17	-1.31	0.76
9	-0.21	-0.43	1.74	2.35	-1.48	0.06
10	-0.10	0.25	2.50	2.30	-0.68	1.56
Mean	-0.37	0.25	0.96	0.99	-0.08	-0.03
Absolute mean	1.17	0.71	1.32	2.75	0.84	1.13

Translation AP: a positive value means that the mandible was positioned more anteriorly than planned, a negative value means that the mandible was positioned more posteriorly than planned. Translation LR: a positive value means that the mandible was positioned more to the right compared to the planning, a negative value means that the mandible was positioned more to the left compared to the planning. Translation UD: a positive value means that the mandible was displaced more cranially compared to the planning, a negative value means that the mandible was displaced more cranially compared to the planning. Pitch: a positive value means an anti-clockwise rotation compared to the planning, a negative value means a clockwise rotation compared to the planning. Roll: a positive value means an anti-clockwise rotation around the horizontal axis compared to the planning, a negative value means a clockwise rotation around the horizontal axis compared to the planning. Yaw: a positive value means an anti-clockwise rotation around the vertical axis compared to the planning, a negative value means a clockwise rotation around the vertical axis compared to the planning.

Discussion

Three-dimensional (3D) treatment planning in orthognathic surgery provided surgeons with an opportunity to perform virtual osteotomies prior to the actual surgery in order to correct dysgnathia in a more predictable way. In order to obtain a favorable surgical outcome, an accurate translation of the 3D planning to the patients was required. To asses skeletal changes in the course of the orthognathic treatment, three distinct approaches were used in previous studies: the calculation of linear and angular differences between reference points [5, 18-23], the use of distance maps to evaluate the differences between the surface of the planned and postoperative jaw segments [24-27], and finally the computation of intra-class coefficients of reference points and reference angles [2].

In all aforementioned methods, cephalometric landmarks need to be identified multiple times on the virtual 3D model, both prior to surgery and after surgery. The error caused by the identification of landmarks ranged from 0.02 mm to 2.47 mm [15, 28, 29]. As the same landmarks had to be identified twice, the total landmark identification error could be regarded as the sum of individual landmark identification errors, which might easily exceeded the clinical relevant error margin of 0.5 mm. In relation to the error between the 3D planning and postoperative outcome which ranged from 0.03 mm to 3.71 mm in the present study (table 4), the landmark identification error could easily have influenced a good clinical interpretation of the results. Therefore, a further reduction in the landmark identification error is crucial in the evaluation of skeletal changes throughout an orthognathic treatment.

Two approaches can be applied to overcome the landmark identification error, the fully automatic landmark recognition [30, 31] or the elimination of landmark based measurement, as proposed in this study. The essence of automatic landmark recognition is the reduction and elimination of random, observer-dependent landmark identification errors. Despite various validation studies, an identification error smaller than 2 mm is still hard to accomplish [30, 31]. A recent study by Makram et al. [32] revealed an error range of 0.3 mm to 2.8 mm for a 3D mesh based protocol for the automatic localization of cephalometric landmarks, impeding its application in the daily practice. The relatively large errors did not only arise from challenges in the computation of artificial intelligence algorithms in recognizing the anatomic relevant structures, they were also caused by streak artifacts that were frequently present as the result of orthodontic appliances, which hampered an accurate automatic recognition of anatomical structures [30].

By eliminating the necessity to identify cephalometric landmarks in each CBCT dataset through the voxel-based registration of jaw segments, as proposed in this study, the clinically relevant translational and rotational movements of each jaw segment could be computed from the rotation matrices of the jaw segments during the registration process. The translational and rotational movements of the jaw segments on the sagittal, vertical and transverse plane could be computed directly from the translation matrices by the OrthoGnathicAnalyser, instead of through interpolation from conventional cephalometric measurements. The three landmarks that were identified on each jaw segment in this study were used solely to construct the virtual triangles to allow the calculation of translation matrices, not for making cephalometric measurements. In this way, this VBM based method has eliminated the need for multiple identifications of cephalometric landmarks and is free of landmark identification errors. As a consequence, the proposed VBM method in the OrthoGnathicAnalyser overcomes measurement inaccuracies as a result of multiple landmark identification or automatic landmark recognition.

The results of the current study demonstrated an excellent reproducibility of the OrthoGnathicAnalyser in the quantification of skeletal displacements between two CBCT datasets. The very low intra-observer and inter-observer variations in measurement error of well below 0.25 mm and high ICCs (> 0.97) supported the observer-independent character of the measurements obtained from the OrthoGnathicAnalyser. The minimal variations found between the different measurements seemed to be the results of small intrinsic alignment errors caused by VBM as described by previous studies [11, 33]. As these inaccuracies were approximately half the size of a voxel (0.4 mm) and far less than the clinically accepted error margin of 0.5 mm, they can be regarded as clinically irrelevant. Compared to the measurement errors of conventional 3D cephalometry which ranged from 0.02 mm till 2.47 mm, the errors found with the OrthoGnathicAnalyser were clinically negligible. It is clear that the OrthoGnathicAnalyser can provide far more reproducible results with regard to the quantification of jaw displacements.

Despite the high consistency in the measurement of skeletal displacement by the OrthoGnathicAnalyser, it should be noted that the reproducibility of measurements concerning the proximal segments was lower than for the maxilla and distal mandibular segment. The lower intra-observer and inter-observer ICC could have been the result of the fact that the proximal segments were registered using SBM whereas the maxilla and distal mandibular segment were registered using VBM. SBM was used for the proximal mandibular segments to counteract the image artifacts as a result of the sagittal split osteotomy.

During SBM the observer had to color the area on which the SBM is performed. The input required from the observer is thus higher than in VBM, during which the observer only had to select the volume of interest. It was plausible that this more observer-dependent action in SBM could have influenced the reproducibility of the registration process of the proximal segments negatively, as described by Almukthar et al. [34] Another point of interest was the segmentation of the proximal segments. In most patients, the condyles were not completely segmented and reconstructed. The incomplete reconstruction of condyles could also have affected the accuracy of SBM, which is dependent on a good surface integrity of the matching objects.

When assessing the accuracy of the mandible, it is of major importance whether the postoperative CBCT scan was acquired in the optimal occlusion, as how the 3D planning was made. If the postoperative CBCT was acquired in a suboptimal occlusion, a discrepancy in position of the mandible between the 3D planning and the postoperative outcome could occur. To limit the role of occlusion, it is essential to perform the scanning protocol correctly.

The clinical analyses of ten patients using the OrthoGnathicAnalyser demonstrated that the interocclusal wafer provided a good control of the positioning of the maxilla and mandible on the transverse plane. In line with the findings of previous studies [35-37], the interocclusal wafer had provided far less control in the vertical direction. The vertical discrepancy between the 3D planning and the postoperative position of the maxilla was two to three times higher than in the transverse direction. Several studies suggested the intraoperative use of a nasion pin or other external reference point, to aid the positioning of the maxilla on the vertical plane [5, 38-41]. The clinical analyses of the twenty-three patients using the OrthoGnathicAnalyser showed an adequate position of the maxilla and mandible in the left/right direction with a deviation of respectively 0.32 mm and 0.75 mm which is in line with other findings. [5, 43] In the cranial/caudal direction a slightly larger deviation was congruent with other findings. [7,43] In the maxilla the anterior/posterior deviation was ≤ 1.00 mm while in the mandible a larger deviation was seen.

With regard to the accuracy in the translation of the 3D planning to the patient in the sagittal direction, it was remarkable that all maxillae and mandiblae were positioned more posteriorly. The condylar position might be changed during surgery by muscle tone and gravity as the patient was placed in the supine position, affecting the optimal condylar seating [42]. Also the translation of the 3D planned pitch to the patient seemed to be difficult. A possible reason for the relatively large discrepancy found in the pitch can be positional errors due to bone interferences between the pterygoid plate and the osteotimized maxilla. Especially in cases in which impaction of the maxilla is planned, premature bone contact might occur. Other influential factors for the discrepancy found between the planned and the postoperative maxillary position might be the non-centric relation of the mandible when the surgical guide is used to guide the maxilla to its desired position, the use of intermaxillary fixation and a glabella pin. A clinical study with a larger population with the application of the glabella pin is now ongoing to provide more insight in the factors that may have influenced this.

The OrthoGnathicAnalyser can also be applied during the postoperative follow-up, for example to quantify the skeletal relapse one or two years postoperatively, or to compare the outcome of different surgical strategies such as maxilla versus mandible first. The additional value of new techniques such as intraoperative navigation, patient specific preoperatively fabricated splints and patient specific preoperative milled fixation plates can be evaluated systematically and objectively using this newly developed tool.

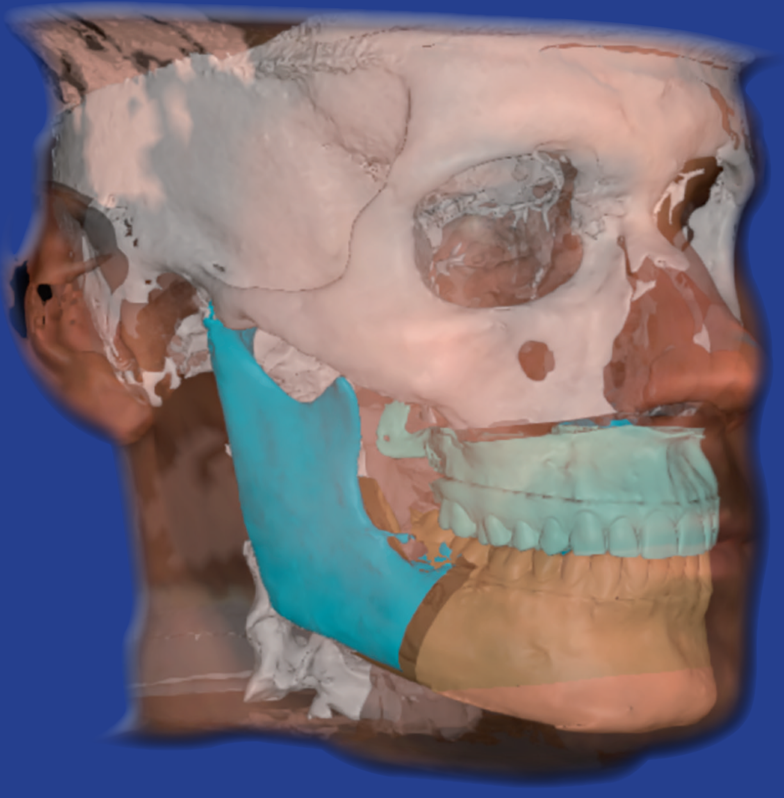
In conclusion, the OrthoGnathicAnalyser is a novel and objective tool to quantify the displacement of jaw segments in orthognathic surgery, eliminating the need for multiple landmark identification as in conventional cephalomatric analysis. With this newly developed observer independent semi-automatic tool, the accuracy of the 3D planning and surgical outcome of orthognathic surgery can be analyzed in an objective, reproducible and systematic way. With the results of the current validation study we believe that the OrthoGnathicAnalyser provides the clinicians a new powerful tool to evaluate and optimize the accuracy of 3D planning in bimaxillary surgery.

References

1. Swennen GR, Mollemans W and Schutyser F (2009) Three-dimensional treatment planning of orthognathic surgery in the era of virtual imaging. J Oral Maxillofac Surg 67: 2080-2092.
2. Aboul-Hosn Centenero S and Hernandez-Alfaro F (2012) 3D planning in orthognathic surgery: CAD/CAM surgical splints and prediction of the soft and hard tissues results - our experience in 16 cases. J Craniomaxillofac Surg 40: 162-168.
3. Schendel SA and Jacobson R (2009) Three-dimensional imaging and computer simulation for office-based surgery. J Oral Maxillofac Surg 67: 2107-2114.
4. Kim BC, Lee CE, Park W, Kim MK, Zhengguo P, et al. (2011) Clinical experiences of digital model surgery and the rapid-prototyped wafer for maxillary orthognathic surgery. Oral surgery, oral medicine, oral pathology, oral radiology, and endodontics 111: 278-285.e271.
5. Sun Y, Luebbers HT, Agbaje JO, Schepers S, Vrielinck L, et al. (2013) Accuracy of upper jaw positioning with intermediate splint fabrication after virtual planning in bimaxillary orthognathic surgery. J Craniofac Surg 24: 1871-1876.
6. Ferguson JW and Luyk NH (1992) Control of vertical dimension during maxillary orthognathic surgery. A clinical trial comparing internal and external fixed reference points. J Craniomaxillofac Surg 20: 333-336.
7. Ong TK, Banks RJ and Hildreth AJ (2001) Surgical accuracy in Le Fort I maxillary osteotomies. The British journal of oral & maxillofacial surgery 39: 96-102.
8. Haas Jr OL, Becker OE and de Oliveira RB (2014) Computer-aided planning in orthognathic surgery-systematic review. Int J Oral Maxillofac Surg.
9. Stokbro K, Aagaard E, Torkov P, Bell RB and Thygesen T (2014) Virtual planning in orthognathic surgery. Int J Oral Maxillofac Surg 43: 957-965.
10. Swennen GR, Mollemans W, De Clercq C, Abeloos J, Lamoral P, et al. (2009) A cone-beam computed tomography triple scan procedure to obtain a three-dimensional augmented virtual skull model appropriate for orthognathic surgery planning. J Craniofac Surg 20: 297-307.
11. Maes F, Collignon A, Vandermeulen D, Marchal G and Suetens P (1997) Multimodality image registration by maximization of mutual information. IEEE Trans Med Imaging 16: 187-198.
12. Nada RM, Maal TJ, Breuning KH, Berge SJ, Mostafa YA, et al. (2011) Accuracy and reproducibility of voxel based superimposition of cone beam computed tomography models on the anterior cranial base and the zygomatic arches. PloS one 6: e16520.
13. Plooij JM, Swennen GR, Rangel FA, Maal TJ, Schutyser FA, et al. (2009) Evaluation of reproducibility and reliability of 3D soft tissue analysis using 3D stereophotogrammetry. Int J Oral Maxillofac Surg 38: 267-273.
14. Xi T, van Loon B, Fudalej P, Berge S, Swennen G, et al. (2013) Validation of a novel semi-automated method for three-dimensional surface rendering of condyles using cone beam computed tomography data. Int J Oral Maxillofac Surg 42: 1023-1029.
15. Swennen GR, Schutyser F, Barth EL, De Groeve P and De Mey A (2006) A new method of 3-D cephalometry Part I: the anatomic Cartesian 3-D reference system. J Craniofac Surg 17: 314-325.

16. van Loon B, van Heerbeek N, Bierenbroodspot F, Verhamme L, Xi T, et al. (2015) Three-dimensional changes in nose and upper lip volume after orthognathic surgery. Int J Oral Maxillofac Surg 44: 83-89.
17. Gower JC and Dijksterhuis GB (2004) Procrustes problems. Oxford ; New York: Oxford University Press. xi, 233 p. p.
18. Xia JJ, Gateno J, Teichgraeber JF, Christensen AM, Lasky RE, et al. (2007) Accuracy of the computer-aided surgical simulation (CASS) system in the treatment of patients with complex craniomaxillofacial deformity: A pilot study. J Oral Maxillofac Surg 65: 248-254.
19. Zinser MJ, Mischkowski RA, Sailer HF and Zoller JE (2012) Computer-assisted orthognathic surgery: feasibility study using multiple CAD/CAM surgical splints. Oral surgery, oral medicine, oral pathology and oral radiology 113: 673-687.
20. Li B, Zhang L, Sun H, Yuan J, Shen SG, et al. (2013) A novel method of computer aided orthognathic surgery using individual CAD/CAM templates: a combination of osteotomy and repositioning guides. The British journal of oral & maxillofacial surgery 51: e239-244.
21. Hsu SS, Gateno J, Bell RB, Hirsch DL, Markiewicz MR, et al. (2013) Accuracy of a computer-aided surgical simulation protocol for orthognathic surgery: a prospective multicenter study. J Oral Maxillofac Surg 71: 128-142.
22. Shehab MF, Barakat AA, AbdElghany K, Mostafa Y and Baur DA (2013) A novel design of a computer-generated splint for vertical repositioning of the maxilla after Le Fort I osteotomy. Oral surgery, oral medicine, oral pathology and oral radiology 115: e16-25.
23. De Riu G, Meloni SM, Baj A, Corda A, Soma D, et al. (2014) Computer-assisted orthognathic surgery for correction of facial asymmetry: results of a randomised controlled clinical trial. The British journal of oral & maxillofacial surgery 52: 251-257.
24. Marchetti C, Bianchi A, Bassi M, Gori R, Lamberti C, et al. (2006) Mathematical modeling and numerical simulation in maxillo-facial virtual surgery (VISU). J Craniofac Surg 17: 661-667; discussion 668.
25. Mazzoni S, Badiali G, Lancellotti L, Babbi L, Bianchi A, et al. (2010) Simulation-guided navigation: a new approach to improve intraoperative three-dimensional reproducibility during orthognathic surgery. J Craniofac Surg 21: 1698-1705.
26. Tucker S, Cevidanes LH, Styner M, Kim H, Reyes M, et al. (2010) Comparison of actual surgical outcomes and 3-dimensional surgical simulations. J Oral Maxillofac Surg 68: 2412-2421.
27. Hernandez-Alfaro F and Guijarro-Martinez R (2013) New protocol for three-dimensional surgical planning and CAD/CAM splint generation in orthognathic surgery: an in vitro and in vivo study. Int J Oral Maxillofac Surg 42: 1547-1556.
28. Titiz I, Laubinger M, Keller T, Hertrich K and Hirschfelder U (2011) Repeatability and reproducibility of landmarks--a three-dimensional computed tomography study. Eur J Orthod.
29. Katkar RA, Kummet C, Dawson D, Moreno Uribe L, Allareddy V, et al. (2013) Comparison of observer reliability of three-dimensional cephalometric landmark identification on subject images from Galileos and i-CAT cone beam CT. Dento maxillo facial radiology 42: 20130059.

30. Shahidi S, Bahrampour E, Soltanimehr E, Zamani A, Oshagh M, et al. (2014) The accuracy of a designed software for automated localization of craniofacial landmarks on CBCT images. BMC Med Imaging 14: 32.
31. Gupta A, Kharbanda OP, Sardana V, Balachandran R and Sardana HK (2015) A knowledge-based algorithm for automatic detection of cephalometric landmarks on CBCT images. Int J Comput Assist Radiol Surg.
32. Makram M KH (2014) Reeb Graph for Automatic 3D Cephalometry. IJIP 8: 17-29.
33. Nada RM, Maal TJJ, Breuning KH, Berge SJ, Mostafa YA, et al. (2011) Accuracy and Reproducibility of Voxel Based Superimposition of Cone Beam Computed Tomography Models on the Anterior Cranial Base and the Zygomatic Arches. PloS one 6.
34. Almukhtar A, Ju X, Khambay B, McDonald J and Ayoub A (2014) Comparison of the accuracy of voxel based registration and surface based registration for 3D assessment of surgical change following orthognathic surgery. PloS one 9: e93402.
35. Ellis E, 3rd (1990) Accuracy of model surgery: evaluation of an old technique and introduction of a new one. J Oral Maxillofac Surg 48: 1161-1167.
36. Turvey TA (1982) Simultaneous mobilization of the maxilla and mandible: surgical technique and results. J Oral Maxillofac Surg 40: 96-99.
37. Schneider M, Tzscharnke O, Pilling E, Lauer G and Eckelt U (2005) Comparison of the predicted surgical results following virtual planning with those actually achieved following bimaxillary operation of dysgnathia. J Craniomaxillofac Surg 33: 8-12.
38. Van Sickels JE, Larsen AJ and Triplett RG (1986) Predictability of maxillary surgery: a comparison of internal and external reference marks. Oral surgery, oral medicine, and oral pathology 61: 542-545.
39. Polido WD, Ellis E, 3rd and Sinn DP (1991) An assessment of the predictability of maxillary repositioning. Int J Oral Maxillofac Surg 20: 349-352.
40. Bouchard C and Landry PE (2013) Precision of maxillary repositioning during orthognathic surgery: a prospective study. Int J Oral Maxillofac Surg 42: 592-596.
41. Kretschmer WB, Zoder W, Baciut G, Bacuit M and Wangerin K (2009) Accuracy of maxillary positioning in bimaxillary surgery. The British journal of oral & maxillofacial surgery 47: 446-449.
42. Lee CY, Jang CS, Kim JW, Kim JY and Yang BE (2013) Condylar repositioning using centric relation bite in bimaxillary surgery. Korean journal of orthodontics 43: 74-82.
43. Y. Sun, H. T. Luebbers, J. O. Agbaje, I. Lambrichts, and C. Politis, “The Accuracy of Image-Guided Navigation for Maxillary Positioning in Bimaxillary Surgery,” Journal of Craniofacial Surgery, vol. 25, pp. 1095–1099, May 2014.



Chapter 7

Achievability of 3D planned bimaxillary osteotomies: maxilla-first versus mandible-first surgery.

Liebregts JHF*, Baan HF*, de Koning M, Ongkosuwito E, Bergé SJ, Maal TJ, Xi T.

* Both authors contributed equally

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Abstract

Purpose: The present study was aimed to investigate the effects of sequencing a two-component surgical procedure for correcting malpositioned jaws (bimaxillary osteotomies); specifically, surgical repositioning of the upper jaw—maxilla, and the lower jaw—mandible.

Materials and methods: Within a population of 116 patients requiring bimaxillary osteotomies, the investigators analyzed whether there were statistically significant differences in postoperative outcome as measured by concordance with a preoperative digital 3D virtual treatment plan. In one group of subjects (n=58), the maxillary surgical procedure preceded the mandibular surgery. In the second group (n=58), the mandibular procedure preceded the maxillary surgical procedure. A semi-automated analysis tool (OrthoGnathicAnalyser) was applied to assess the concordance of the postoperative maxillary and mandibular position with the cone beam CT-based 3D virtual treatment planning in an effort to minimize observer variability.

Results: The results demonstrated that in most instances, the maxilla-first surgical approach yielded closer concordance with the 3D virtual treatment plan than a mandibular-first procedure.

Conclusion: In selected circumstances, such as a planned counterclockwise rotation of both jaws, the mandible-first sequence resulted in more predictable displacements of the jaws.

Introduction

Over the last decades, the surgical approach used during bimaxillary surgery, either maxillary-first or mandibular-first sequence, has been a controversial topic in the field of orthognathic surgery (corrective jaw surgery). The traditional approach is to operate on the maxilla first. Notably, several recent publications have described encouraging results with the mandible first sequencing protocol[1-3], with Perez and Ellis demonstrating the benefit of this approach in patients with counterclockwise (CCW) mandibular rotation and downgrafting of the posterior maxilla[4]. Despite these recent reports, there is still limited clinical and scientific consensus on which surgical approach taken during corrective jaw surgery can provide the most predictable clinical result.

Recently, computer-assisted 3D virtual surgical plannings have been shown to increase the predictability of the postoperative outcomes, and has increasingly become the standard approach for complex orthognathic reconstructions[5]. The standard approach to transfer the virtual planning from the computer to the patient during surgery, is the use of 3D printed interocclusal splints. These splints act as an important control in order to correctly position the maxilla and mandible in the planned positions[5-7].

A key consideration when using 3D virtual surgical planning is the accuracy of the system in obtaining the planned respositioning of the maxilla and mandible. Therefore, several analytic tools, such as the OrthoGnathicAnalyser (OGA), have been developed to evaluate the surgical accuracy of the computer-assisted surgical approach robustly. Compared to conventional cephalometry, OGA is able to quantify the concordance of the postoperative maxillary and mandibular positions with the 3D surgical planning without the need to identify anatomical landmarks multiple times, thereby minimizing the observer variability. With OGA , the accuracy of 3D planning and surgical outcome of bimaxillary surgery with different sequencing protocols can be analysed in an objective, reproducible and systematic way[8].

The aim of this study was to investigate the effects of sequencing bimaxillary osteotomies, maxilla-first versus mandible-first surgical protocol, on the achievability of the 3D virtually planned repositioning of the maxilla and mandible.

Patients and Methods

Patients who underwent bimaxillary osteotomies consecutively in the period from 2010 to 2014 at the Department of Oral and Maxillofacial Surgery in Radboud University Nijmegen Medical Centre were included in this study. The inclusion criteria were a non-syndromatic dysgnathia requiring bimaxillary osteotomies with or without genioplasty and the availability of a CBCT scan before and directly after surgery. All patients received preoperative orthodontic treatment to align their teeth and had a minimum of 24 teeth. The exclusion criteria were the usage of a chin support during CBCT-scanning, previous history of facial trauma with fractures of facial bones, or a history of orthognatic surgery, with the exception of a SARME (Surgically Assisted Rapid Maxillary Expansion) procedure.

This study was conducted in accordance with the World Medical Association Declaration of Helsinki on medical research ethics. The approval of this study was granted by the Institutional Review Board (CMO Arnhem-Nijmegen, #181/2005) and informed consent were obtained for this study. All patient data were anonymized and de-identified prior to analysis.

Data acquisition

CBCT scans were acquired four weeks prior to surgery and within one week after bimaxillary surgery using a standard CBCT scanning protocol (i-CAT, 3D Imaging System, Imaging Sciences International Inc, Hatfield, PA, USA) in “Extended Field” modus (FOV: 16 cm diameter/22 cm height; scan time: 2x20s; voxel size: 0.4 mm). Patients were scanned while seated in natural head position. They were asked to swallow, to relax their lips and facial muscles and to keep their eyes open. The acquired CBCT data were exported in DICOM format and imported into Maxilim® software (Medicim NV, Mechelen, Belgium).

Surgical planning

In Maxilim®, a 3D virtual augmented head model was rendered and positioned in a reference frame as described by Swennen et al. [9] Subsequently, virtual osteotomies were performed to simulate the Le Fort I and BSSO osteotomies.

The maxillary and mandibular segments were positioned to the desired positions to create a harmonious 3D soft tissue facial profile, as simulated in real-time by the Maxilim software using the mass tensor model based soft tissue simulation. If required, an additional virtual chin osteotomy was simulated. Based on the 3D virtual planning, one intermediate and one final interocclusal splint were milled to transfer the virtual planning to the patient in the operating theatre.

Between 2010 – 2012 the clinical protocol for bimaxillary osteotomy was to start with the BSSO that was followed by the Le Fort I osteotomy (mandible-first). After 2012 this protocol was changed, and the Le Fort I was performed prior to the BSSO (maxilla-first).

Surgical procedure

All bimaxillary osteotomies were performed or supervised by one experienced surgeon (MdK). After nasotracheal intubation, the mucobuccal fold of the maxilla and the mandibular ramus regions were infiltrated with local anaesthetic (Ultracain Ds-Forte). In cases of mandible-first procedure, a BSSO was performed according to the Hunsuck modification[10]. After the completion of the osteotomies using osteotomes, the distal segment of the mandible was placed in the planned position using the prefabricated interocclusal intermediate splint and stabilized with intermaxillary fixation (IMF). The proximal segments were gently pushed backward and upward to seat the condyles. The mandibular segments were fixed with two titanium miniplates (one on each side) and monocortical screws (Champy 2.0 mm, KLS Martin, Tuttlingen, Germany). Following the BSSO, a Le Fort I procedure was performed. After an incision in the gingivobuccal sulcus and elevation of mucoperiosteum and nasal mucosa, the osteotomies were made with a reciprocal saw at the Le Fort I level. The lateral nasal walls and nasal septum were osteotomized with nasal osteotome. The piriform aperture and nasal spine were rounded. After mobilization of the maxilla, it was positioned in the planned position using a prefabricated final interocclusal splint. Fixation was performed with four 1.5 mm miniplates (KLS Martin, Tuttlingen, Germany) and 4 mm screws, one paranasal and one on the maxillary buttress on each side. Alar cinch suture and VY sutures were used accordingly. The mucosa was closed with a 3-0 Vicryl suture (Ethicon, Johnson and Johnson Medical, Norderstedt, Germany). Depending on the stability of the occlusion, the interocclusal splint was left in place and tight elastics were used in the first week after surgery. Guiding elastics were applied after the first week, in conjunction with the postoperative orthodontic treatment. In cases of maxillary first procedure, the Le Fort I osteotomy was carried out first, after which the BSSO was performed. The surgical protocol and method of fixation were identical as described in the mandible-first procedure.

3D analysis of 3D planned and actual postoperative positioning of jaws

The accuracy of the postoperative surgical result was compared to the virtual planning and evaluated using the following steps.

Step 1: The 3D rendered pre- and postoperative 3D virtual head models were aligned by using voxel-based registration upon the anterior cranial base [11, 12].

Step 2: Virtual triangles were constructed on the maxilla and distal mandibular segment by using previously validated cephalometric landmarks (table 1) [8, 13].

Step 3: The preoperative virtually osteotomized maxilla and distal mandibular segment were translated to the 3D planned position in Maxilim® by voxel-based registration. The landmarks placed on the preoperative maxilla and mandible, and thus the previously constructed triangles were translated along with the maxilla and mandible to the 3D planned position.

The coordinates of the triangles were imported into the OGA to compute the 3D planned sagittal, vertical and transverse translations as well as rotations (pitch, roll and yaw) of the maxilla and distal mandibular segment.

Step 4: The maxilla and mandibular segments were again translated from the 3D planned position to the postoperative position through voxel-based registration that resulted in a displacement of the virtual triangle. The coordinates of the landmarks (virtual triangle) in the postoperative position were imported into the OGA. The translation and rotation differences of the maxilla and distal mandibular segment between the 3D planning and actual postoperative results were calculated[8].

Table 1: Definitions of the 3D cephalometric landmarks.

Reference landmarks	Description of landmarks	Bilateral
Nasion (N)	The midpoint of the frontonasale suture.	
Sella (S)	The center of the hypophyseal fossa.	
Porion (Por)	The most superior point of the meatus acusticus e-ternus.	X
Orbitale (Or)	The most inferior point of the orbital rim.	X
Landmarks maxilla		
Upper incisor (UI)	The most mesial point of the incisor edge of the right upper central incisor.	
Mesial cusp 16	The most inferior point of mesial cusp of the crown of the right first upper molar.	
Mesial cusp 26	The most inferior point of mesial cusp of the crown of the left first upper molar.	
Landmarks mandible		
Lower incisor (LI)	The most mesial point of the incisor edge of the left lower central incisor.	
Mesial cusp 36	The most superior point of mesial cusp of the crown of the left first lower molar.	
Mesial cusp 46	The most superior point of mesial cusp of the crown of the right first lower molar.	

Statistical analysis

Statistical data analyses were performed with SPSS 22.0.1 (IBM Corp., Armonk, NY, USA). The mean and absolute mean differences between the 3D planning and postoperative results were calculated. Analysis of variance (ANOVA) was used to test for differences in postoperative results and the planning between the maxillary first and mandible-first groups with correction for possible confounding factors at the 5% level of significance ($p \leq 0.05$). Univariate and multivariate regression analysis were applied to identify the prognostic factors that influence the postoperative result.

Results

In this cohort study, 116 consecutive patients were enrolled (80 female (69 %); 36 male (31%)), with a mean age at surgery of 28 years (range 16 – 57 years; table 2). Of the 116 patients who underwent bimaxillary surgery, 58 patients (50%) were operated using the maxilla-first protocol whereas the other 58 patients (50%) were treated with the mandible-first surgical protocol. Before bimaxillary surgery, 33 patients underwent a surgically assisted rapid maxillary expansion (15 in the maxilla-first group and 18 in the mandible-first group), with an additional 61 patients undergoing a genioplasty during surgery (33 in the maxilla-first group and 28 in the mandible-first group). As shown in Table 2, no differences within patient related factors and surgical displacements were found between the maxilla-first and mandible-first groups.

Table 2: Patient demographics Age, gender and surgical difference distribution within the study population

		Maxillary first Surgery	Mandible first Surgery
Population (n=116)		58	58
Age	Mean	28.6	27.5
	SD	11.0	10.6
	Range	16-57	16-55
Male (n = 36)		15	21
Female (n = 80)		43	37
SARME in history		15	18
Genioplasty		33	28

SD: Standard Deviation

Planned values

No significant differences in surgical displacement (translations and rotations) of the bimaxillary complex were found between the maxilla-first and mandible-first groups, except for the direction and magnitude of maxillary pitch (table 3). In the maxilla-first group a mean pitch of 1.98° in the clockwise (CW) direction was found whereas the mean pitch in the mandible-first group was 0.39° in the CCW direction ($p=0.01$).

Table 3: Planned surgical translations and rotations of the maxilla between maxilla-first and mandible-first patients.

		Maxillary first	**Mandible first**	**P-value**
		Mean ± SD	Mean ± SD	
Maxillary Translations (mm)	Anterior/Posterior	3.90 ± 1.73	4.35 ± 1.83	0.17
	Left/Right	-0.04 ± 1.68	-0.16 ± 1.42	0.67
	Cranial/Caudal	-0.45 ± 2.91	-0.13 ± 2.91	0.56
Maxillary Rotations(°)				
	Pitch	1.98 ± 3.91	-0.39 ± 0.5.99	**0.01**
	Roll	-0.30 ± 2.05	-0.07 ± 1.99	0.53
	Yaw	0.07 ± 1.48	0.14 ± 1.42	0.78
Mandibular Translations (mm)	Anterior/Posterior	-8.02 ± 5.69	-7.32 ± 4.58	0.47
	Left/Right	-0.05 ± 2.54	-0.35 ± 2.44	0.21
	Cranial/Caudal	1.07 ± 3.12	0.36 ± 3.68	0.26
Mandibular Rotations(°)	Pitch	-0.11 ± 4.57	-1.21 ± 6.46	0.29
	Roll	-0.32 ± 2.24	-0.08 ± 2.30	0.57
	Yaw	0.07 ± 2.57	-0.07 ± 2.64	0.57

Translation Anterior/Posterior: a positive value means that the maxilla was planned anteriorly, a negative value means that the maxilla was planned posteriorly. **Translation Left/Right:** a positive value means that the maxilla was planned to the right, a negative value means that the maxilla was planned to the left. **Translation Cranial/Caudal**: a positive value means that the maxilla was planned cranially, a negative value means that the maxilla was planned caudally. **Rotation Pitch:** a positive value means a counterclockwise rotation, a negative value means a clockwise rotation. **Rotation Roll:** a positive value means a counterclockwise rotation around the horizontal axis, a negative value means a clockwise rotation around the horizontal axis. **Rotation Yaw:** a positive value means a counterclockwise rotation around the vertical axis, a negative value means a clockwise rotation around the vertical axis. Data presented as means ± SD.

Overall achievability

The overall comparison between the pre-surgical 3D plannings to the measured rotation and translations of the bimaxillary complex after surgery, in the maxilla-first and mandible-first groups, are displayed in table 4 and 5, respectively. In both groups, the achieved pitch showed the largest deviation compared to the 3D planning, whereas the achieved roll showed the least deviation (figure 1). Concerning the translational displacement, the anterior/posterior displacement was the least accurate whereas the left/right displacement deviated the least from the 3D planning in both the maxilla-first and mandible-first group (figure 2).

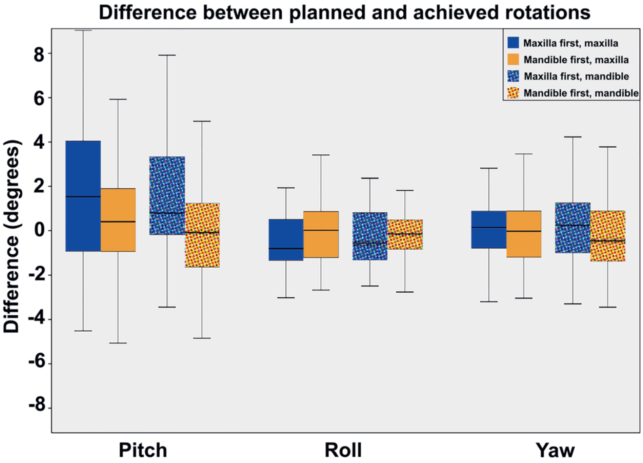

Figure 1: Boxplot of the differences between planned rotations and the postoperative outcome for the mandible and maxilla. Both the maxilla- and mandible-first groups are displayed in the boxplot. The whiskers of the boxplot represent the 25th and 75th percentiles. For the pitch the largest deviation is seen, the smallest deviation is seen in the roll. A negative pitch means that the achieved pitch is larger than the planned pitch, the same goes for the roll and yaw.

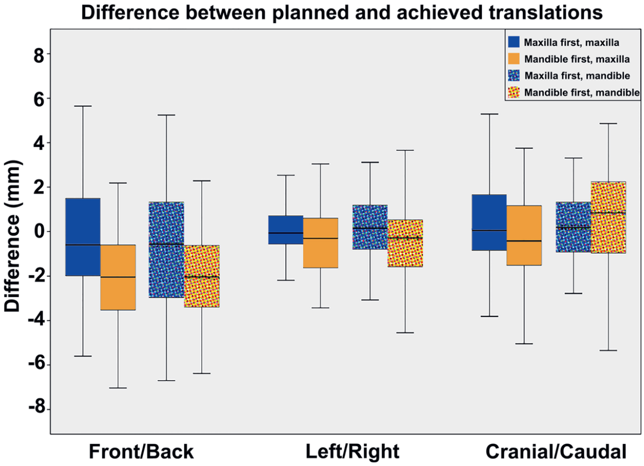

Figure 2: Boxplot of the differences between planned translations and the postoperative outcome for the mandible and maxilla. Both the maxilla- and mandible-first groups are displayed in the boxplot. The whiskers of the boxplot represent the 25th and 75th percentiles. For the front/back translation the largest deviation is seen, the smallest deviation is seen in the left/right translation. A negative front/back translation means that the achieved front/back translation is larger than the planned front/back translation, the same goes for the left/right and cranial/caudal translation.

Predictability of translational displacements

In the maxilla-first group, the achievability of the anterior displacement of the maxilla was significantly higher, compared to the mandible-first group (table 4). A discrepancy between the planning and the postoperative result of 0.45 ± 2.52 mm versus 1.97 ± 1.86 mm respectively (p<0.01) was found. The achieved anterior displacement was smaller than the planned movement in almost all cases. Concerning the anterior positioning of the mandible, a similar association was found, in favour of the maxilla-first group (0.73 ± 2.65 mm versus 2.11 ± 2.13 mm respectively, p=0.01). The precision of the mandibular positioning was lower than the maxilla in both groups. Neither statistical significant differences nor clinical relevant differences in the achievability of the vertical and transverse displacements were found between the maxilla-first and mandible-first groups.

Predictability of rotational displacements

With regard to rotational displacements, the CW pitch of the mandible was attained more precisely in the mandible-first group compared to the maxilla-first group, a discrepancy of 1.30 ± 2.20 ° versus 3.10 ± 2.83 ° (p=0.02) was found (table 5). No significant difference between the achievability of a CW maxillary pitch and a CCW maxillary pitch was present between the two groups (p=0.07). In the maxilla-first group, a CW pitch was more difficult to accomplish than a CCW pitch, resulting in an inaccuracy of 1.96° and 1.11° respectively. The mean discrepancies between the planned and achieved roll and yaw of the maxilla and mandible were below 1.2° in both groups.

Table 4: Surgical planned, realized and difference values for the maxilla in both mandible- and maxilla first patients. Translations are given in millimeter, while rotations are given in degrees.

		Maxilla first					Mandible first					
		n	Planned Mean ±SD	Realized Mean ± SD	Difference Mean ± SD	p-value*	n	Planned Mean ± SD	Realized Mean ±SD	Difference Mean ± SD	p-value*	p-value**
Translation												
X	Left	18	1.91 ± 0.86	1.84 ± 1.46	0.07 ± 1.02	0.79	33	1.25 ± 1.09	0.37 ± 1.37	0.88 ± 1.52	**0.01**	0.06
	Right	14	2.28 ± 0.84	1.66 ± 1.81	0.62 ± 1.62	0.19	20	0.00 ± 0.00	0.81 ± 1.68	0.81 ± 1.68	0.27	0.58
	None	26	0.00 ± 0.00	0.07 ± 1.19	-0.07 ± 1.19	0.78	5	1.10 ± 0.85	0.80 ± 1.19	0.30 ± 1.40	0.14	0.05
Y	Anterior	56	4.04 ± 1.58	3.58 ± 2.51	0.45 ± 2.52	0.28	58	4.35 ± 1.81	2.39 ± 2.04	1.97 ± 1.86	**0.00**	**0.00**
	Posterior	0	-	-	-	-	0	-	-	-	-	-
	None	2	0.00 ± 0.00	5.17 ± 0.47	-5.17 ± 0.47	-	0	-	-	-	-	-
Z	Cranial	23	2.78 ± 1.67	3.16 ± 2.47	0.38 ± 2.04	0.39	31	2.06 ± 1.66	1.89 ± 2.32	0.17 ± 2.20	0.67	0.36
	Caudal	33	2.47 ± 1.33	2.31 ± 2.59	0.16 ± 1.98	0.65	26	2.74 ± 1.70	2.90 ± 1.96	-0.16 ± 1.23	0.52	0.48
	None	2	0.00 ± 0.00	5.13 ± 1.07	5.13 ± 1.07	0.13	1	0.00 ± 0.00	-0.94 ± 0.00	-0.94 ± 0.00	-	-
Rotation												
Pitch	CW	32	4.78 ± 2.04	2.82 ± 3.26	1.96 ± 2.73	**0.00**	27	5.35 ± 2.89	3.04 ± 2.46	2.48 ± 1.90	**0.00**	0.59
	CCW	9	4.21 ± 2.90	3.10 ± 3.01	1.11 ± 1.60	**0.04**	29	5.76 ± 3.38	3.99 ± 2.78	1.77 ± 2.63	**0.00**	0.62
	None	17	0.00 ± 0.00	1.92 ± 2.81	-1.92 ± 2.81	**0.02**	2	0.00 ± 0.00	-0.16 ± 0.79	-0.16 ± 0.79	0.57	0.09
Roll	CW	22	2.10 ± 1.36	1.26 ± 1.55	0.84 ± 1.39	**0.02**	29	1.94 ± 1.41	1.18 ± 1.02	0.76 ± 1.23	0.01	0.98
	CCW	11	2.60 ± 1.76	2.95 ± 2.42	0.35 ± 1.22	0.21	24	1.93 ± 1.36	1.41 ± 1.31	0.52 ± 1.62	0.26	0.11
	None	25	0.00 ± 0.00	0.33 ± 0.98	-0.33 ± 0.98	0.11	5	0.00 ± 0.00	0.04 ± 0.97	0.04 ± 0.97	0.92	0.26
Yaw	CW	17	1.36 ± 1.07	1.00 ± 1.58	0.36 ± 1.69	0.32	28	1.30 ± 0.90	0.41 ± 2.00	0.89 ± 1.67	**0.05**	0.38
	CCW	14	1.93 ± 1.23	0.96 ± 1.70	0.97 ± 1.51	0.16	27	1.17 ± 1.22	0.53 ± 1.39	0.64 ± 1.47	0.04	0.94
	None	27	0.00 ± 0.00	0.04 ± 1.14	-0.04 ± 1.14	0.50	3	0.00 ± 0.00	0.39 ± 1.21	-0.39 ± 1.21	0.25	0.17

Translation Anterior/Posterior: a positive value means that the mandible was positioned more posteriorly than planned, a negative value means that the mandible was positioned more anteriorly than planned. **Translation Left/Right:** a positive value means that the mandible was positioned more to the right compared to the planning, a negative value means that the mandible was positioned more to the left compared to the planning. **Translation Cranial/Caudal:** a positive value means that the mandible was displaced more cranially compared to the planning, a negative value means that the mandible was displaced more cranially compared to the planning. **Rotation Pitch:** a positive value means an anti-clockwise rotation compared to the planning, a negative value means a clockwise rotation compared to the planning. **Rotation Roll:** a positive value means an anti-clockwise rotation around the horizontal axis compared to the planning, a negative value means a clockwise rotation around the horizontal axis compared to the planning. **Rotation Yaw:** a positive value means an anti-clockwise rotation around the vertical axis compared to the planning, a negative value means a clockwise rotation around the vertical axis compared to the planning. Data presented as means ± SD. CW: Clockwise, CCW: Counterclockwise. *: p-value between planned and realized value, **: p-value between the difference of the mandible-first and maxilla-first.

Table 5: Surgical planned, realized and difference values for the mandible in both mandible and maxilla first patients. Translations are given in millimeter while rotations are given in degrees.

		Maxilla first					Mandible first					
		n	Planned Mean ± SD	Realized Mean ± SD	Difference Mean ± SD	p-value*	n	Planned Mean ± SD	Realized Mean ± SD	Difference Mean ± SD	p-value*	p-value**
Translation												
X	Left	33	1.34 ± 0.98	1.03 ± 2.23	0.31 ± 1.97	0.39	31	2.06 ± 1.64	0.93 ± 1.94	1.13 ± 1.54	0.00	0.06
	Right	20	2.91 ± 2.64	2.00 ± 3.13	0.91 ± 1.82	0.02	27	1.61 ± 1.49	1.34 ± 1.46	0.27 ± 1.46	0.36	0.14
	None	5	0.00 ± 0.00	0.56 ± 1.11	-0.56 ± 0.11	0.84	0	-	-	-	-	-
Y	Anterior	50	9.61 ± 4.23	8.88 ± 4.96	0.73 ± 2.65	0.06	52	8.28 ± 3.73	6.17 ± 3.44	2.11 ± 2.13	0.00	0.01
	Posterior	6	2.56 ± 2.04	4.83 ± 3.25	2.27 ± 2.01	0.05	6	1.03 ± 0.44	2.50 ± 0.74	1.47 ± 1.05	0.03	0.45
	None	2	0.00 ± 0.00	5.79 ± 5.79	-5.79 ± 5.79	-	0	-	-	-	-	-
Z	Cranial	33	3.25 ± 2.03	2.56 ± 3.09	0.69 ± 2.16	0.08	34	2.94 ±1.43	1.79 ± 2.74	1.16 ± 2.40	0.01	0.52
	Caudal	20	2.23 ± 1.37	2.44 ± 1.98	-0.21 ± 2.00	0.61	24	3.29 ± 2.53	3.35 ± 2.60	-0.05 ± 1.98	0.90	0.84
	None	5	0.00 ± 0.00	1.38 ± 3.19	1.38 ± 3.19	0.50	0	-	-	-	-	-
Rotation												
Pitch	CW	27	3.56 ± 3.11	0.46 ± 3.63	3.10 ± 2.83	0.00	21	5.75 ± 3.90	4.45 ± 3.74	1.30 ± 2.20	0.02	0.02
	CCW	30	3.66 ± 2.63	3.52 ± 3.46	0.15 ± 2.53	0.74	37	5.16 ± 3.53	4.21 ± 3.04	0.95 ± 2.08	0.01	0.10
	None	1	0.00 ± 0.00	6.75 ± 1.17	-6.75 ± 1.17	-	0	-	-	-	-	-
Roll	CW	33	1.66 ± 1.61	1.03 ± 1.67	0.71 ± 1.11	0.00	35	1.47 ± 1.38	0.90 ± 1.28	0.56 ± 0.97	0.02	0.86
	CCW	24	1.51 ± 1.63	1.44 ± 2.15	0.07 ± 1.24	0.80	23	2.03 ± 1.70	1.39 ± 1.50	0.64 ± 1.15	0.02	0.13
	None	1	0.00 ± 0.00	0.21 ± 1.13	-0.21 ± 1.13	-	0	-	-	-	-	-
Yaw	CW	29	1.62 ± 1.69	0.93 ± 2.09	0.72 ± 1.40	0.01	29	2.04 ± 1.77	0.85 ± 1.46	1.19 ± 1.56	0.00	0.21
	CCW	28	2.09 ± 1.75	0.77 ± 1.90	1.40 ± 1.94	0.00	29	1.90 ± 1.68	1.10 ± 1.24	0.81 ± 0.61	0.01	0.29
	None	1	0.00 ± 0.00	0.55 ± 0.55	0.55 ± 0.61	-	0	-	-	-	-	-

Translation Anterior/Posterior: a positive value means that the mandible was positioned more posteriorly than planned, a negative value means that the mandible was positioned more anteriorly than planned. **Translation Left/Right:** a positive value means that the mandible was positioned more to the right compared to the planning, a negative value means that the mandible was positioned more to the left compared to the planning. **Translation Cranial/Caudal:** a positive value means that the mandible was displaced more cranially compared to the planning, a negative value means that the mandible was displaced more cranially compared to the planning. **Rotation Pitch:** a positive value means an anti-clockwise rotation compared to the planning, a negative value means a clockwise rotation compared to the planning. **Rotation Roll:** a positive value means an anti-clockwise rotation around the horizontal axis compared to the planning, a negative value means a clockwise rotation around the horizontal axis compared to the planning. **Rotation Yaw:** a positive value means an anti-clockwise rotation around the vertical axis compared to the planning, a negative value means a clockwise rotation around the vertical axis compared to the planning. Data presented as means ± SD. CW: Clockwise, CCW: Counterclockwise. *: p-value between planned and realized value, **: p-value between the difference of the mandible-first and maxilla-first.

Discussion

The sequence of osteotomies in bimaxillary surgery has been debated frequently in the field of orthognathic surgery[14]. To date, a limited number of studies have been conducted on the accuracy of sequence in bimaxillary osteotomies. This is first 3D clinical cohort study, to our knowledge, which evaluates the influences of maxilla-first or mandible-first surgical sequence of bimaxillary osteotomies on the achievability of the 3D virtual treatment planning.

The strength of the present study is not only the use of 3D CBCT data to carry out the preoperative 3D planning and postoperative evaluation, but also the application of the newly designed and validated tool, the OGA[8]. In contrast to all conventional 2D and 3D cephalometric analyses, the OGA eliminates the necessity of identifying anatomical landmarks multiple times. By overcoming the landmark identification error, the OGA is an observer independent, semi-automatic tool, which is able to analyse the accuracy of the 3D planning and surgical outcome in an objective, reproducible and systematic way. Thus, it is now possible to identify and quantify small 3D-translational and -rotational discrepancies in the jaw position between two CBCTs.

The ideal study design to evaluate the influence of sequencing bimaxillary osteotomies and the achievability of 3D planning is a randomized controlled trial, having patients who are randomly assigned to the maxilla-first and mandible-first groups, while controlling all possible covariates. However, in the clinical practice, this ideal study design may encounter grave ethical issues. Therefore, a retrospective cohort study was set up. The clinical protocol and principles of 3D planning were identical in both groups. The sequence of bimaxillary surgery was only dependent on the year of operation and not influenced by covariates. In this way, the selection bias was kept to a minimum. This is reflected by the fact that all patient characteristics and surgical movements did not differ significantly between the maxilla-first and mandible-first groups (except for the pitch of maxilla).

Our results have demonstrated that the positioning of the bimaxillary complex is generally more accurate when the maxilla is operated first, especially in the anterior displacement of the jaws. These results differ from those presented by Ritto et al.[3] who has stated that the both the maxilla-first and mandible-first surgery could provide a reliable outcome. As the mean displacement of the maxilla was comparable between the two studies (4 mm), we believe that the difference is caused by the use of cephalograms and conventional cephalometry. The measurement errors in our study are significantly reduced by applying the state-of-art 3D imaging technology, thereby revealing the true underlying differences between the maxilla-first and mandible-first groups.

The double seating of the condyles in the mandible-first group could have induced more accuracies. During surgery the condyles are prone to displacements in their fossa as the result of manipulations of the proximal segments during fixation of the distal mandibular segment [15]. Small discrepancies in the condylar seating (1 mm or less) can create significant occlusal interferences, leading to significant deviations in jaw positioning[3]. This heavily impacts the mandible-first surgical approach, as the condylar seating needs to be performed twice, which not only affects the mandibular positioning, but also the maxillary positioning. Therefore, the overall accuracy of the bimaxillary positioning is in favour of the maxilla-first sequence, in which the condylar seating is only carried out once (only influencing the mandibular positioning). Thus, a better accuracy of the maxillary positioning is achieved compared to mandibular positioning, in both the maxilla-first and mandible-first groups.

Previous studies [1, 3, 4, 16] have described that mistakes in the transfer of the correct mandibular position by face-bow registration to the articulator, will lead to an incorrect maxillary position. Therefore, the mandibular-first surgery is more accurate as it is less prone to errors caused by the incorrect mounting of the inferior model. By using a 3D-CBCT-based operation planning, coupled with the use of a wax bite to seat the condyles in centric relationship during CBCT scanning, the condyle-fossa remains stable throughout the planning process[17]. This eliminates the need to correct for inaccuracies in the planning phase by using a mandible-first surgical approach, as the preoperative planning of bimaxillary osteotomy is optimized with 3D planning. Thus, in combination with 3D virtual planning of orthognathic surgery, the inherent advantages of maxilla-first sequence prevail.

The pitch showed the largest rotational deviation of all displacements. This can be the cause of bone interferences between the pterygoid plates and the osteotimized posterior maxilla. Intraoperatively it is hard to visually check for bone interferences in the posterior maxilla. This can result in premature bone contacts and lead to a deviation in the pitch. Another reason for the larger inaccuracies in the pitch might be the non-centric relation of the mandible when the interocclusal splint is used to set the maxilla in to its desired position [1].

In line with the findings of Hsu et al.[18] a lower achievability of the preoperative planning is seen in both the maxilla-first and mandible-first groups for the translations and rotations of the mandible compared to the maxilla. As this finding is present in both groups, a possible cause can be the positioning of the mandible during postoperative CBCT scanning. The postoperative CBCT scan was acquired without the interposition of the final splint. This may lead to a different occlusion than planned due to occlusal interferences, causing a larger discrepancy between the 3D planned and actually achieved mandibular position. In addition, the neuromuscular is not yet accomplished one week following bimaxillary surgery. As the CBCT scans were acquired without the use of elastics, traction from soft tissues surrounding the bimaxillary complex would have caused displacement of the mandible in the opposite direction to the surgical movements during the scanning process. Therefore, the concordance between the postoperative mandibular position and the 3D planning was inferior to that of the maxillary position. The position of the maxilla was not affected by the presence of the splint, elastics nor the occlusion.

The results from the present study highlighted the correlation between the magnitude of the translational and rotational movements, and the achievability of the 3D planning. The planned translations and rotations of more than 4 mm or 4 degrees showed a significant larger discrepancy between planning and post-operative outcome compared to cases with a smaller translations and rotations, particularly in the left/right translations and pitch of the maxilla ($p< 0.03$ and $p< 0.01$) and yaw of the mandible ($p < 0.01$). These findings are in line with the study of Semaan and Goonewardene[19]. In their analyses of the accuracy of Le Fort I surgeries, a greater maxillary advancement tended to be accompanied by more inaccuracies, such as an over-rotation of the maxilla in cases of a CW pitch and a maxillary under-rotation if a CCW pitch was planned. Soft tissue traction on the maxilla and the positioning of the osteotomy line would have influenced the accuracy of surgery.

While the maxilla first sequence is generally preferred [1, 20] and found to be more accurate in this study, the mandible first sequence would be favoured in two specific situations:

1 CCW rotation of the bimaxillary complex.
   In contrast to the anterior maxillary and mandibular displacements, the mandible-first operating sequence was able to achieve a CCW pitch of the mandible which was more accurate compared to the maxilla-first protocol. This objective finding has confirmed what Perez and Ellis[4] postulated earlier, that it is preferable to operate the mandible first when performing a CCW rotation of the bimaxillary complex. In cases of maxilla-first sequence, when a CCW of the maxilla is required, the interocclusal wafer is thicker anteriorly than posteriorly, making the intermaxillary fixation more difficult to manage. In addition, there is little bony support of the posterior maxilla which makes the positioning and fixation of the maxilla more prone to errors. Since the fixation of a CCW pitched maxilla is more challenging and since the maxilla is subdued to reactive forces during the subsequent mandibular osteotomy and fixation, the stability and predictability would be greater when the mandible would be operated first[20].
2. Segmental Le Fort I osteotomies
   Cottrell and Wolford described that the mandible-first sequence would make complex dual-arch bimaxillary osteotomies, such as segmental Le Fort I osteotomies, more reliable by avoiding tension on the repositioned maxilla during the mandibular surgery [20]. When performing the segmental Le Fort I osteotomies prior to mandibular surgery, traction on the weakened maxillary segments is exerted,

> which may influence the position of the segments and the subsequent mandibular position. By inverting the sequence, the maxillary segments can be positioned using the splint that is firmly attached to the newly positioned mandible, facilitating a more stable positioning of the maxillary segments. As all maxillas were operated in one-piece in the present study, this possible advantage of a mandible-first sequence could not be observed. Future 3D clinical studies are recommended to provide evidence for this sequencing protocol in segmental Le Fort I osteotomies. As long as a stable fixation of the maxilla can be achieved, the maxilla-first sequence should considered to be the first choice.

It should be underlined that when performing a mandible-first surgery, the mandibular osteotomies should be carried out meticulously and a stable fixation of the mandibular segments is required. In cases of a bad-split during mandibular surgery, an accurate positioning of the maxilla can be very challenging. The management of such unforeseen events in cases of mandible-first surgery should be in experienced hands.

An important step in the 3D virtual planning of bimaxillary osteotomies is the “virtual mandibular autorotation” which is in some cases required. An example is the downgrafting of the maxilla in the maxilla-first sequence. A realistic autorotation of the mandible is required to predict the subsequent mandibular position and the required movements of the mandible in order to create a harmonious facial profile. When a large CW or CCW rotation of the mandible is planned in the mandible-first sequence, the virtual mandible will also undergo “virtual mandibular autorotation”. Up till today, the virtual autorotation is still a weak point in the 3D virtual surgery planning as “virtual mandibular autorotation” is based on one single rotation over a predefined axis through both condyles. In reality, the autorotation of the mandible is a combination of rotational and translational movements of the condyles. Therefore, this should be one of the focuses of future studies on the accuracy of 3D virtual orthognathic planning.

Whether the maxilla or mandible should be operated first is still up to the surgeon to decide. The surgeons experience and preferences play an important role in the choice for maxilla-first or mandible-first surgery. While there appears to be advantages to support the use of mandibular-first sequence in specific cases, future prospective studies on its reliability, accuracy, and short- and long-term outcomes are required. As the present study has provided evidence for a superior predictability of maxilla-first surgery, the authors recommend the use of maxilla-first sequencing protocol unless a CCW pitch of the mandible is planned.

The sequence of bimaxillary osteotomies influences the achievability of the 3D virtual operation planning significantly. With maxilla-first surgery, the 3D planned translational and rotational movements of the maxilla and mandible can be accomplished more accurately compared to mandible-first surgery. However, in cases of bimaxillary CCW pitch, the mandible-first surgery is preferred. 3D virtual planning in combination with an optimised sequencing of osteotomies provide highly predictable results in bimaxillary surgery.

References

1. Perez, D. and E. Ellis, 3rd, *Sequencing bimaxillary surgery: mandible first.* J Oral Maxillofac Surg, 2011. **69**(8): p. 2217-24.
2. Turvey, T., *Sequencing of two-jaw surgery: the case for operating on the maxilla first.* J Oral Maxillofac Surg, 2011. **69**(8): p. 2225.
3. Ritto, F.G., et al., *Accuracy of maxillary positioning after standard and inverted orthognathic sequencing.* Oral Surg Oral Med Oral Pathol Oral Radiol, 2014. **117**(5): p. 567-574.
4. Perez, D. and E. Ellis, 3rd, *Implications of Sequencing in Simultaneous Maxillary and Mandibular Orthognathic Surgery.* Atlas Oral Maxillofac Surg Clin North Am, 2016. **24**(1): p. 45-53.
5. Ellis, E., 3rd, *Accuracy of model surgery: evaluation of an old technique and introduction of a new one.* J Oral Maxillofac Surg, 1990. **48**(11): p. 1161-7.
6. Turvey, T.A., *Simultaneous mobilization of the maxilla and mandible: surgical technique and results.* J Oral Maxillofac Surg, 1982. **40**(2): p. 96-9.
7. Schneider, M., et al., *Comparison of the predicted surgical results following virtual planning with those actually achieved following bimaxillary operation of dysgnathia.* J Craniomaxillofac Surg, 2005. **33**(1): p. 8-12.
8. Baan, F., et al., *A New 3D Tool for Assessing the Accuracy of Bimaxillary Surgery: The OrthoGnathicAnalyser.* PLoS One, 2016. **11**(2): p. e0149625.
9. Swennen, G.R., et al., *A cone-beam computed tomography triple scan procedure to obtain a three-dimensional augmented virtual skull model appropriate for orthognathic surgery planning.* J Craniofac Surg, 2009. **20**(2): p. 297-307.
10. Hunsuck, E.E., *A modified intraoral sagittal splitting technic for correction of mandibular prognathism.* Journal of oral surgery (American Dental Association : 1965), 1968. **26**(4): p. 250-3.
11. Maes, F., et al., *Multimodality image registration by maximization of mutual information.* IEEE Trans Med Imaging, 1997. **16**(2): p. 187-98.
12. Nada, R.M., et al., *Accuracy and reproducibility of voxel based superimposition of cone beam computed tomography models on the anterior cranial base and the zygomatic arches.* PLoS One, 2011. **6**(2): p. e16520.
13. Swennen, G.R., et al., *A new method of 3-D cephalometry Part I: the anatomic Cartesian 3-D reference system.* J Craniofac Surg, 2006. **17**(2): p. 314-25.
14. Borba, A.M., et al., *Mandible-first sequence in bimaxillary orthognathic surgery: a systematic review.* Int J Oral Maxillofac Surg, 2016. **45**(4): p. 472-5.
15. Chen, S., et al., *Short- and long-term changes of condylar position after bilateral sagittal split ramus osteotomy for mandibular advancement in combination with Le Fort I osteotomy evaluated by cone-beam computed tomography.* J Oral Maxillofac Surg, 2013. **71**(11): p. 1956-66.
16. Olszewski, R. and H. Reychler, *[Limitations of orthognathic model surgery: theoretical and practical implications].* Rev Stomatol Chir Maxillofac, 2004. **105**(3): p. 165-9.

17. Aboul-Hosn Centenero, S. and F. Hernandez-Alfaro, *3D planning in orthognathic surgery: CAD/CAM surgical splints and prediction of the soft and hard tissues results - our experience in 16 cases.* J Craniomaxillofac Surg, 2012. **40**(2): p. 162-8.
18. Hsu, S.S., et al., *Accuracy of a computer-aided surgical simulation protocol for orthognathic surgery: a prospective multicenter study.* J Oral Maxillofac Surg, 2013. **71**(1): p. 128-42.
19. Semaan, S. and M.S. Goonewardene, *Accuracy of a LeFort I maxillary osteotomy.* Angle Orthod, 2005. **75**(6): p. 964-73.
20. Cottrell, D.A. and L.M. Wolford, *Altered orthognathic surgical sequencing and a modified approach to model surgery.* J Oral Maxillofac Surg, 1994. **52**(10): p. 1010-20; discussion 1020-1.

Chapter 8

One-year postoperative skeletal stability of 3D planned bimaxillary osteotomies: maxilla-first versus mandible-first surgery.

Liebregts JHF, Baan HF, van Lierop P, de Koning M, Bergé SJ, Maal TJ, Xi T.

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Abstract

Purpose: Orthognathic surgery is carried out to correct jaw deformities and to improve facial aesthetics. However, controversy surrounds whether the maxilla- or mandible-first surgery approach leads to better surgical outcomes. In our previous study, we have shown that in most instances, the maxilla-first surgical approach yielded closer concordance with the 3D virtual treatment plan than a mandibular-first procedure. However, the post-operative stability of each approach has not been investigated. Therefore, this one-year follow-up study was set-up and investigated the postoperative skeletal stability of the 3D planned translations and rotations after either the maxilla- or mandible-first surgery.

Materials and methods: 106 patients who underwent bimaxillary surgery and had an individualized 3D virtual operation plans, received either maxilla-first (n=53) or mandible-first group (n=53) surgery. 3D milled interocclusal splints were used during surgery to position the jaws. One year postoperatively a cone-beam computed tomography (CBCT) scan was made to assess the effects using the OrthoGnathicAnalyser.

Results: The mean sagittal, vertical and transverse relapse was less than 1.8 mm and no significant differences were found in relapse between the maxilla-first or the mandibular-first surgical procedure.

Conclusion: Overall, this study shows that 3D virtual planning in combination with an optimised sequencing of osteotomies provides predictable long-term results in bimaxillary surgery.

Introduction

In the past decade, significant controversy has surrounded the surgical approach taken during orthognathic surgery (corrective jaw surgery), in particular the sequencing of bimaxillary osteotomies. Traditionally, surgeons have opted to first operate on the maxilla, and then subsequently correct the osteotomies in the mandible. However, more recently several publications have highlighted the benefits of adopting the mandible first sequencing protocol, particularly in the downgrafting of the maxilla and a counterclockwise (CCW) rotation of the jaws [1-5]. Yet, there is little consensus on whether the maxilla-first or mandible-first surgical approach is more advantageous in terms of predictability and long-term stability of the postoperative results.

To obtain a harmonious facial profile and a stable dental occlusion, computer-assisted 3D virtual surgical planning is increasingly being used to improve the predictability of the postoperative outcomes in orthognathic surgery [6]. An accurate transfer of the 3D planned jaw positions to the patient is required to achieve the virtually planned positions of the jaws at the end of the operation. Recently our group has demonstrated that using the maxilla-first surgical approach, the 3D planned translational and rotational movements of the maxilla and mandible can be accomplished more accurately, compared to the mandibular-first approach[4]. However, in cases of bimaxillary CCW pitch, the mandible-first surgical approach is preferred because this sequence results in more predictable displacements of the jaws [3, 4].

The postoperative skeletal stability is a major concern in obtaining satisfactory long-term results following bimaxillary osteotomies. Skeletal relapse is frequently reported, with an incidence varying between 2.0% and 50.3% [7], and as a result the maxilla and mandible tend to return to their preoperative positions, leading to an enlarged overbite, malocclusion and deteriorating facial aesthetics. Relapse is associated with surgery related factors, such as the magnitude of the surgical displacement of jaws and the surgical technique. However, there is no published evidence on the association between surgical approaches (maxilla-first or mandible-first) on the postoperative skeletal stability. Therefore, this study has evaluated the one-year postoperative skeletal stability of 3D planned bimaxillary osteotomies in patients who underwent either maxilla- or mandible-first surgical protocols.

Patients and Methods

Patients who underwent bimaxillary osteotomies in the period from 2010 to 2014 at the Department of Oral and Maxillofacial Surgery in Radboud University Nijmegen Medical Centre were included in this study. The inclusion criteria were a non-syndromatic dysgnathia requiring bimaxillary osteotomies with or without genioplasty and the availability of a CBCT scan before and one year after surgery. All patients received preoperative orthodontic treatment to align their teeth and had a minimum of 24 teeth. The exclusion criteria were previous history of facial trauma with fractures of facial bones, or a history of orthognathic surgery, except a SARME (Surgically Assisted Rapid Maxillary Expansion) procedure.

This study was conducted in compliance with the World Medical Association Declaration of Helsinki on medical research ethics. The approval of the institutional review board (CMO Arnhem-Nijmegen, #181/2005) and informed consent were obtained for this study. All patient data were anonymized and de-identified prior to analysis.

Data acquisition

CBCT scans were acquired four weeks prior to surgery and within one year after bimaxillary surgery using a standard CBCT scanning protocol (i-CAT, 3D Imaging System, Imaging Sciences International Inc, Hatfield, PA, USA) in “Extended Field” modus (FOV: 16 cm diameter/22 cm height; scan time: 2x20s; voxel size: 0.4 mm). Patients were scanned while seated in natural head position. They were asked to swallow, to relax their lips and facial muscles and to keep their eyes open. The acquired CBCT data were exported in DICOM format and imported into Maxilim® software (Medicim NV, Mechelen, Belgium).

Surgical planning

In Maxilim®, a 3D virtual augmented head model was rendered and positioned in a reference frame as described by Swennen et al[8]. Subsequently, virtual osteotomies were performed to simulate the Le Fort I and BSSO osteotomies. The maxillary and mandibular segments were positioned into the desired positions in order to create a harmonious 3D soft tissue facial profile, as simulated in real-time by the Maxilim® software using the mass tensor model based soft tissue simulation[9]. If the facial profile required, an additional virtual chin osteotomy was simulated. Based on the 3D virtual planning, one intermediate and one final interocclusal splint were milled to transfer the virtual planning to the patient in the operating theatre.

Between 2010-2012 the clinical protocol for bimaxillary osteotomies was to start with the BSSO that was followed by the Le Fort 1 (mandible-first). After 2012 this protocol was changed and the Le Fort 1 was performed prior to the BSSO (maxilla-first).

Surgical procedure

All bimaxillary osteotomies were performed or supervised by one experienced surgeon (MdK). After nasotracheal intubation, the mucobuccal fold of the maxilla and the mandibular ramus regions were infiltrated with local anaesthetic (Ultracain Ds-Forte). In cases of mandible-first procedure, a BSSO was performed according to the Hunsuck modification (Hunsuck,

1968) [10]. After the completion of the osteotomies using osteotomes, the distal segment of the mandible was placed in the planned position using the prefabricated interocclusal intermediate splint and stabilized with intermaxillary fixation (IMF). The proximal segments were gently pushed backward and upward to seat the condyles. The mandibular segments were fixed with two titanium miniplates (one on each side) and monocortical screws (Champy 2.0 mm, KLS Martin, Tuttlingen, Germany). Following the BSSO, a Le Fort I procedure was performed. After an incision in the gingivobuccal sulcus and elevation of mucoperiosteum and nasal mucosa, the osteotomies were made with a reciprocal saw at the Le Fort I level. The lateral nasal walls and nasal septum were osteotomized with a nasal osteotome. The piriform aperture and nasal spine were rounded. After mobilization of the maxilla, it was positioned in the planned position using a prefabricated final interocclusal splint. Fixation was performed with four 1.5 mm miniplates (KLS Martin, Tuttlingen, Germany) and 4 mm screws, one paranasal and one on the maxillary buttress on each side. Alar cinch suture and VY sutures were used accordingly. The mucosa was closed with a 3-0 Vicryl suture (Ethicon, Johnson and Johnson Medical, Norderstedt, Germany). In cases of maxillary first procedure, the Le Fort I osteotomy was carried out first, after which the BSSO was performed. The surgical protocol and method of fixation were identical as described in the mandible-first procedure.

Postsurgical protocol

Depending on the stability of the occlusion, the final interocclusal splint was removed or left in place. Tight elastics were applied during the first postoperative week to keep a proper occlusion. After the first week, these elastics were replaced by guiding elastics, and were maintained for approximately two weeks. Postoperative orthodontic treatment occurred between three to four weeks after surgery.

3D analysis of 3D planned and 1-year postoperative positioning of jaws

The accuracy of the one-year postoperative surgical result was compared to the postoperative result and evaluated using the following steps.

Step 1: The 3D rendered pre- and postoperative 3D virtual head models were aligned by using voxel-based registration upon the anterior cranial base [11, 12].

Step 2: Virtual triangles were constructed on the maxilla and distal mandibular segment by using previously validated cephalometric landmarks [13].

Step 3: The preoperative virtually osteotomized maxilla and distal mandibular segment were translated to the 3D planned position in Maxilim® by voxel-based registration. The landmarks placed on the preoperative maxilla and mandible, and thus the previously constructed triangles were translated along with the maxilla and mandible to the 3D planned position. The coordinates of the triangles were imported into the OGA [14] to compute the

3D planned sagittal, vertical and transverse translations as well as rotations (pitch, roll and yaw) of the maxilla and distal mandibular segment.

Step 4: The maxilla and mandibular segments were again translated from the 3D planned position to the postoperative position through voxel-based registration, which resulted in a displacement of the virtual triangle. The coordinates of the landmarks (virtual triangle) in the postoperative position were imported into the OGA. The translational and rotational differences of the maxilla and distal mandibular segment between the actual postoperative surgical results and the one-year postoperative surgical results were calculated [14] (figure 3).

Statistical Analysis

Statistical data analyses were performed with SPSS 23 for Windows (IBM Corp., Armonk, NY, USA). Mean relapse (difference) was calculated for both the mandible and maxilla in six different planes: translation – horizontal (anterior/posterior), lateral (left/right), vertical (up/down); rotation – pitch (CW/ CCW), roll (CW/CCW) and yaw (CW/CCW) (figures 1 and 2.). All rotations were measured in degrees (°) and all translations in millimetres (mm). A one-way ANOVA and paired t-tests were used to assess the postoperative relapse between the directly postoperative and 1-year postoperative CBCT scans, based on the 5% level of significance ($p \leq 0.05$). To evaluate the influence of the different directions on relapse, differences between the mean relapse of opposite directions (CW/CCW, anterior/posterior, left/right and up/down) were compared by using one-way ANOVA and were shown with a 5% level of significance. Univariate regression analyses were performed to identify the influence of different patient variables and operation variables on relapse. These results were shown as partial eta squared (partial η^2), which is the proportion of variance accounted for by individual variables.

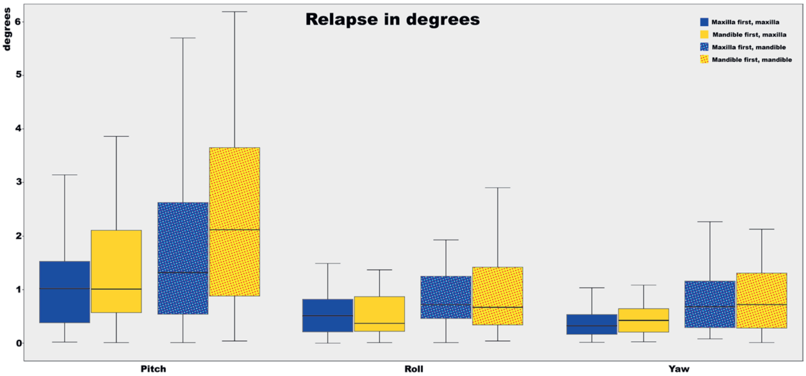


Figure 1. Boxplot of the differences between planned rotations and the postoperative outcome for the mandible and maxilla. Both the maxilla- and mandible-first groups are displayed in the boxplot. The whiskers of the boxplot represent the 25th and 75th percentiles. For the pitch the largest deviation is seen, the smallest deviation is seen in the roll. A negative pitch means that the achieved pitch is larger than the planned pitch. The same applies for the roll and yaw.

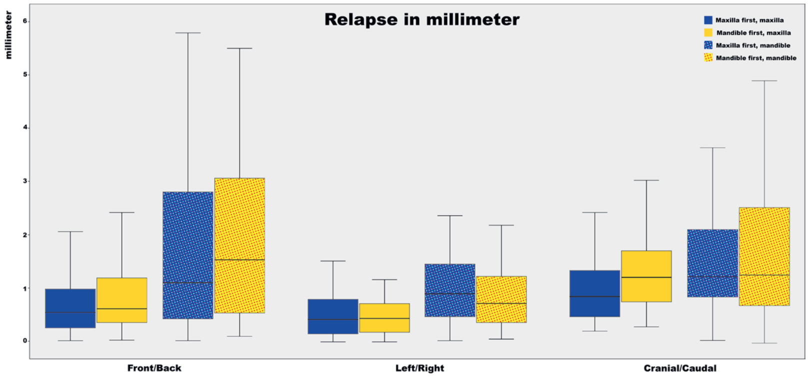


Figure 2. Boxplot of the differences between planned translations and the postoperative outcome for the mandible and maxilla. Both the maxilla- and mandible-first groups are displayed in the boxplot. The whiskers of the boxplot represent the 25th and 75th percentiles. The largest deviation is shown in the front/back translation, the smallest deviation is shown in the left/right translation. A negative front/back translation means that the achieved front/back translation is larger than the planned front/back translation; the same goes for the left/right and cranial/caudal translation.

Results

The clinical cohort consisted of patients who underwent bimaxillary osteotomies at Radboud University between 2010 and 2014 (n=116) [4]. In this one-year follow-up study, data from 106 patients (n=73 female (69%); n=33 male (31%); mean age 28 (range 16-57; table 1)) were analysed to determine the level of skeletal relapse after undergoing either maxilla-first (n=53) or mandible-first (n=53) bi-maxillary surgery. In 57 patients an additional genioplasty was also performed (maxilla-first n=30; mandible-first n=27). The patient cohort also included 28 patients (26%), which had undergone a previous surgically assisted rapid maxillary expansion (SARME) prior to their bimaxillary surgery (maxilla-first n=12; mandible-first group n=16; table 1). The post-operative CBCT-scan was acquired at 10.2 ± 3.0 months following surgery.

Table 1: Age, gender and surgical difference distribution within the study population

		Maxilla-first surgery	Mandible-first surgery
Population (n=106)		53 (50%)	53 (50%)
Age	Mean	28.3	28.3
	SD	11.3	10.9
	Range	16-57	16-55
Male (n = 33)		14 (26%)	19 (36%)
Female (n = 73)		39 (74%)	34 (64%)
SARME in history		12 (23%)	16 (30%)
Genioplasty		30 (57%)	27 (51%)

SD: Standard Deviation

Overall skeletal relapse

The overall postoperative skeletal relapse of the maxilla and mandible in terms of translation and rotation are shown in table 2. In patients who underwent the maxilla-first surgical approach, only the cranial/caudal translational movements showed a significant post-operative relapse (cranial: 0.7 ± 1.1 mm, $p < 0.01$; caudal: 0.7 ± 1.4 mm, $p < 0.01$). The remaining translational movements in the maxilla (left/right, anterior/posterior), were <0.3 mm and did not reach statistical significance.

For the overall translational directions of the mandible, only the posterior (1.8 ± 1.2 mm, $p < 0.01$) and caudal (1.4 ± 2.0 mm, $p < 0.01$) translations displayed relapses greater than 1 mm. For the rotational movements of the maxilla the postoperative relapse was below 1°, except for the pitch which showed the largest skeletal relapse (CW (=clockwise) 1.0^{o} ± 1.3°, $p < 0.01$; CCW (=counterclockwise) 0.9^{o} ± 1.6°, $p < 0.01$). The same trend was seen in the mandible, where the pitch was associated with the largest skeletal relapse (CW 0.8^{o} ± 1.9°, $p = 0.02$; CCW 2.3^{o} ± 2.6°, $p < 0.01$).

Table 2: Translations and rotations of the maxilla and mandible after 1 week, 1 year and the postoperative relapse. Translations are given in millimetres; rotations are given in degrees.

		Maxilla					Mandible				
		n	CBCT 1 wk Mean ±SD	CBCT 1 yr Mean ± SD	Relapse (1wk-1yr) Mean ± SD	p-value	n	CBCT 1 wk Mean ±SD	CBCT 1 yr Mean ± SD	Relapse (1wk-1yr) Mean ± SD	p-value
Translation											
X	Left	51	1.4 ± 1.1	1.3 ± 1.2	0.2 ± 0.9	0.20	62	1.6 ± 1.5	1.1 ± 1.7	0.5 ± 1.3	**0.00**
	Right	55	1.2 ± 1.2	1.1 ± 1.2	0.2 ± 0.8	0.11	44	1.9 ± 1.8	1.3 ± 2.0	0.7 ± 2.0	0.04
Y	Anterior	97	3.3 ± 2.1	3.1 ± 2.1	0.2 ± 1.3	0.19	92	8.1 ± 3.8	7.6 ± 3.2	0.5 ± 2.3	0.05
	Posterior	9	0.7 ± 0.5	0.5 ± 1.2	0.2 ± 1.2	0.56	14	3.1 ± 1.4	1.3 ± 1.9	1.8 ± 1.2	**0.00**
Z	Caudal	57	2.8 ± 2.0	2.1 ± 1.9	0.7 ± 1.4	**0.00**	52	3.2 ± 1.9	1.8 ± 2.3	1.4 ± 2.0	**0.00**
	Cranial	48	3.0 ± 2.3	2.2 ± 2.3	0.7 ± 1.1	**0.00**	54	3.0 ± 2.4	2.2 ± 2.8	0.8 ± 2.0	**0.00**
Rotation											
Pitch	CCW	58	3.0 ± 2.7	2.0 ± 2.7	1.0 ± 1.3	**0.00**	70	3.9 ± 3.1	1.7 ± 2.9	2.3 ± 2.6	**0.00**
	CW	48	3.5 ± 2.5	2.6 ± 2.5	0.9 ± 1.6	**0.00**	36	4.0 ± 3.1	3.2 ± 3.1	0.8 ± 1.9	**0.02**
Roll	CCW	52	1.6 ± 1.5	1.1 ± 1.5	0.4 ± 0.7	**0.00**	46	1.5 ± 1.5	0.9 ± 1.4	0.6 ± 1.1	**0.00**
	CW	54	1.1 ± 0.8	0.8 ± 1.0	0.3 ± 0.8	**0.01**	59	1.2 ± 1.1	0.5 ± 0.9	0.8 ± 1.1	**0.00**
Yaw	CCW	52	1.3 ± 1.0	1.0 ± 1.1	0.3 ± 0.6	**0.00**	57	1.3 ± 1.0	1.1 ± 1.4	0.2 ± 1.3	0.20
	CW	53	1.1 ± 1.1	0.9 ± 1.2	0.2 ± 0.8	**0.03**	49	1.6 ± 1.5	1.3 ± 1.6	0.4 ± 1.1	**0.03**

CBCT: Cone-Beam Computed Tomography, SD: Standard Deviation, 1wk: one week, 1yr: one year, CW: Clockwise, CCW: Counterclockwise

Relapse maxilla-first approach versus mandible-first approach

The postoperative skeletal relapse of the maxilla and mandible for both the maxilla-first and mandible-first group, in terms of pitch, roll and yaw, and in terms of sagittal, vertical and transverse translations are shown in figures 1 and 2. With regard to rotational movements, the pitch showed the largest rotational relapse in both the maxilla-first (CW 0.6^{o} ± 1.4°, p=0.04; CCW 0.6^{o} ± 1.2°, p=0.02) and mandible-first group (CW 1.4^{o} ± 1.8°, $p < 0.01$; CCW 1.2^{o} ± 1.2°, $p < 0.01$). For the translational directions of the maxilla, the median relapses of all directions are below 1 mm except for the cranial/caudal displacement in the mandible-first group (median = 1.4 mm). As for the mandible, the largest relapse is seen in the front/back direction in both the maxilla-first (median = 1.1 mm) and mandible-first (median = 1.5 mm) groups.

No significant differences were found for the skeletal relapse of the maxilla between the maxilla-first and mandible-first groups (table 3). As for the mandible, the maxilla-first group displayed significant less relapse concerning the CCW pitch compared to the mandible-first group, 1.6 ± 2.6° and 2.9 ± 2.5° (p = 0.04), respectively (table 4). A statistical significant difference was also found in the mandibular relapse of the posterior displacement (p=0.02), in favour of the maxilla-first group.

Prognostic factors for skeletal relapse

Univariate regression analysis was applied to explore the influence of different patient and surgery characteristics on skeletal relapse. The sequence of the surgery did not have influence on skeletal relapse in both the maxilla and mandible. Among factors such as gender, age, magnitude of surgical advancement and the counterclockwise pitch movement of the maxilla and mandible, the magnitude of intraoperative displacement exhibited the highest explained variance (5.3 – 30.3%) for nearly all directions in both the maxilla and mandible. This indicated a larger amount of surgical jaw displacement resulted in more postoperative relapse (B 0.160 – 0.451). The counterclockwise pitch of the maxilla, and in particular of the mandible, also had a relatively large influence on skeletal relapse, with an explained variance of 4.8% and 28.4% respectively.

Table 3: Surgical displacements directly after surgery, one year after surgery and the relapse between one week and one year after surgery in the maxilla for both the maxilla-first group and the mandible first group. Translations are given in millimeter, rotations are given in degrees.

		Maxilla first					Mandible first					
		n	**CBCT 1 wk Mean ±SD**	**CBCT 1 yr Mean ± SD**	**Relapse Mean ± SD**	**p-value***	**n**	**CBCT 1 wk Mean ± SD**	**CBCT 1 yr Mean ± SD**	**Relapse Mean ± SD**	**p-value***	**p-value****
Translation												
X	Left	29	1.7 ± 1.1	1.5 ± 1.3	0.2 ± 1.0	0.36	22	1.2 ± 0.9	1.01 ± 1.0	0.2 ± 0.8	0.36	0.94
	Right	24	1.3 ± 1.3	1.1 ± 1.3	0.3 ± 0.9	0.13	31	1.2 ± 1.1	1.07 ± 1.2	0.1 ± 0.7	0.49	0.37
Y	Anterior	49	3.8 ± 2.2	3.6 ± 2.2	0.1 ± 1.3	0.45	48	2.8 ± 1.8	2.55 ± 1.8	0.2 ± 1.3	0.28	0.80
	Posterior	4	0.4 ± 0.3	0.2 ± 1.8	0.2 ± 1.7	0.85	5	0.9 ± 0.6	0.66 ± 0.4	0.3 ± 0.7	0.40	0.91
Z	Caudal	29	3.1 ± 2.0	2.6 ± 1.8	0.5 ± 1.1	**0.02**	29	2.4 ± 2.0	1.45 ± 2.0	1.0 ± 1.6	**0.00**	0.17
	Cranial	24	3.3 ± 2.4	2.8 ± 2.7	0.5 ± 1.2	0.05	24	2.6 ± 2.1	1.66 ± 1.8	0.9 ± 0.9	**0.00**	0.19
Rotation												
Pitch	CCW	25	2.5 ± 2.6	1.9 ± 3.2	0.6 ± 1.2	**0.02**	33	3.2 ± 2.9	2.05 ± 2.3	1.2 ± 1.2	**0.00**	0.09
	CW	28	3.6 ± 2.7	3.0 ± 2.8	0.6 ± 1.4	**0.04**	20	3.4 ± 2.1	1.94 ± 1.9	1.4 ± 1.8	**0.00**	0.08
Roll	CCW	29	1.7 ± 1.8	1.3 ± 1.8	0.4 ± 0.6	**0.00**	23	1.3 ± 1.1	0.92 ± 1.0	0.4 ± 0.8	**0.02**	0.83
	CW	24	1.2 ± 0.9	0.9 ± 1.1	0.3 ± 1.0	0.14	30	1.1 ± 0.8	0.81 ± 0.9	0.3 ± 0.6	**0.01**	1.00
Yaw	CCW	24	1.3 ± 1.1	1.0 ± 1.1	0.3 ± 0.4	**0.00**	29	1.2 ± 1.0	0.94 ± 1.1	0.3 ± 0.7	0.06	0.97
	CW	29	1.1 ± 1.0	0.9 ± 1.4	0.2 ± 0.9	0.23	24	1.2 ± 1.2	0.96 ± 1.1	0.3 ± 0.6	**0.03**	0.76

SD: Standard deviation, CBCT: Cone-Beam Computed Tomography, 1wk: one week, 1yr: one year, CW: Clockwise, CCW: Counterclockwise. *: p-value between surgical displacements 1 week after surgery and 1 year after surgery, **: p-value between the difference in relapse of the mandible-first and maxilla-first group.

Table 4: Surgical displacements directly after surgery, one year after surgery and the relapse between one week and one year after surgery in the mandible for both the maxilla-first group and the mandible first group. Translations are given in millimeter, rotations are given in degrees.

		Maxilla first					Mandible first					
		n	CBCT 1 wk Mean ±SD	CBCT 1 yr Mean ± SD	Relapse Mean ± SD	p-value*	n	CBCT 1 wk Mean ±SD	CBCT 1 yr Mean ± SD	Relapse Mean ± SD	p-value*	p-value**
Translation												
X	Left	35	1.7 ± 1.5	0.9 ± 1.8	0.7 ± 1.5	**0.01**	27	1.5 ± 1.5	1.2 ± 1.6	0.3 ± 1.0	0.14	0.19
	Right	18	2.1 ± 2.4	1.4 ± 2.3	0.8 ± 2.5	0.22	26	1.8 ± 1.3	1.2 ± 1.8	0.6 ± 1.6	0.08	0.79
Y	Anterior	46	9.8 ± 3.9	9.0 ± 3.3	0.8 ± 2.3	**0.03**	46	6.5 ± 3.0	6.3 ± 2.5	0.2 ± 2.3	0.59	0.21
	Posterior	7	3.6 ± 1.7	2.5 ± 2.0	1.1 ± 1.0	**0.03**	7	2.6 ± 0.8	0.1 ± 0.8	2.5 ± 1.0	**0.00**	**0.02**
Z	Caudal	27	2.6 ± 1.4	1.4 ± 2.0	1.1 ± 1.6	**0.00**	25	3.8 ± 2.2	2.2 ± 2.6	1.6 ± 2.3	**0.00**	0.42
	Cranial	26	3.4 ± 2.7	2.8 ± 3.1	0.6 ± 2.0	0.14	28	2.6 ± 2.1	1.5 ± 2.4	1.1 ± 1.9	**0.01**	0.41
Rotation												
Pitch	CCW	36	3.5 ± 3.4	1.9 ± 3.5	1.6 ± 2.6	**0.00**	34	4.3 ± 2.6	1.4 ± 2.1	2.9 ± 2.5	**0.00**	**0.04**
	CW	17	2.7 ± 2.3	2.5 ± 2.4	0.3 ± 1.7	0.55	19	5.1 ± 3.4	3.8 ± 3.6	1.3 ± 2.1	**0.02**	0.12
Roll	CCW	26	1.7 ± 1.8	1.0 ± 1.5	0.7 ± 1.1	**0.00**	20	1.4 ± 1.0	0.9 ± 1.3	0.5 ± 1.1	0.05	0.65
	CW	27	1.3 ± 1.0	0.6 ± 0.9	0.7 ± 0.9	**0.00**	33	1.1 ± 1.1	0.3 ± 0.8	0.8 ± 1.2	**0.00**	0.91
Yaw	CCW	26	1.4 ± 1.1	1.1 ± 1.8	0.3 ± 1.5	0.29	31	1.2 ± 1.0	1.1 ± 1.1	0.2 ± 1.2	0.49	0.64
	CW	27	1.9 ± 1.6	1.4 ± 1.8	0.4 ± 1.2	0.07	22	1.3 ± 1.2	1.1 ± 1.3	0.3 ± 1.0	0.24	0.55

SD: Standard deviation, CW: Clockwise, CCW: Counterclockwise. *: p-value between surgical displacements 1 week after surgery and 1 year after surgery, **: p-value between the difference in relapse of the mandible-first and maxilla-first group.

Discussion

Bimaxillary surgery is used to correct misaligned jawbones (osteotomies), resulting in both balanced and stable dental occlusions as well as harmonious facial aesthetics. However, either early, or late onset postoperative instability (relapse) has been shown to obtaining satisfactory long-term results. This unintended surgical outcome may lead to postoperative changes both in terms of function and aesthetics and may significantly affect the patient’s overall quality of life. Early postoperative skeletal relapse occurs shortly (< 6 months) after the initial surgery, due to suboptimal condylar seating or slippage at the osteotomies sites [7, 15-17]. Late relapse, on the other hand, tends to occur from six to twelve months after surgery. The pathophysiology of delayed skeletal relapse differs from the acute setting, and is believed to occur due to certain patient characteristics, such as type and magnitude of surgical displacement, and condylar resorption [18-20]. Previous studies have shown that postoperative skeletal relapse may be due to the patient’s anatomical characteristics [16, 21-23], the magnitude of surgical displacements [7, 24] the direction of jaw displacements [19], the use of osteosynthesis materials [25, 26] and the role of condylar resorption [27, 28]. However, it remains unclear if the sequencing of bimaxillary osteotomies (maxilla- or mandible-first) may also influence postoperative skeletal relapse. To the author’s knowledge, the current study is the first comparative work to address this topic.

The results of the present study demonstrated that after one year the sequence of osteotomies in bimaxillary surgery does not appear to influence the one-year postoperative skeletal relapse. The skeletal relapse in the maxilla-first and mandible-first groups was comparable, ranging between 0.1 – 1.0 mm for the maxilla and 0.2 – 1.6 mm for the mandible. Subgroup analyses showed that the only difference in skeletal relapse between the two groups was present in the CCW pitch and posterior movement of the mandible in favour of the maxilla-first group. As the mean difference in relapse between both groups for CCW pitch and posterior displacement of the mandible were 1.3^{o} and 1.4 mm respectively, well below the clinically relevant threshold of 2^{o} and 2 mm, it is unlikely that the sequence of surgery has a clinically significant impact on the long-term postoperative skeletal stability. The overall postoperative skeletal stability of the maxilla was greater than that of the mandible. This finding was consistent with previous studies [29-32]. Compared to the maxilla, the skeletal relapse of the mandible is additionally influenced by adaptive changes in the temporomandibular joints and condyles and is thus generally larger. In addition, the larger skeletal relapse of the mandible could also be attributed to the inaccuracies in the positioning of the condyles during the acquisition of one-year postoperative CBCT scans.

Although, the sequence of osteotomies did not appear to affect post-operative relapse, this study has shown an impact of jaw translations and rotations on one-year skeletal relapse, with the magnitude of surgical displacement and skeletal relapse of the maxilla and mandible comparable to previous studies [33, 34].

This suggests that surgical movement is an important contributor in skeletal relapse, and that a larger surgical movement and a CCW rotation of the bimaxillary complex increases the soft tissue and muscular tensions surrounding the jaws. This agrees with the systematic review by Joss & Vassalli (2009) who have shown increased vertical relapse in patients with a low mandibular plane angle, and an increased horizontal relapse in patients with high mandibular plane angle [7]. Thus, this study coupled to the findings of previous research [22, 26, 35, 36] has indicated that pronounced skeletal relapse occurs when increased force is exerted on the jaw segments in the opposite direction of the desired movement.

An advantage of the present study is the utilisation of the newly developed and clinically validated OrthoGnathicAnalyser (OGA) [14] . The non-profit OGA software was developed at the 3D lab in Radboud University Nijmegen Medical Centre (the Netherlands) by the authors. This analysis method was used to evaluate the patient's postoperative skeletal relapse. This differs from majority of previous research [37, 38], in which linear and angular measurements on (2D) lateral cephalograms were used to assess the postoperative skeletal relapse. In contrast to all conventional 2D and 3D cephalometric analyses, the OGA eliminates the necessity of identifying anatomical landmarks multiple times [14]. By overcoming the landmark identification error, the OGA is an observer independent, semi-automatic tool, which is able to analyse the accuracy of the 3D planning and surgical outcome in an objective, reproducible and clinically relevant way. In a recently published systematic review, this tool was reported as currently the best method for assessing planning accuracy [39]. The drawback of the OGA was that it was software dependent and could only used with Maxilim® planning software. In the past year, the 3D lab has made progress in updating the OGA software. At this moment OGA is no longer software or platform dependent and can operate on any computer anywhere in the world.

A limitation of this study is the clinical study design. The ideal study design to evaluate the influence of sequencing bimaxillary osteotomies and the stability of 3D planning is a randomized controlled trial, having patients who are randomly assigned to the maxilla-first and mandible-first groups, while controlling all possible covariates. However, in clinical practice, this ideal study design may encounter grave ethical issues. Therefore, this retrospective cohort study has been set up. The clinical protocol and principles of 3D planning were identical in both groups.

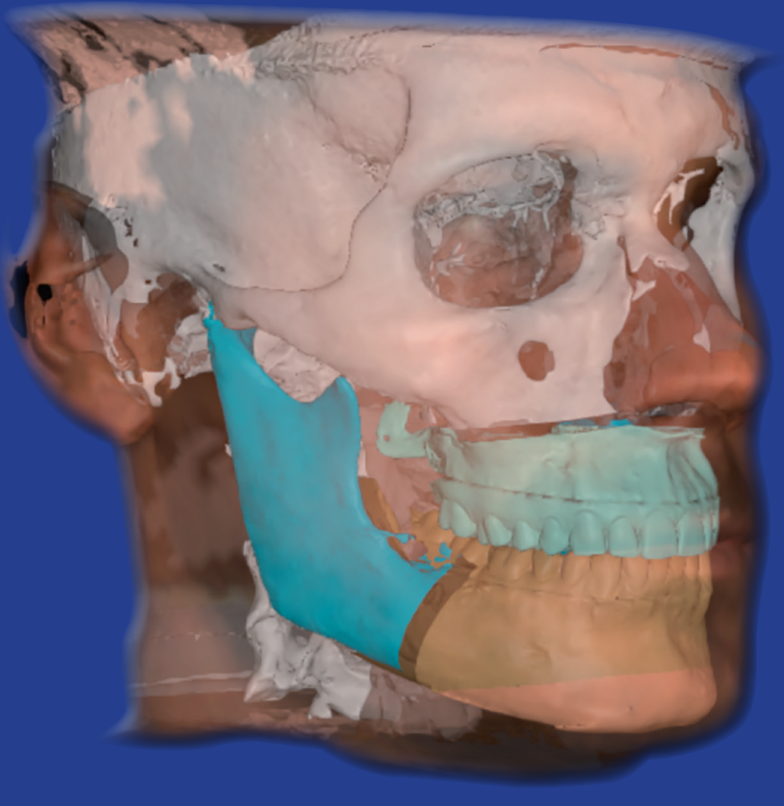
With respect to our previous study [4], which investigated the effects of sequencing bimaxillary osteotomies (maxilla-first versus mandible-first) on the achievability of the 3D virtually planned bimaxillary surgeries, it can be concluded that the sequence of surgery is more of clinical importance to the achievability of the 3D virtually planned repositioning of the jaws, rather than the stability of the achieved postoperative results. It is a choice of the surgeon to choose the most suitable sequence of bimaxillary osteotomies in each case. Taking the results of both studies into account, the maxilla-first approach remains to be a reliable and predictable surgical approach for the correction of bimaxillary anomalies. In certain circumstances, such as a planned CCW rotation of both jaws, the mandible-first sequence tends to result in more predictable displacement of the jaws. Overall, this study has shown that 3D virtual planning in combination with an optimised sequencing of osteotomies provides long-term predictable results in bimaxillary surgery.

References

1. Perez, D. and E. Ellis, 3rd, *Sequencing bimaxillary surgery: mandible first.* J Oral Maxillofac Surg, 2011. **69**(8): p. 2217-24.
2. Perez, D. and E. Ellis, 3rd, *Implications of Sequencing in Simultaneous Maxillary and Mandibular Orthognathic Surgery.* Atlas Oral Maxillofac Surg Clin North Am, 2016. **24**(1): p. 45-53.
3. Ritto, F.G., et al., *Accuracy of maxillary positioning after standard and inverted orthognathic sequencing.* Oral Surg Oral Med Oral Pathol Oral Radiol, 2014. **117**(5): p. 567-574.
4. Liebregts, J., et al., *Achievability of 3D planned bimaxillary osteotomies: maxilla-first versus mandible-first surgery.* Sci Rep, 2017. **7**(1): p. 9314.
5. Turvey, T., *Sequencing of two-jaw surgery: the case for operating on the maxilla first.* J Oral Maxillofac Surg, 2011. **69**(8): p. 2225.
6. Stokbro, K., et al., *Virtual planning in orthognathic surgery.* Int J Oral Maxillofac Surg, 2014. **43**(8): p. 957-65.
7. Joss, C.U. and I.M. Vassalli, *Stability after bilateral sagittal split osteotomy advancement surgery with rigid internal fixation: a systematic review.* J Oral Maxillofac Surg, 2009. **67**(2): p. 301-13.
8. Swennen, G.R., et al., *A cone-beam computed tomography triple scan procedure to obtain a three-dimensional augmented virtual skull model appropriate for orthognathic surgery planning.* J Craniofac Surg, 2009. **20**(2): p. 297-307.
9. Mollemans, W., et al., *Predicting soft tissue deformations for a maxillofacial surgery planning system: from computational strategies to a complete clinical validation.* Med Image Anal, 2007. **11**(3): p. 282-301.
10. Hunsuck, E.E., *A modified intraoral sagittal splitting technic for correction of mandibular prognathism.* Journal of oral surgery (American Dental Association : 1965), 1968. **26**(4): p. 250-3.
11. Maes, F., et al., *Multimodality image registration by maximization of mutual information.* IEEE Trans Med Imaging, 1997. **16**(2): p. 187-98.
12. Nada, R.M., et al., *Accuracy and reproducibility of voxel based superimposition of cone beam computed tomography models on the anterior cranial base and the zygomatic arches.* PLoS One, 2011. **6**(2): p. e16520.
13. Swennen, G.R., et al., *A new method of 3-D cephalometry Part I: the anatomic Cartesian 3-D reference system.* J Craniofac Surg, 2006. **17**(2): p. 314-25.
14. Baan, F., et al., *A New 3D Tool for Assessing the Accuracy of Bimaxillary Surgery: The OrthoGnathicAnalyser.* PLoS One, 2016. **11**(2): p. e0149625.
15. Arnett, G.W., S.B. Milam, and L. Gottesman, *Progressive mandibular retrusion--idiopathic condylar resorption. Part I.* Am J Orthod Dentofacial Orthop, 1996. **110**(1): p. 8-15.
16. Mobarak, K.A., et al., *Mandibular advancement surgery in high-angle and low-angle class II patients: different long-term skeletal responses.* Am J Orthod Dentofacial Orthop, 2001. **119**(4): p. 368-81.
17. Kim, Y.J., et al., *Condylar positional changes up to 12 months after bimaxillary surgery for skeletal class III malocclusions.* J Oral Maxillofac Surg, 2014. **72**(1): p. 145-56.

18. Xi, T., et al., *The role of mandibular proximal segment rotations on skeletal relapse and condylar remodelling following bilateral sagittal split advancement osteotomies.* J Craniomaxillofac Surg, 2015. **43**(9): p. 1716-22.
19. Mucedero, M., et al., *Stability factors after double-jaw surgery in Class III malocclusion. A systematic review.* Angle Orthod, 2008. **78**(6): p. 1141-52.
20. Jakobsone, G., et al., *Three-year follow-up of bimaxillary surgery to correct skeletal Class III malocclusion: stability and risk factors for relapse.* Am J Orthod Dentofacial Orthop, 2011. **139**(1): p. 80-9.
21. Hoppenreijs, T.J., et al., *Long-term evaluation of patients with progressive condylar resorption following orthognathic surgery.* Int J Oral Maxillofac Surg, 1999. **28**(6): p. 411-8.
22. Borstlap, W.A., et al., *Stabilisation of sagittal split advancement osteotomies with miniplates: a prospective, multicentre study with two-year follow-up. Part III--condylar remodelling and resorption.* Int J Oral Maxillofac Surg, 2004. **33**(7): p. 649-55.
23. Eggensperger, N., et al., *Short- and long-term skeletal relapse after mandibular advancement surgery.* Int J Oral Maxillofac Surg, 2006. **35**(1): p. 36-42.
24. Han, J.J., et al., *Relapse after SSRO for mandibular setback movement in relation to the amount of mandibular setback and intraoperative clockwise rotation of the proximal segment.* J Craniomaxillofac Surg, 2014. **42**(6): p. 811-5.
25. Proffit, W.R., T.A. Turvey, and C. Phillips, *The hierarchy of stability and predictability in orthognathic surgery with rigid fixation: an update and extension.* Head & Face Medicine, 2007.
26. Hernandez-Alfaro, F., et al., *Three-Dimensional Analysis of Long-Term Stability After Bilateral Sagittal Split Ramus Osteotomy Fixed With a Single Miniplate With 4 Monocortical Screws and 1 Bicortical Screw: A Retrospective 2-Center Study.* J Oral Maxillofac Surg, 2017. **75**(5): p. 1036-1045.
27. Chen, S., et al., *Short- and long-term changes of condylar position after bilateral sagittal split ramus osteotomy for mandibular advancement in combination with Le Fort I osteotomy evaluated by cone-beam computed tomography.* J Oral Maxillofac Surg, 2013. **71**(11): p. 1956-66.
28. Kim, Y.I., et al., *Cone-beam computerized tomography evaluation of condylar changes and stability following two-jaw surgery: Le Fort I osteotomy and mandibular setback surgery with rigid fixation.* Oral Surg Oral Med Oral Pathol Oral Radiol Endod, 2011. **111**(6): p. 681-7.
29. Ayoub, A.F., et al., *Stability of bimaxillary osteotomy following surgical correction of class II skeletal deformities: a two-centre study.* Br J Oral Maxillofac Surg, 1997. **35**(2): p. 107-15.
30. Xi, T., et al., *Three-dimensional analysis of condylar remodeling and skeletal relapse following bimaxillary surgery: A 2-year follow-up study.* J Craniomaxillofac Surg, 2017. **45**(8): p. 1311-1318.
31. Ayoub, A.F., D.R. Stirrups, and K.F. Moos, *The stability of bimaxillary osteotomy after correction of skeletal Class II malocclusion.* Int J Adult Orthodon Orthognath Surg, 1993. **8**(3): p. 155-70.
32. Moen, K., et al., *Dental or skeletal relapse after sagittal split osteotomy advancement surgery? Long-term follow-up.* J Oral Maxillofac Surg, 2011. **69**(11): p. e461-8.
33. Arpornmaeklong, P., J.M. Shand, and A.A. Heggie, *Skeletal stability following maxillary impaction and mandibular advancement.* Int J Oral Maxillofac Surg, 2004. **33**(7): p. 656-63.

34. Schwartz, K., M. Rodrigo-Domingo, and T. Jensen, *Skeletal Stability after Large Mandibular Advancement (> 10 mm) with Bilateral Sagittal Split Osteotomy and Skeletal Elastic Intermaxillary Fixation.* J Oral Maxillofac Res, 2016. **7**(2): p. e5.
35. Joss, C.U. and U.W. Thuer, *Stability of the hard and soft tissue profile after mandibular advancement in sagittal split osteotomies: a longitudinal and long-term follow-up study.* Eur J Orthod, 2008. **30**(1): p. 16-23.
36. Van Sickels, J.E., et al., *Technical factors accounting for stability of a bilateral sagittal split osteotomy advancement: wire osteosynthesis versus rigid fixation.* Oral Surg Oral Med Oral Pathol Oral Radiol Endod, 2000. **89**(1): p. 19-23.
37. Park, K.H., G.K. Sandor, and Y.D. Kim, *Skeletal stability of surgery-first bimaxillary orthognathic surgery for skeletal class III malocclusion, using standardized criteria.* Int J Oral Maxillofac Surg, 2016. **45**(1): p. 35-40.
38. Kor, H.S., H.J. Yang, and S.J. Hwang, *Relapse of skeletal class III with anterior open bite after bimaxillary orthognathic surgery depending on maxillary posterior impaction and mandibular counterclockwise rotation.* J Craniomaxillofac Surg, 2014. **42**(5): p. e230-8.
39. Gaber, R.M., et al., *A Systematic Review to Uncover a Universal Protocol for Accuracy Assessment of 3-Dimensional Virtually Planned Orthognathic Surgery.* J Oral Maxillofac Surg, 2017.



Chapter 9

Does Mandible-first Sequencing Increase Maxillary Surgical Accuracy in Bimaxillary Procedures?

Stokbro K, Liebregts JHF, Baan HF, Bell RB, Maal TJ, Thygesen T, Xi T.

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Abstract

Introduction: In bimaxillary procedures, it is important to know how the chosen sequence affects the surgical outcome. The purpose of this study was to explore whether the theoretical advantages of using the mandible-first procedure were supported by clinical data.

Methods: The investigators performed a retrospective investigation on a cohort compiled from 3 published, retrospective studies. The sample was composed of patients treated at Radboud University Nijmegen Medical Center from 2010 to 2014 and Odense University Hospital from 2011 to 2015. The inclusion criterion was bimaxillary surgery without maxillary segmentation. The exclusion criterion was the lack of a virtual surgical plan. The primary outcome variable was surgical accuracy, defined as the mean difference between the obtained outcome and the virtual surgical plan. The primary predictor variable was the comparison between mandible-first and maxilla-first sequencing. Secondary predictors were inferior maxillary repositioning and counter clockwise (CCW) rotation. The confounding variable was the virtually planned reposition. Results were analyzed by mixed-model regression encompassing all variables, followed by a detailed analysis of positive results using 2-sample *t*-tests.

Results: Overall, 145 patients were included for analysis (98 females, mean age 28 years). Operating on the mandible first significantly influenced maxillary positioning and placed the maxilla 1.5 mm posterior and with 1.4 degrees of CCW rotation compared to virtual surgical planning. The surgical sequence interaction with maxillary rotation showed similar surgical accuracy between maxilla-first with clockwise rotation and mandible-first with CCW rotation. Inferior maxillary repositioning resulted in the maxilla being placed 1.7 mm (maxilla-first) and 2.0 mm (mandible-first) posterior to the planned position.

Conclusion: Surgical accuracy was significantly influenced by the sequencing in bimaxillary procedures. It remains important to know how the chosen sequence affects the surgical outcome so that the virtual surgical plan can be adjusted accordingly.

Introduction

At present, the surgeon's preference dictates whether the mandible or maxillary is operated on first in bimaxillary procedures[1]. This preference relies on old dogmas carried over from wire fixation or plaster cast models mounted in semi-adjustable articulators[2–5]. With 3-dimensional (3D) virtual surgical planning (VSP), the old dogmas must be reevaluated as previous strengths and weaknesses may no longer be relevant[6,7]. Surgeons may not wish to change the sequence they are familiar with, but it remains vitally important to know how the chosen sequence affects the surgical outcome. Thereby, the desired maxillary position may be achieved by adjusting the VSP to include the affected surgical accuracy.

The theoretical advantages of positioning the mandible first have been debated at length without a definite consensus being reached[2–4,8,9]. In theory, the surgical splint design should provide advantages with regard to sequencing the mandible or maxilla first, depending on the rotation of the maxilla-mandibular-complex. Clockwise (CW) rotation is believed to be more accurate using the maxilla-first approach, while counter clockwise (CCW) rotation should be more accurate using the mandible-first approach[4,5]. However, only 3 studies have compared the 2 sequences in large cohort studies, and none have evaluated how CW or CCW rotation influence the clinical outcome when the mandible or maxilla is sequenced first[1,10–12].

Unstable procedures such as inferior maxillary repositioning also affect the clinical outcome, and may cause the maxilla to be placed 1 to 2 mm posterior to the planned position[13,14]. Theoretically, the mandible-first approach should increase surgical accuracy in inferior maxillary repositioning because this sequence can be performed without autorotation of the condyles[4,15]. However, no one has evaluated the clinical effect on surgical accuracy of sequencing the mandible or maxilla first in inferior maxillary repositioning[16].

While the surgical splint dictates the jaw's position in the sagittal and transverse directions, the vertical direction is under the direct control of the surgeon. Reliable measurement points are crucial for accurate vertical positioning of the maxilla. Using the medial canthal ligament instead of a bony fixated reference pin may affect the surgical outcome in the vertical dimension[17,18]. However, no previous study has evaluated the clinical influence of using the medial canthal ligament for vertical measurements in patients in whom 3D VSP is planned compared with use of fixed external reference pin[6,7].

The purpose of this study was to evaluate whether the theoretical advantages of operating on the mandible first were supported by the clinical data. The null-hypothesis was that no difference existed between sequencing the maxilla or the mandible first. This study seeks to address the following research questions:

(1) Was the overall surgical accuracy affected by the maxillary/mandibular sequencing?

(2) Was the surgical accuracy in CCW rotation affected by maxillary/mandibular sequencing compared with CW rotation?

(3) Was the surgical accuracy in inferior maxillary repositioning affected by maxillary/ mandibular sequencing compared with maxillary impaction?

(4) Was the vertical accuracy affected by using the medial canthal ligament (Odense) compared with an external reference pin (Nijmegen)?

Materials and Methods

To address the research questions, the authors implemented a retrospective study using the combined clinical data from 3 published, retrospective studies[10,19,20]. The cohorts were derived from populations of patients treated in the Department of Oral and Maxillofacial Surgery, Radboud University Nijmegen Medical Center (Nijmegen, the Netherlands), and in the Department of Oral and Maxillofacial Surgery, Odense University Hospital (Odense, Denmark). The studies could be combined because the data were measured by comparable protocols; however, the cohorts' inclusion and exclusion criteria differed between the studies. Study 1 (Nijmegen) analyzed 116 consecutive patients treated with bimaxillary procedures without maxillary segmentation from 2010 to 2014[10]. Study 2 (Odense) analyzed 30 patients with bimaxillary procedures including maxillary segmentation, randomly selected from a population of 72 patients treated from 2011 to 2013[19]. Study 3 (Odense) analyzed 20 consecutive patients treated with inferior maxillary repositioning, mono- or bimaxillary procedure from 2013 to 2015[20].

The criteria for inclusion of participants in the combined cohort were (1) they had been were participants in the previously published studies and (2) they had undergone bimaxillary orthognathic surgery without maxillary segmentation. The exclusion criterion for the combined cohort was the absence of the virtual surgical plan in the dataset. This study was exempt from ethical approval due to its retrospective nature. Participants and data were treated in accordance with the Declaration of Helsinki.

Variables

The primary outcome variable was the difference between the planned and the obtained surgical repositioning of the maxilla. The primary predictor variable was the sequencing with the maxilla- or mandible-first approach. Secondary predictors were planned CW or CCW rotation of the maxilla and planned inferior or superior maxillary repositioning. The primary confounding variable was the virtually planned reposition (Continuous). Other clinical variables of interest were age, sex.

Virtual surgical planning and orthognathic surgery

Cone beam computed tomography (CBCT) scans were performed before surgery and within 7 days after surgery. All patients were scanned with the mandible in centric relation to the fossa by relaxing the muscles and maintaining the jaw position at the first occlusal contact during the scan. In Nijmegen, the VSP was performed in house using Maxilim-software (Medicim NV, Mechelen, Belgium); in Odense, VSP was performed in collaboration with 3D systems (3D systems, Rock Hill, SC) using Dolphin 3D Surgery-software (Dolphin Imaging and Management, Chatsworth, CA). During VSP, the condylar segments were rotated around the condylar hinge point, set at the most lateral part of the condylar head, but not otherwise repositioned in the fossa.

The maxilla and mandible were repositioned according to the treatment plan using surgical splints. To ensure an unaltered position of the dentition and optimize the fitting of the surgical splint, no active orthodontics was carried out following the preoperative CBCT used for the VSP. The preoperative conditions were evaluated by visual inspection, and the fit of the surgical splint was appraised initially before the osteotomy to assure that the preoperative conditions agreed with the VSP. The vertical height was controlled by calipers, measuring from a bony anchored nasion reference pin (Nijmegen) or from the right medial canthal ligament (Odense). The mandible was bilaterally fixated by 3 bicortical screws (Biomet 2.0, Zimmer corp., Warsaw, IN, USA) (Odense) or 1 miniplate fixated by 4 monocortical screws (Champy 2.0, KLS Martin, Tuttlingen, Germany) (Nijmegen). The maxilla was fixated by 4 miniplates: in Nijmegen, 1.5 KLS Martin (KLS Martin, Tuttlingen, Germany), and in Odense, 2.0 Biomet (Zimmer corp., Warsaw, IN, USA). Local reposition of bony segments was performed but without extraoral bone grafting.

The sequence for operating on the mandible or maxilla first was changed in the Nijmegen cohort for all consecutive patients from operating on the mandible first in 2010–12 to operating on the maxilla first in 2013–14. In the Odense cohort, the mandible was always operated on first.

Outcome measurements

Measurements were performed according to previously validated software algorithms: The OrthoGnathicAnalyser (Nijmegen)[21] and a semi-automatic algorithm using 3D Slicer (Odense)[22]. Both systems have 95% reproducibility within 0.3 mm.

The mean linear reposition was calculated from the midline at the edge of the upper central incisors (UCI). All measurements were recorded in relative numbers according to the positive values of the axes: right (mediolateral axis), anterior (anteroposterior axis) and superior (superoinferior axis).

Rotation was measured in degrees around the Centroid (C) point. The centroid point was calculated as the mean of 3 dental reference points: the top of the mesiobuccal cusp on the first molar on each side (M6R and M6L) and the UCI[23,24]. A positive yaw moved UCI to the left relative to the C point. A positive pitch moved UCI superior to the C point. A positive roll moved M6R superior to the C point (Fig. 1).

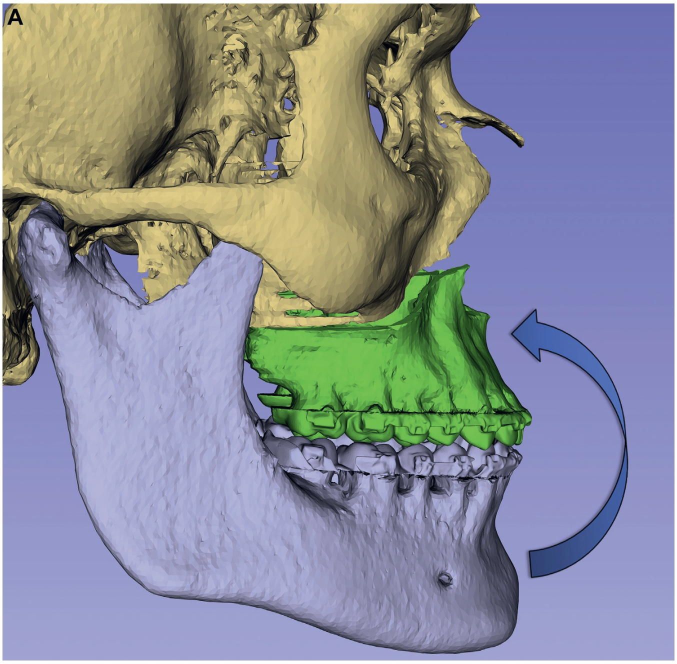


Figure 1. (3 pieces). Rotation of the maxilla. A: A positive pitch moved the upper central incisor cranially. B: A positive roll moved the right first molar cranially. C: A positive yaw moved the upper central incisor to the left.

Statistics

Data were analyzed using STATA 15.1 (STATA Corp Lt, College Station, TX, USA). The descriptive variables were analyzed by chi-squared test, one-way ANOVA analysis and 2-sample *t*-tests to evaluate cohort differences between procedures and centers. The primary outcome and predictor variables depended on multiple spatial measurements along 3 axes in the same patient. Therefore, the data were treated as clustered to allow for fixed and random effects both within and between the patients. A linear mixed model was built by treating the outcome in 3 axes as repeated measurements within the same patient, and therefore, they were all influenced by the patient’s response to the confounding and hypothesis-generating variables. All hypotheses generating variables and confounding variable were included in the final model.

Thereby, the linear mixed model analysis could be performed to accommodate the multilevel analysis of the individuals and simultaneously adjusting for the confounding variables. If the mixed model regression was significant for predictor variables, the data were further explored; differences within groups were analyzed by Student's 1-sample *t*-test, and differences between groups were analyzed by 2-sample *t*-tests. The level of statistical significance in all tests was set at $P \leq 0.05$. Clinical significance was defined by the authors as differences in mean of more than 1 mm and rotations of more than 2 degrees, which indicates consistent unidirectional inaccuracies that are large enough to be addressed clinically by the surgeons.

Results

Of the 166 patients considered for this study, data in 145 patients could be included (Fig. 2). The total sample size was 145 participants, with 68% females and a mean age of 28 years (Table 1). All patients sequenced with the maxilla-first procedure were operated on in the surgical department at Nijmegen. Patients were evenly distributed and in sufficient numbers in the groups: mandible surgery first, CCW rotation and inferior maxillary repositioning. The linear planned repositioning did not differ significantly between the 2 study centers. The planned pitch was more negative in the maxilla-first group, and more CCW rotation of the maxilla was planned in this group.

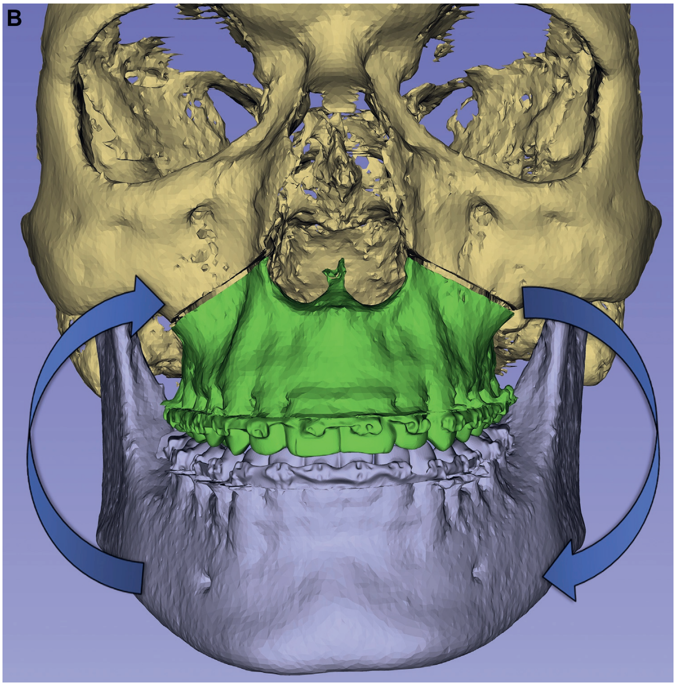


Figure 2. Inclusion and exclusion criteria for combined cohort.

Table 1. Descriptive cohort analysis

	Nijmegen Mx first	Nijmegen Md first	Odense Md first	*P* Value*	*P* Value$
Participants (N)	57	58	30		
Female gender	43	37	18	.250	.104
Mean age (yr)	29	28	27	.737	.459
Range (yr)	16-57	16-55	18-64		
Test of hypotheses					
Mandible-first sequence	0	58	30	**.000**	**.000**
CCW rotation	19	32	18	**.006**	.086
Inferior maxillary reposition	33	27	18	.354	.425
Planned Maxillary translation:					
Right	−0.04 (1.70)	−0.16 (1.42)	-0.58 (1.12)	.266	.295
Anterior	3.96 (1.67)	4.35 (1.83)	2.60 (2.91)	**.001**	.566
Superior	−0.31 (2.98)	−0.13 (2.92)	0.22 (2.49)	.716	.539
Planned Maxillary rotation:					
Pitch	−2.02 (3.94)	0.39 (5.99)	1.57 (4.31)	**.003**	**.001**
Roll	0.31 (2.07)	0.07 (1.99)	0.12 (1.72)	.801	.511
Yaw	−0.07 (1.49)	−0.14 (1.42)	0.10 (1.63)	.692	.981

Abbreviations: Md, Mandible. Mx, Maxilla. Yr, years. CCW, counter clockwise rotation.
Note: Translation and rotation measurements are presented as mean (standard deviations).
* ANOVA evaluation between all 3 groups.
$ Student's *t*-test between Mandible-first and Maxilla-first groups.

Incorporating all 3 hypotheses into 1 global, statistical model revealed that both surgical sequencing and inferior maxillary repositioning significantly influenced surgical accuracy (Table 2). The mixed model regression showed the VSP had a significant influence on surgical precision. For each millimeter of advancement, the surgical accuracy decreased, indicating that larger advancements deviated more from the plan. Plotting the planned reposition against the surgical accuracy in the anterior axis showed a correlation that accounted for 15–34% of the difference in surgical accuracy. Plotting the planned reposition against the surgical accuracy in the vertical axis showed almost no correlation (coefficient of determination, R^2 = 0.5% and 7%) despite a significant correlation in the mixed model regression. Both surgical sequencing and inferior maxillary repositioning significantly influenced surgical accuracy, but counter clockwise rotation did not significantly influence surgical accuracy. However, to further analyze the influence on surgical accuracy all 3 hypothesis variables were further explored.

Table 2. Mixed linear regression analysis of internal correlation and confounding variables

	β	*P* Value	95 % Confidence interval	
			Lower limit	Upper limit
Anterior (baseline)	.14	**.002**	.05	.23
Superior (addition to baseline)	-.34	**.000**	-.50	-.19
Right (addition to baseline)	.06	.628	-.17	.28
Test of hypotheses				
Maxilla-first	.57	**.003**	.19	.95
Inferior maxillary repositioning	-.98	**.000**	-1.42	-.55
CCW rotation	.31	.127	-.09	.70
Age (yr)	-.01	.108	-.03	.00
Female gender	-.10	.606	-.49	.28
Constant	-.46	.106	-1.03	.10
SD (constant)	$2x10^{-13}$		$3x10^{-15}$	$1x10^{-11}$
SD (residual)	1.84		1.73	1.97

Abbreviations: Yr, years. SD, standard deviation.
Note: The outcome measurement for mixed model regression was the difference between planned and obtained movement.

Testing the primary hypothesis, there was a significant difference between maxilla-first and mandible-first sequencing along the right and anterior axis and a difference in pitch as well (Table 3). Operating on the mandible first placed the maxilla posterior with an additional CCW rotation. The maxilla-first approach had a larger variance than the mandible-first approach, and the standard deviation increased from 2.0 mm to 2.6 mm. The posterior positioning in the mandible-first sequencing was considered clinically relevant.

Surgical accuracy in maxillary rotation

Maxillary rotation influenced the surgical accuracy differently depending on whether the maxilla or the mandible was operated on first. The surgical accuracy was almost identical between the use of CCW rotation in the mandible-first procedure and the use of CW rotation in the maxilla-first procedure (Table 4). The CCW rotation in maxilla-first sequencing positioned the maxilla 1.3 mm anterior to the planned position. In contrast, the CW rotation in the mandible-first procedure positioned the maxilla almost 2 mm posterior to the planned position. This difference was clinically relevant but not statistically different from the 2 reference procedures.

Table 3. Overall difference between planned and obtained surgical repositioning

	Mandible-first (*N*=88)			Maxilla-first (*N*=57)			*P* Value$
	Mean	SD	*P* Value*	Mean	SD	*P* Value*	Md–Mx
Linear Maxillary difference							
Right	0.42	(1.65)	**.019**	−0.17	(1.31)	.341	**.025**
Anterior	−1.49	(2.01)	**.000**	−0.35	(2.65)	.327	**.004**
Superior	−0.22	(1.76)	.242	0.32	(2.07)	.253	.096
Rotational Maxillary difference							
Pitch	1.42	(2.86)	**.000**	−0.25	(2.90)	.415	**.001**
Roll	−0.54	(1.24)	**.002**	−0.15	(1.40)	.329	.088
Yaw	0.12	(1.52)	.543	−0.19	(1.57)	.258	.236

Abbreviation: SD, standard deviation.
* Student's 1-sample independent *t*-test.
$ Student's 2-sample independent *t*-test of the difference between the maxilla-first or mandible-first group.

Table 4. The surgical sequence interaction with maxillary rotation

Linear distance (mm)	N	Mandible-first	N	Maxilla-first	*P* Value*
Clockwise rotation (CW):	38		38		
Right		0.39 (1.37)		0.05 (0.99)	.222
Anterior		−1.93 (1.85)		−1.18 (2.35)	.127
Superior		-0.60 (1.58)		0.31 (2.04)	**.035**
Counter clockwise rotation (CCW):	50		19		
Right		0.45 (1.85)		−0.59 (1.74)	**.037**
Anterior		−1.16 (2.09)		1.33 (2.45)	**.000**
Superior		0.06 (1.84)		0.34 (2.18)	.602
P Value* CW vs CCW					
Right		.854		.081	
Anterior		.074		**.000**	
Superior		.080		.955	

Abbreviations: SD, standard deviation.
Note: Translation and rotation measurements are presented as mean (standard deviations).
* Student's two sample independent *t*-test.

Surgical accuracy in inferior maxillary repositioning

Inferior maxillary repositioning also significantly influenced surgical accuracy. In inferior maxillary repositioning, the maxilla was positioned 1.7 mm (maxilla-first) to 2.0 mm (mandible-first) posterior to the planned position, which was statistically significant, regardless of whether the mandible or maxilla was operated on first (Table 5). In superior maxillary repositioning, the maxilla-first approach placed the maxilla 1.5 mm anterior to the planned position, while the mandible-first placed the maxilla 0.9 mm posterior to the planned position. The difference between the 2 sequences in superior maxillary repositioning was statistically significant.

The interaction between the sequencing, rotation and inferior maxillary repositioning could not be further analyzed in this study because only 3 patients were operated on using inferior maxillary repositioning, CCW rotation and the maxilla-first sequence.

Table 5. The surgical sequence interaction with superior/inferior maxillary repositioning

Linear distance (mm)	N	Mandible-first	N	Maxilla-first	*P* Value*
Superior maxillary reposition	43		24		
Right		0.32 (1.63)		−0.54 (1.64)	**.041**
Anterior		−0.93 (1.93)		1.45 (2.77)	**.000**
Superior		–0.34 (2.10)		0.53 (2.17)	.114
Inferior maxillary reposition	45		33		
Right		0.52 (1.69)		0.11 (0.95)	.211
Anterior		−2.03 (1.96)		−1.65 (1.60)	.370
Superior		–0.11 (1.36)		0.16 (2.01)	.484
P Value* superior vs inferior					
Right		.583		.064	
Anterior		**.010**		**.000**	
Superior		.541		.510	

Abbreviations: SD, standard deviation.
Note: Translation and rotation measurements are presented as mean (standard deviations).
* Student’s two sample independent *t*-test.

Medial canthal ligament compared with external reference pin

Finally, the vertical surgical accuracy was not influenced by using the medial canthal ligament (Odense) compared with using an external fixed reference pin (Nijmegen). Comparing the planned, obtained and surgical accuracy in the vertical axes showed no significant difference between the 2 methods (Table 6). Visualizing the surgical accuracy for each patient according to planned vertical reposition showed that the medial canthal ligament group was nested within the external fixed reference pin group. Thus, using the medial canthal ligament did not seem to influence surgical accuracy or variation in the vertical dimension.

Table 6. Surgical accuracy in vertical dimension using external reference pin and medial canthal ligament

Vertical measurements	Reference pin (N=58)	Canthal ligament (N=30)	*P* Value*
Planned	–0.13 (2.92)	0.22 (2.49)	.561
Obtained	–0.31 (3.22)	–0.08 (2.31)	.701
Difference	–0.18 (1.83)	–0.30 (1.64)	.759

Note: Measurements are along the superior axis and presented as mean (standard deviation). Positive measurements are superior and negative measurements are inferior. In this analysis, all patients were operated by the mandible-first approach.
Abbreviation: Ext ref pin, external reference pin. SD, standard deviation.
*Student's two sample independent t-test.

Discussion

The purpose of this study was to explore whether the theoretical advantages of operating on the mandible first were supported by the clinical data. All research questions were answered: (1) The overall surgical accuracy was affected by the maxillary/mandibular sequencing. The maxilla-first sequencing was centered closer around the planned reposition than the mandibular-first, while the mandible-first approach resulted in significant posterior reposition. The maxilla-first approach resulted in larger variances than the mandible-first approach. (2) The surgical accuracy in the CW and CCW rotation was not statistically significantly influenced by the sequencing. However, the procedures appeared to be more accurate for CCW rotation when the mandible was operated on first and for CW rotations when the maxilla was operated on first. (3) Inferior maxillary repositioning placed the maxilla posterior to the planned position regardless of sequencing. Sequencing the maxilla or mandible first affected surgical accuracy in superior maxillary repositioning. (4) There was no significant difference in vertical accuracy using the medial canthal ligament compared with a bony fixated, external reference pin.

Not all theoretical advantages of sequencing the mandible first could be found in the clinical data. Theoretically, operating on the mandible first should result in closer adaptation to the planned maxillary repositioning, since the condyles are initially seated in central relation during the operation. This will prevent any incorrect seating during the preoperative scan to be transferred to the surgical reposition. If the condyles are seated incorrectly in the preoperative scan, the condyles will reposition into centric relation when the patient is under general anesthesia, thereby, changing the position of the mandible[25]. If the maxilla is positioned against the unoperated mandible, an incorrect seating during the preoperative scan may cause the maxilla to be placed posterior to the planned position[24]. But the clinical data did not support all the theoretical advantages of operating on the mandible first. The maxilla-first approach did result in a larger variance in surgical accuracy; however, the mean was centered closer to the planned position than it was with the mandible-first approach. In contrast, operating on the mandible first resulted in the maxilla being positioned posterior to the intended position. This posterior positioning was further explored in the subgroups of patients in whom CW/CCW rotation of the maxilla-mandibular-complex or superior/inferior maxillary repositioning was performed.

Maxillary rotation

Rotation of the maxilla-mandibular-complex resulted in the same level of surgical accuracy in CCW rotation in the mandible-first group and CW rotation in the maxilla-first group. This is consistent with the proposed theoretical accuracy of the surgical splint design[4,5]. Choosing the maxilla-first sequence in association with CCW rotation placed the maxilla significantly anterior to the planned position, while CW rotation in mandible-first sequencing resulted in a clinically relevant, 1.9 mm posterior positioning. If surgeons do not wish to alternate between sequencing the mandible or maxilla first, this difference in surgical accuracy should be addressed in the VSP to achieve the desired maxillary position.

Inferior maxillary repositioning

Inferior maxillary repositioning is known to be among the least predictable and unstable surgical procedures. It is unknown whether the posterior position is caused by inaccuracy during the surgery or immediate postoperative relapse, but the posterior discrepancy occurred independent of the mandible-first or maxilla-first approach. This 1.7 mm (maxilla-first) to 2.0 mm (mandible-first) posterior discrepancy to the planned position should be considered in the design of the VSP. If the anticipated 2-mm inaccuracy is not judged to be esthetically acceptable, additional maxillary advancement could be beneficial to the patient and should be considered in the final VSP.

Adjusting the virtual surgical plan

Adjusting for the discrepancies between VSP and clinical outcome should be performed for either CW/CCW rotation or inferior maxillary reposition but not for both. As these discrepancies stem from the same cohort, adjusting for both rotation or inferior reposition would adjust the patient’s discrepancy twice. The interaction between the sequencing, rotation and inferior maxillary repositioning could not be further analyzed in this study as only 3 patients were operated on using inferior maxillary repositioning, CCW rotation and maxilla-first sequence. Thus, surgeons must choose to adjust the VSP according to either CW/CCW rotation or inferior maxillary repositioning. The inferior maxillary repositioning seemed to influence surgical accuracy more than CW/CCW rotation, with a larger β-coefficient and lower *P* value.

Possible explanations for the posterior maxillary position

The mechanisms that caused this posterior maxillary position were not evaluated, as this study was designed only to evaluate whether a systematic difference existed between the VSP and the obtained surgical outcome. In speculating on the possible cause, it is worth noting that during inferior maxillary reposition, the maxilla was placed posteriorly independent of whether the mandible or maxilla was operated on first. Furthermore, the superior maxillary repositioning was placed more anteriorly compared to the inferior maxillary repositioning.

The authors believe that the posterior position in inferior maxillary repositioning may be caused by immediate relapse either intraoperatively due to additional compression of the temporomandibular joint or postoperatively due to settling of the osteosynthesis material during the subsequent Le Fort 1 operation[13,26,27]. Furthermore, in superior maxillary repositioning, the maxilla may be displaced anteriorly if there are bony interferences at the pterygopalatine junction or surrounding the greater palatine nerve and artery. This anterior displacement will cause the maxilla to be positioned anterior to the planned position when the maxilla is operated on first, while the maxilla will be positioned anterior to the mandibular position when the mandible is operated on first. However, we can only speculate on the possible underlying mechanisms because the findings of this study do not provide a definite explanation. Identifying the mechanisms behind the posterior maxillary position will require prospective studies in more homogeneous cohorts in which a single surgical factor is evaluated at a time.

External reference measurements

Controlling the vertical dimension was not influenced by using different external reference points. Using the medial canthal ligament for measuring the vertical dimension has previously been described as accurate, affecting the vertical surgical accuracy with a mean of 0.3 mm[17,28]. This study's result of 0.3 mm difference between the planned and obtained outcome was in accordance with the findings in 2D lateral cephalometric tracings and was considered well within the acceptable limits. Likewise, visualizing each patient's vertical surgical accuracy, plotted against the planned reposition, showed the medial canthal ligament patients matched outcomes in the external reference pin patients. Thus, using the medial canthal ligament can be considered a reliable alternative to using a fixed reference pin.

Comparable literature

Apart from the included article (study 1)[10], only 2 retrospective cohort studies have previously evaluated the surgical accuracy in the maxilla-first versus the mandible-first approach[11,12]. Both studies were planned with plaster cast models in a semi-adjustable articulator, and the outcome was evaluated on lateral cephalometric tracings. Salmen et al.[11] found a difference between the groups (*N* = 16 patients/group) in the vertical direction but not in the horizontal direction[11]. All patients were treated with advancement and impaction, similar to the maxillary superior repositioning group. The upper first incisor was positioned 0.8 mm posterior to the planned positioning in the mandible-first group and 0.3 mm posterior in the maxilla-first approach, which was not statistically significant. In the vertical dimension, the upper first incisor was positioned 1.0 mm inferior to the planned position in the mandible-first approach and 0.1 mm superior in the maxilla-first procedures, which was considered statistically significant. In contrast, this study found a significant horizontal difference between the sequences, while there was no significant vertical difference. The study by Ritto et al.[12] found no significant influence in sequencing the maxilla or mandible first, and there was a slightly larger absolute variance in the maxilla-first group than in the mandible-first group (*N* = 20 patients/group). Thus, the results from this study do not reflect the results found in the literature. The difference between this study's results and the literature may have several causes. The surgery was planned using VSP, which enables accurate placement of the condylar positioning along with accurate occlusal plane re-creation. The outcome was measured in 3D with improved measurement tools with a reproducibility of less than 0.3 mm[21,22], while the measurement reproducibility for cephalometric tracing was between 0.46 to 1.68 mm[11]. Thus, this study should more accurately reflect the surgical outcome achieved by 3D planning and computer-assisted design and manufactured surgical splints.

Limitations and future perspectives

There remains a number of limitations and unanswered questions regarding the potential benefits of sequencing the mandible first. This study focuses exclusively on the maxillary position compared with the planned position; therefore, differences in mandibular positioning and final occlusion were not addressed in this study. Especially the final occlusion is of interest since this is of major importance for the success of the surgical procedure. Operating on the mandible first should, theoretically, transfer any errors in condylar seating to the maxilla. Thereby, it is acceptable that the maxilla is positioned posterior to the planned position to preserve the ideal occlusion in the final surgical splint. The final occlusion may not be evaluated sufficiently by CBCT scans but may be addressed more accurately by intraoral scans of the postoperative occlusion instead.

Future studies may wish to address whether interactions occurred between inferior maxillary repositioning and CCW rotation. There may also exist a threshold with which the benefit of the appropriate sequence becomes more obvious. In this study, the inferior reposition and CCW rotation were only measured overall, including both minor and major repositions in one outcome, without interactions and detailed subgroup analysis. Combining additional future studies into a larger cohort analysis may enable researchers to further explore whether such interactions or thresholds exist. When combining future studies, it is important that the outcome measurements are sufficiently reliable, to ensure the quality of each patient's data in a combined cohort study. Including less reliable outcome measurements may mask potential benefits of the appropriate sequencing in bimaxillary procedures.

Finally, this study relies on 3D printed splints to position the moving segments. Although computer-aided designed and manufactured splints accurately fit and reposition the moving segments[29], the looseness of the TMJ may affect the surgical accuracy and position of the segments[24]. The surgical accuracy is expected to improve if the moving segments can be positioned without relying on the opposite jaw position. Using 3D printed, patient-specific plates to position the moving segments may improve the surgical accuracy[30,31]. However, the clinical benefit of waferless maxillary positioning must also be evaluated in future randomized controlled studies.

In conclusion, it remains vitally important to know how the chosen sequence affects the surgical outcome. None of the sequences proved superior in all surgical outcomes, and no absolute “winner” could be identified. Operating on the mandible first decreased the variance in surgical accuracy but resulted in a maxillary position posterior to the planned position. Especially the subgroup of patients treated with inferior maxillary repositioning was positioned posterior to the planned position in both the mandible-first and the maxilla-first approach. This posterior discrepancy should be addressed by additional advancement in the VSP to position the maxilla closer to the planned position. Thus, both sequences may achieve closer adherence to the desired maxillary position by adjusting the VSP to include the effects on surgical accuracy.

References

1. Borba AM, Borges AH, Cé PS, Venturi BA, Naclério-Homem MG, Miloro M: Mandible-first sequence in bimaxillary orthognathic surgery: a systematic review. Int J Oral Maxillofac Surg 45: 472, 2015.
2. Cottrell DA, Wolford LM: Altered orthognathic surgical sequencing and a modified approach to model surgery. J Oral Maxillofac Surg 52: 1010, 1994.
3. Ellis E: Bimaxillary surgery using an intermediate splint to position the maxilla. J Oral Maxillofac Surg 57: 53, 1999.
4. Perez D, Ellis E: Sequencing bimaxillary surgery: mandible first. J Oral Maxillofac Surg 69: 2217, 2011.
5. Turvey T: Sequencing of two-jaw surgery: The case for operating on the maxilla first. J Oral Maxillofac Surg 69: 2225, 2011.
6. Stokbro K, Aagaard E, Torkov P, Bell RB, Thygesen T: Virtual planning in orthognathic surgery. Int J Oral Maxillofac Surg 43: 957, 2014.
7. Ellis E: Computer-Aided Surgical Planning for Orthognathic Surgery. J Oral Maxillofac Surg 74: 1302, 2016.
8. Buckley MJ, Tucker MR, Fredette SA: An alternative approach for staging simultaneous maxillary and mandibular osteotomies. Int J Adult Orthodon Orthognath Surg 2: 75, 1987.
9. Posnick JC, Ricalde P, Ng P: A modified approach to “model planning” in orthognathic surgery for patients without a reliable centric relation. J Oral Maxillofac Surg 64: 347, 2006.
10. Liebregts J, Baan F, Koning M de, Ongkosuwito E, Bergé S, Maal T, Xi T: Achievability of 3D planned bimaxillary osteotomies: maxilla-first versus mandible-first surgery. Sci Rep 7: 9314, 2017.
11. Salmen FS, Oliveira TFM de, Gabrielli MAC, Pereira Filho VA, Real Gabrielli MF: Sequencing of bimaxillary surgery in the correction of vertical maxillary excess: retrospective study. Int J Oral Maxillofac Surg 47: 708, 2018.
12. Ritto FG, Ritto TG, Ribeiro DP, Medeiros PJ, Moraes M De: Accuracy of maxillary positioning after standard and inverted orthognathic sequencing. Oral Surg Oral Med Oral Pathol Oral Radiol 117: 567, 2014.
13. Proffit WR, Turvey TA, Phillips C: Orthognathic surgery: a hierarchy of stability. Int J Adult Orthodon Orthognath Surg 11: 191, 1996.
14. Proffit WR, Turvey TA, Phillips C: The hierarchy of stability and predictability in orthognathic surgery with rigid fixation: an update and extension. Head Face Med 3: 21, 2007.
15. Turvey T a: Maxillary expansion: a surgical technique based on surgical-orthodontic treatment objectives and anatomical considerations. J Maxillofac Surg 13: 51, 1985.
16. Convens JMC, Kiekens RMA, Kuijpers-Jagtman AM, Fudalej PS: Stability of Le Fort I maxillary inferior repositioning surgery with rigid internal fixation: a systematic review. Int J Oral Maxillofac Surg 44: 609, 2015.
17. Gil JN, Campos FEB, Claus JDP, Gil LF, Marin C, Freitas SFT de: Medial Canthal Region as an External Reference Point in Orthognathic Surgery. J Oral Maxillofac Surg 69: 352, 2011.

18. Jacobson R, Sarver DM: The predictability of maxillary repositioning in LeFort I orthognathic surgery. Am J Orthod Dentofac Orthop 122: 142, 2002.
19. Stokbro K, Aagaard E, Torkov P, Bell RB, Thygesen T: Surgical accuracy of three-dimensional virtual planning: a pilot study of bimaxillary orthognathic procedures including maxillary segmentation. Int J Oral Maxillofac Surg 45: 8, 2016.
20. Stokbro K, Thygesen T: Surgical Accuracy in Inferior Maxillary Reposition. J Oral Maxillofac Surg, 2018.
21. Baan F, Liebregts J, Xi T, Schreurs R, Koning M de, Bergé S, Maal T: A New 3D Tool for Assessing the Accuracy of Bimaxillary Surgery: The OrthoGnathicAnalyser. PLoS One 11: e0149625, 2016.
22. Stokbro K, Thygesen T: A 3-Dimensional Approach for Analysis in Orthognathic Surgery—Using Free Software for Voxel-Based Alignment and Semiautomatic Measurement. J Oral Maxillofac Surg 76: 1316, 2018.
23. Xia JJ, Gateno J, Teichgraeber JF, Christensen AM, Lasky RE, Lemoine JJ, Liebschner M a K: Accuracy of the computer-aided surgical simulation (CASS) system in the treatment of patients with complex craniomaxillofacial deformity: A pilot study. J Oral Maxillofac Surg 65: 248, 2007.
24. Hsu SS-P, Gateno J, Bell RB, Hirsch DL, Markiewicz MR, Teichgraeber JF, Zhou X, Xia JJ: Accuracy of a computer-aided surgical simulation protocol for orthognathic surgery: a prospective multicenter study. J Oral Maxillofac Surg 71: 128, 2013.
25. Borba AM, Ribeiro-Junior O, Brozoski MA, Cé PS, Espinosa MM, Deboni MCZ, Miloro M, Naclério-Homem MG: Accuracy of perioperative mandibular positions in orthognathic surgery. Int J Oral Maxillofac Surg 43: 972, 2014.
26. Ellis E, Carlson DS, Frydenlund S: Stability of midface augmentation: an experimental study of musculoskeletal interaction and fixation methods. J Oral Maxillofac Surg 47: 1062, 1989.
27. Sickels JE Van, Richardson DA: Stability of orthognathic surgery: A review of rigid fixation. Br J Oral Maxillofac Surg 34: 279, 1996.
28. Jacobson R, Sarver DM: The predictability of maxillary repositioning in LeFort I orthognathic surgery. Am J Orthod Dentofacial Orthop 122: 142, 2002.
29. Shaheen E, Sun Y, Jacobs R, Politis C: Three-dimensional printed final occlusal splint for orthognathic surgery: design and validation. Int J Oral Maxillofac Surg, 2016.
30. Stokbro K, Bell RB, Thygesen T: Patient-Specific Printed Plates Improve Surgical Accuracy In Vitro. J Oral Maxillofac Surg, 2018.
31. Heufelder M, Wilde F, Pietzka S, Mascha F, Winter K, Schramm A, Rana M: Clinical accuracy of waferless maxillary positioning using customized surgical guides and patient specific osteosynthesis in bimaxillary orthognathic surgery. J Cranio-Maxillofacial Surg 45: 1578, 2017.

Chapter 10

General discussion and future perspectives

Introduction

This thesis aims to investigate how three-dimensional (3D) planning in orthognathic surgery can be optimized and fully utilized in daily practice. The results of clinical studies that investigate different factors regarding the surgical accuracy and postoperative stability are discussed extensively in the first section of this chapter, "Concerning the research questions", in which the research questions stated in the introduction of this thesis are answered based on the obtained clinical data. The potential influences of the newly gained insights, technological advances and conceptual changes in the treatment planning, outcome, and evaluation of orthognathic patients on daily clinical practice in orthognathic surgery are appraised in the second part of this chapter, "Future perspectives".

Concerning the research questions

What is the accuracy of the Mass Tensor Model (MTM)-based 3D facial soft tissue simulation in BSSO mandibular advancement and bimaxillary osteotomies?

Interest in the prediction of soft tissue response to hard tissue movements has grown in recent decades. The conventional landmark-based 2D cephalometric analysis seems to be an insufficient tool for 3D prediction as it does not take into account the third dimension. With the introduction of CBCT, oral maxillofacial surgeons obtained a new imaging modality to depict the facial soft tissue and hard tissue in 3D. Knowledge of hard tissue and the facial soft tissue response not only helps to guide the surgical movements of the osteotomy segments but also informs surgeons about the need for preparative orthodontic decompensation to achieve the required surgical skeletal correction. With these interventions, the purpose of orthognathic surgery is not only to correct the facial dysmorphology from a functional point of view, but also to obtain an aesthetic enhancement of the patient's face. Therefore, an accurate treatment planning is very important to obtain good postoperative results (1).

Although the MTM-based 3D facial soft tissue simulation in Maxilim® software is routinely used for the 3D soft tissue based planning of BSSO and bimaxillary surgery at the Department of OMF Surgery at Radboudumc, when starting, little clinical data on the accuracy of the computerized 3D simulation of postoperative soft tissue changes had been published. A clinical study involving 100 patients who had undergone mandibular advancement using BSSO was therefore set up to evaluate the accuracy of the 3D simulation of soft tissue changes (Chapter 2). In this study, both the accuracy of simulation for the whole face and the accuracy of specific facials regions that were altered during surgery were investigated and included in the data analyses. For the entire face, the mean absolute error was 0.9 ± 0.3 mm, and the mean absolute 90th percentile was 1.9 mm. Among all 100 patients, the absolute mean error was less than or equal to 2 mm. The facial subregion with the least accurate results was the lower lip area, with a mean absolute error of 1.2 ± 0.5 mm.

Another clinical study involving 60 patients who had undergone bimaxillary surgery was set up to evaluate the accuracy of the 3D simulation of soft tissue changes (Chapter 3). The mean absolute error between the 3D simulation and the actual postoperative facial profile was 0.8 ± 0.22 mm for the face as a whole. In this study, the accuracy of the simulation (mean absolute error <=2 mm) for the whole face, the upper lip, lower lip, and chin subregions were 100%, 93%, 90%, and 95%, respectively. In this study too, the accuracy of soft tissue simulation in the lower lip region was the least accurate. As a prediction error of less than 2 mm is generally considered to be clinically acceptable (2-4), the accuracy of the MTM-based Maxilim® software is considered to be accurate enough for clinical use as an aid in treatment planning, communication with the patient, and shared decision-making.

In Chapter 4, a clinical study involving 60 patients who had undergone bimaxillary surgery was set up to evaluate the accuracy of the 3D simulation of soft tissue changes, on the width of the nose at alar base. Despite using different closing sutures – the VY closure and the alar cinch technique – widening of the alar base width was perceived, with an absolute mean of 1.6 ± 1.1 mm. The 3D cephalometric analysis of the simulation versus the actual postoperative results showed a mean absolute error of 1.0 ± 0.9 mm. No correlation between the simulation error of alar widening and maxillary advancement was found. These findings indicate that the MTM-based soft tissue simulation can be used to predict soft tissue changes following orthognathic surgery.

Despite the encouraging result, clinicians should be aware of the relatively large errors in the prediction of the lower lip and nasal region. This finding may be a result of a non-linear correlation between the hard tissue and soft tissue ratio, as reported in previous studies (5-8). As a greater jaw advancement has been shown to result in more inaccuracies in the surgical transfer of virtual surgical planning, a larger error in the soft tissue simulation is expected (9, 10). It might therefore be more difficult to accurately simulate the postoperative soft tissue profile of greater jaw displacements, even if the surgery is conducted accurately.

Due to the relatively small study population, the present studies were unable to include all possible (age, gender, smoker/non-smoker, skin type, BMI, etc.) factors in the analysis and exhibit the exact role of those factors in the prediction of the postoperative lip position. From a theoretical point of view, it would probably be impossible to incorporate all of these clinical parameters into the MTM algorithm to simulate the postoperative position and morphology of the lips.

The findings presented above were all found using the MTM model for the soft tissue simulation. In the field of facial soft tissue simulation in orthognathic surgery, different methodologies and software can be used: the Mass Spring Model, the Finite Element Model, and the Mass Tensor Model. The Dolphin software uses the Finite Element Model and Resnick et al. reported that the ability to predict 3D soft tissue changes was limited, with an accuracy that may be acceptable for linear changes but not for lateral facial points (11). Peterman et al. (12) reported various degrees of accuracy at each soft tissue landmark in the horizontal and vertical axes, with soft tissue prediction in the lower lip region the least accurate (3.86 mm ± 2.53). A similar result of low prediction accuracy for the lower lip region was reported by Pektas et al. (13). Another commercially available software, SurgiCaseCMF (based on the Finite Element Model), was analyzed by Bianchi et al. (5) and Marchetti et al. (14); they reported that the percentage of error was less than 2 mm in 91% of patients, but in both studies, an important error in the areas of lips and chin was reported. Khambay et al., Terzic et al., and Ullah et al. used 3dMDvultus (Mass Spring Model) to predict soft tissue changes. In general, they reported that its use on specific anatomical regions was more meaningful than on the full face (15-17). Moreover, they reported an insufficient prediction accuracy, in particular for the lower part of the face with mean errors exceeding 3 mm (17), and also for the nasal and paranasal regions. Surprisingly, the reported prediction results seemed to be reliable for lips and chin, with a mean error of 0.64 mm.

In summary, it can be concluded that the MTM-based 3D prediction software is able to give surgeons a realistic and clinically useful prediction of the postoperative facial soft tissue profile following BSSO and bimaxillary surgery. However, the surgeon should be aware that, although the MTM model can provide a good representation of an average simulation, in some individual cases the planning did not predict the postoperative facial soft tissue profile very well.

Can Principal Component Analysis (PCA) be applied to evaluate the 3D changes in soft tissue facial profile following orthognathic surgery?

In 2014, a new 3D photogrammetry-based automated method for quantifying variations in soft tissue facial profiling using PCA was developed in our department. This new method can automatically quantify the facial appearance of the chin region of dysgnathic patients. The specific facial variations were defined as unique variations (UVs) and the effect of each UV on the soft tissue facial profile was investigated. The UVs that described the variations in the retrusion of the mandible were used to distinguish patients with mandibular hypoplasia from the control population. 3D photographs of 25 female patients who had undergone a BSSO and of 70 female control patients were acquired. A clockwise rotation of the mandible and a shortening of the lower part of the face were the most prominent differences between the two groups (UV1). Retrusion of the mandible was more common in the preoperative BSSO patients than in the control group. Consequently, an over-accentuation of the labial-mental fold was more often present in the preoperative BSSO patient group than in the control group (UV2). As a result of BSSO mandibular advancement, the postoperative facial profile in the BSSO group shifted toward the control group. However, the postoperative group did not overlap the control group completely, indicating that many BSSO patients maintained some characteristics of Class II facial profile, despite surgery.

PCA is a suitable technique for reducing the dimensionality of a large dataset. It reduces the number of components (dimensional variations) and makes the large dataset simpler and easier to explore and visualize. PCA also has the advantage of reducing the computational complexity of the model, which makes potential machine learning algorithms run faster. It therefore has the potential to aid the construction of a good neural network for computing deep learning based algorithms in soft tissue simulations in the future.

Due to the novelty and complexity of the PCA technique, little is known from previous studies about the analysis of soft tissue prediction in orthognathic surgery with PCA. Vittert et al. focused on the comparison of postoperative facial appearance with the facial shape of controls using PCA (18). The primary characteristic of the difference in shape was found to be the residual mandibular prognathism in the group of female patients who underwent Le Fort I maxillary advancement. Individual cases were assessed against this type of shape difference, using a quantitative scale to aid clinical audit. Analysis of the combined surgical groups provided strong evidence that surgery reduced asymmetry in some parts of the face such as the upper lip region. No evidence was found that mean asymmetry in post-surgical patients is greater than that in controls.

Compared to the MTM-based simulation model, which lacks accuracy in the prediction of the lip region after BSSO or bimaxillary surgery as described above, the PCA-based model demonstrated the ability to improve the soft tissue simulation of the lip and labial-mental fold. The incorporation of the statistical model in the MTM-based model may have the potential to improve the soft tissue simulation in the 3D virtual planning of orthognathic surgery.

Is it possible to quantify surgical jaw movements without the use of conventional landmark-based cephalometric analysis?

Several methods have been proposed in previous studies to assess the accuracy of surgical jaw movements with regard to the 3D surgical planning (19, 20). All of these methods are based on the use of cephalometric landmarks to quantify 3D spatial differences between the virtual planning and the postoperative position of jaw segments. However, an inherent shortcoming of landmark-based analysis is the summation of landmark identification errors due to the need to identify the same landmarks multiple times in different image datasets. This increasing error may exceed the actual difference between the virtual 3D planning and the postoperative outcome, and thus impede a correct interpretation of the cephalometric analysis. A more accurate, and preferably more automated, approach was therefore required by clinicians. Chapter 6 presented the OrthoGnathicAnalyser (OGA); a novel tool to quantify the displacement of bony segments in orthognathic surgery based on the voxel-based registration of different jaw segments. This innovative method of quantifying the surgical displacement of jaw segments in six degrees of freedom (sagittal, vertical, and transverse translations, as well as pitch, roll, and yaw) was highly reproducible (intraclass correlation coefficients > 0.97).

As it overcomes the landmark identification error, the OGA is an observer-independent, semi-automatic tool that is able to analyze the accuracy of the 3D planning and surgical outcome in an objective, reproducible, and clinically relevant way. In a recently published systematic review, this tool was reported to be the best contemporary method for assessing the achievability of 3D virtual surgical planning in orthognathic surgery (21). The OGA did have the drawback that it was software dependent and could only be used with Maxilim® planning software. However, to overcome these two drawbacks, the 3D Lab has managed in the past year to update the OGA software. At the moment of writing, the OGA is no longer software or platform dependent and is provided without commercial interest to collaborating research centers on various continents, and can operate on any computer anywhere in the world(22).

How does the sequencing of bimaxillary osteotomies affect the achievability and stability of the 3D planned bimaxillary surgeries?

The surgical approach used during bimaxillary surgery, either the maxillary-first or the mandibular-first sequence, has been a controversial topic in the field of orthognathic surgery. Using the scientifically and clinically validated OGA, it is possible to investigate the accuracy of 3D planning in bimaxillary surgery with large patient groups and to analyze the postoperative results in an objective, reproducible, and systemic way.

A clinical study involving 116 patients who had undergone bimaxillary surgery was set up to investigate the effect of sequencing on the surgical accuracy (Chapter 7). The results demonstrated that, in most cases, the maxilla-first surgical approach yielded a closer concordance with the 3D virtual surgical planning than a mandibular-first procedure. Our results demonstrated that the positioning of the bimaxillary complex is generally more accurate when the maxilla is operated first, especially in the anterior displacement of the jaws.

These results differ from those presented by Ritto et al. (23) who stated that both maxilla-first and mandible-first surgery can provide a reliable outcome. As the mean displacement of the maxilla was comparable between the two studies (4 mm), we believe that the difference is caused in methodology – 2D versus 3D imaging – as well as cephalometric analysis versus OGA. The measurement errors in our study are significantly reduced by applying the state-of-art 3D imaging technology, thereby revealing the true underlying differences between the maxilla-first and mandible-first groups.

In Chapter 9, the effects of sequencing in bimaxillary osteotomies were discussed in the study population of Chapter 7 pooled with similar data from the Oral and Maxillofacial Surgery Research Unit at the University of Southern Denmark in Odense. The main conclusion confirmed the finding that, in maxilla-first sequencing, the maxilla was generally placed more accurate around the planned reposition, while the mandible-first approach resulted in a significantly better anterior-posterior position of the maxilla when an impaction of the maxilla was planned. In selected circumstances, such as a planned counter clockwise (CCW) pitch of both jaws, the mandible-first sequence resulted in the more predictable displacement of the jaws. This could be due to bone interferences between the pterygoid plates and the osteotomized posterior maxilla. Intraoperatively, it is hard to visually check for bone interferences in the posterior maxilla. This can result in premature bone contacts and lead to a deviation in the pitch. In the mandible-first approach, these posterior maxillary interferences only influenced the positioning of the maxilla, whereas in the maxillary-first cases, a suboptimal maxillary posterior impaction affected both the maxillary and mandibular positions.

Chapter 8 evaluated the postoperative skeletal stability one year after bimaxillary surgery in the same study cohort, both in the maxilla-first as in the mandible-first group. No significant differences were found in relapse between the two groups. The study showed that the mean sagittal, vertical, and transverse relapse was less than 1.8 mm, consistent with previous findings(24-27).

Results show that the relapse following BSSO advancement was 0.7 mm ± 3.0mm, whereas it was 0.5 mm ± 2.3 mm following a bimaxillary advancement, and therefore significantly lower, despite a similar advancement of 6 mm and 10 mm. Although the sequence of the performed osteotomies did not appear to affect postoperative relapse, this study has shown an impact of jaw translations and rotations on one-year skeletal relapse, with the magnitude of surgical displacement and skeletal relapse of the maxilla and mandible comparable to previous studies (28, 29). This suggests that surgical jaw movements are an important contributor in skeletal relapse, and that a larger surgical movement and a CCW rotation of the bimaxillary complex increase the soft tissue and muscular tensions surrounding the jaws. This is in line with the systematic review by Joss & Vassalli (4), who showed an increased vertical relapse in patients with a low mandibular plane angle, and an increased horizontal relapse in patients with a high mandibular plane angle (4).

In the abovementioned clinical studies, the reliability of the study outcome is increased by focusing exclusively on the surgical accuracy of the maxillary measurements. Maxillary measurements are more reliable than mandibular measurements because maxillary measurements are not affected by the occlusion or the mobility of the temporomandibular joint. Mandibular measurements are affected by the seating of the temporomandibular joints in centric relation with the fossa. If the condyles are not seated properly during the one-week follow-up scan, the displacement will be interpreted as decreased surgical accuracy. Furthermore, patients may still suffer from postoperative edema and paresthesia at the one-week follow-up scan. Maintaining the joints in centric relation while keeping the mandible stable at the first point of occlusal contact can be difficult under such conditions, giving rise to errors in mandibular positioning. Unlike the mandible, the maxillary position is fixated to the midface and cranial base and the position cannot be altered by the patient. Thus, the maxillary measurements used in studies are reliable without being dependent on the patient's cooperation.

A limitation of the studies in Chapters 7-10 is the clinical study design. The ideal study design to evaluate the influence of sequencing bimaxillary osteotomies and the achievability and stability of 3D planning is a randomized controlled trial, with patients who are randomly assigned to the maxilla-first and mandible-first groups, while controlling all possible covariates. However, this ideal study design can encounter grave ethical issues in clinical practice. Therefore, this retrospective cohort study has been set up.

In conclusion, the sequence of bimaxillary procedures is of more clinical importance in terms of the achievability of the 3D virtually planned reposition of the jaws than the stability of the achieved postoperative results. Whether the maxilla or mandibula should be operated first is still up to the surgeon to decide, according to the type of planned jaw movements. It is the task of the surgeon to know how the chosen sequence affects the surgical outcome, so that the virtual surgical plan can be adjusted accordingly.

Conclusion

This thesis has shown that all the research questions could be answered satisfactorily. The additional benefits of 3D preoperative planning and postoperative 3D evaluation of the achieved surgical results have been proven. With 3D simulation, orthognathic surgery has become more accurate and predictable. Throughout this thesis, it became more and more clear that 3D simulation has become indispensable in orthognathic surgery, and indeed has now become the gold standard.

Future perspectives

The implementation of 3D virtual surgical planning and postoperative evaluation in clinical routine practice has introduced a new dimension in the field of orthognathic surgery. The newly gained insights regarding the accuracy of 3D soft tissue simulation on the one hand, and the in-depth analysis of factors affecting the achievability and stability of orthognathic surgeries on the other, have the potential to bring the treatment outcome closer to perfection.

Each individual is unique. Unique characteristics include not only genetics, physiology, and esthetics, but also the psyche, social environment, and wishes of the individual. In the years during which this research was done, the obligation of physicians to inform the patients on the benefits, risks, and prognosis of a medical intervention (informed consent) has been replaced by shared decision-making in Dutch medical legislation. In other words, the traditional paternalistic approach, in which the doctors know best, is evolving into an autonomy-based approach in which the patient demands an important share in producing the final treatment plan. Shared decision-making recognizes both the physician's position and the patient's authority.

To respond to the demand of patients in the contemporary dynamic environment, the treatment philosophy and routine workup in orthognathic surgery need to evolve. Rather than focusing on a perfect occlusion and soft tissue profile that are based on a population average, most orthognathic patients wish to participate more in the process of diagnosis, treatment planning, and postoperative evaluation of the surgical result. This form of participatory healthcare and the ability to incorporate it in the daily orthognathic workflow will become the focal point within the field of orthognathic surgery in the coming decade. So, how can current 3D virtual surgical planning accommodate these anticipated changes in the field of orthognathic surgery?

The concept of the all-in-one orthognathic workflow is key to enabling orthognathic surgery to adapt to the evolving treatment philosophy and patient demands. Instead of the fragmented steps in the current workflow, the all-in-one orthognathic workflow combines and automates each step of the quality cycle; namely the diagnosis, planning, treatment, and evaluation. In this way, the physician and patient have the tools to visualize, modify, and evaluate the orthognathic treatment, to accommodate the shared decision-making and surgical possibilities. The incorporation of orthodontic treatment in this process will further complete the concept of the all-in-one orthognathic workflow.

Diagnosis

The use of 3D imaging and the associated digital tools to quantify the triad of soft tissue, bony tissue, and dentition in the craniofacial region has become the standard in diagnosing dentofacial anomalies. In this process, a patient first undergoes a 3D stereophotogrammetry, followed by a CBCT scan and an intra-oral scan. Additional 2D clinical photographs of the patient are acquired to register the natural head position. Using commercial 3D virtual surgical planning software, a detailed 3D augmented head model can be rendered by loading and combining the 3D image data from these three different imaging modalities. Finally, the 3D augmented head model is manually aligned to the natural head position based on the recorded natural head position from the 2D clinical photographs. With the aid of landmark-based cephalometry, a diagnosis of the dentofacial anomalies at the level of soft tissue, bone tissue and dentition can be made by the surgeon together with the orthodontist.

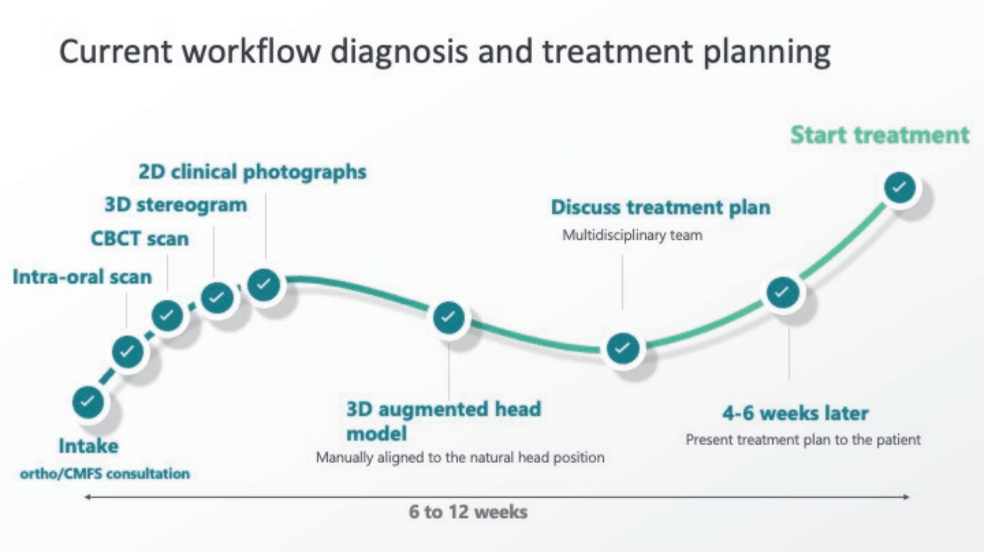


Figure 1: overview of current workflow to obtain a diagnosis and orthognathic treatment plan.

Despite the high accuracy of the 3D augmented head model and the widely accepted landmark-based cephalometry, this current workflow has a few inherent shortcomings:

- 3D rendering of the augmented head model requires manual operation, adjustment, and time;
- adjustment of the 3D augmented head model to the natural head position is subjective and influenced by manual errors;
- cephalometry-based diagnosis is time-consuming and is in many cases inaccurate as it is based on the mean values of a limited population.

The all-in-one diagnostic concept provides a fast and reliable means of rendering a virtual 3D augmented head model and of establishing the final diagnosis. During a single multidisciplinary consultation with the patient and orthodontist, and using a single scan, a computer-aided diagnosis can be established while visualizing the dentofacial anomalies in 3D. The ideal multidisciplinary consultation starts with the patient describing the chief complaint from the functional, aesthetic, and psychosocial points of view. After identifying the subjective need of the patient, the patient undergoes a single scan. By acquiring the 3D stereophotogrammetry and CBCT simultaneously with the patient's head positioned in the natural head position, and by taking intra-orals scans using state-of-the-art intra-oral scanners, the three image datasets and their orientation are transferred wirelessly to a cloud-based server. With the help of artificial intelligence (AI), the image modalities are merged automatically within a minute, forming an accurate 3D virtual augmented head model of the patient. Based on collected big data, an AI algorithm generates the diagnosis at the level of soft tissue, hard tissue, and dentition. While the patient walks back from the scanner to the consultation room, the surgeon and orthodontist can visualize the 3D augmented head model of the patient and confirm the AI-generated diagnosis. Using augmented reality glasses, the patient can view his or her 3D head model in different layers with the dentofacial anomalies highlighted. This all-in-one diagnosis concept establishes a sound base to perform the following step: treatment planning.

Treatment planning

The all-in-one treatment planning concept aims to generate a personalized orthodontics and surgical treatment plan that is able to correct the malocclusion, to improve function, to harmonize facial aesthetics, and to meet the expectations of the patient. The strength of this treatment concept is that, in one single consultation, the chief complaint of the patient is addressed with a tailored treatment plan that is backed by all members of the treatment team and the patient.

The fundaments of the all-in-one treatment planning concept are: 1) the presence of a 3D augmented head model and diagnosis from step 1; 2) the availability of a big database with treatment planning and postoperative results of previous orthognathic procedures; and 3) a clinically validated algorithm that can accurately generate the desired occlusion, bony tissue position, and soft tissue profile from a 3D augmented model with dentofacial anomalies. AI plays a central role in combining the data from these three steps to compute an orthodontic and surgical treatment plan that is able to correct the dentofacial anomalies. By visualizing the final result at the level of soft tissue, bone tissue, and dentition in 3D (using augmented reality), the patient and treatment team can verify the achievability of the proposed plan and change the plan accordingly until a shared decision is reached. At the end of the consultation, the duration and type of orthodontic and surgical treatment, the necessity of teeth extractions and bone-anchored orthodontic devices, and the final treatment result will be clear to all parties. This all-in-one treatment plan is executed in the next step, the actual orthognathic treatment.

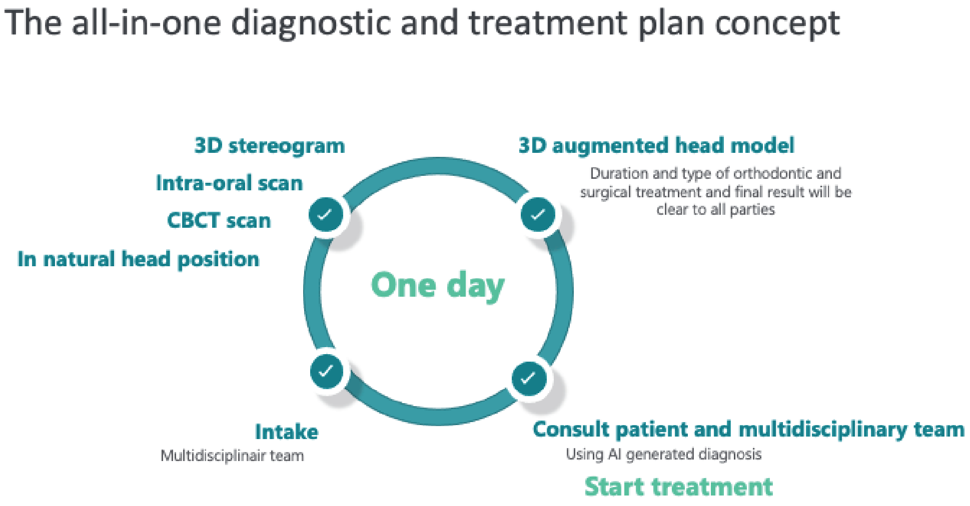


Figure 2: With the all-in-one concept, the patient gets a diagnosis and treatment plan in one day.

Orthodontic and orthognathic treatment

The all-in-one treatment concept aims to apply the orthodontic and orthognathic treatment plan to the patient in an accurate and predictable way in order to achieve the ideal result. Previously, many studies have focused on assessing how well a certain technique such as patient-specific implants or intraoperative navigation are able to transfer the planned jaw movements to the patients. As described before, the all-in-one treatment concept does not rely on one specific tool to achieve the treatment plan. It is rather a larger treatment concept that translates, monitors and adjusts the treatment in real-time in order to reach the predefined result in a predetermined timeframe.

As the orthodontic treatment largely dictates the treatment duration, it is crucial to transfer the teeth to the planned position in a fast and accurate way to facilitate surgery, so that surgery does not need to be compromised to accommodate the inaccuracies of the presurgical orthodontics. This goal can be reached in the short term by implementing the presently available techniques such as indirect bonding, machinal bending of orthodontic wires, orthodontic aligners, and bone-anchored orthodontic devices in an efficient way. The key in the all-in-one treatment concept is regular monitoring and the use of this feedback to adjust the treatment to keep to the plan. By regularly conducting intra-oral scans, and by comparing the actual teeth position to the planned position, an AI-based algorithm can ensure that the orthodontic treatment matches the plan within the predetermined timeframe using the aforementioned techniques. The big advantage of this all-in-one treatment concept compared with a conventional treatment philosophy is that the all-in-one concept adjusts the treatment proactively to meet the goal, whereas the conventional philosophy reacts to unforeseen events. From this point of view, the all-in-one treatment concept eliminates the conventional extensive presurgical documentation of orthognathic patients. Regular intra-oral scanning with 3D stereophotogrammetry monitors the soft tissue and dental movements so that the actual presurgical situation corresponds to the presurgical situation as visualized during the first multidisciplinary consultation.

Orthognathic surgery itself will also evolve in the coming decades. With the emergence of splintless surgery using patient-specific implants, the repositioning and fixation of the jaws can be achieved simultaneously according to the 3D plan. This will in my view serve as a transition toward more automated robot surgery, with a different surgical access compared to conventional orthognathic incisions, and a different pattern in making bone cuts and achieving the final fixation. The jaw movements and the repositioning of the jaw segments can be monitored continuously during surgery with techniques such as object-oriented navigation and infrared/electromagnetic tracking. In this way, real-time surgical adjustments can be made to react to unforeseen events during surgery.

Following surgery, an all-in-one scan of the patient will be acquired as described in step 1. An AI-based algorithm will compare the actual surgical result to the 3D plan, and based on the discrepancies, the postoperative orthodontics will be adjusted to achieve the final occlusion and soft tissue facial profile within the total treatment time. In this way, aided by the evolution in technique, the all-in-one treatment concept will provide a satisfactory treatment result in the eyes of the orthodontist, the surgeon, and the patient.

Evaluation

The all-in-one evaluation concept aims: 1) to provide an objective and automated evaluation of the orthodontic and surgical result at the level of soft tissue, bone tissue, and dentition; and 2) to provide data to optimize the big data and AI-based algorithms that are used in step 1 of the quality cycle in orthognathic surgery.

As described in the previous steps, the all-in-one evaluation concept is continuously present throughout the treatment. Instead of evaluating the treatment outcome at a limited number of evaluation moments, this concept consists of a near continuous monitoring of the dental movements, and two all-in-one evaluation scans (to monitor the triad of soft tissue, bone tissue, and dentition and their interactions): one directly after surgery and one after achievement of the final result. This concept enables a high achievability of the 3D planning proposed at the beginning of the treatment within the determined treatment duration.

Furthermore, to enhance the predictability of each separate previous step, the all-in-one evaluation concept generates essential data. This data should be stored in a safe, anonymized and centralized cloud-based database that is freely available to all peers. In this way, a peerowned and peer-supported international community can be shaped to enhance the level of orthognathic surgery in different regions of the world. As the all-in-one concept does not rely on locally available equipment and is limited neither by the characteristics of the local population nor the locally colored treatment philosophy, there will be a low threshold to implementing this concept in different regions of the world.

Final words

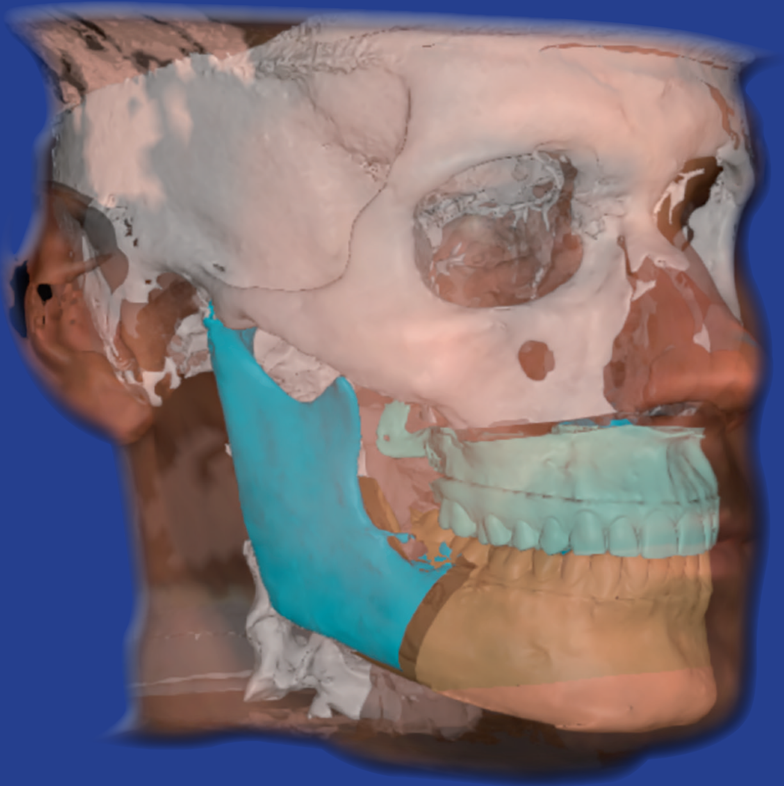
The orthognathic treatment philosophy, technological possibilities, and access to orthognathic care are expected to evolve rapidly in the coming decades. The all-in-one orthognathic concept will enable the orthodontist, surgeon, and patient to embrace these new possibilities and to exploit them to their highest potential, while safeguarding the shared decision-making which will remain the focus and success of orthognathic surgery. This will be an era in which digital technology will serve and digital technology will become human.

References

1. Eckhardt CE, Cunningham SJ. How predictable is orthognathic surgery? European journal of orthodontics. 2004;26(3):303-9.
2. Proffit WR, Phillips C, Dann Ct, Turvey TA. Stability after surgical-orthodontic correction of skeletal Class III malocclusion. I. Mandibular setback. The International journal of adult orthodontics and orthognathic surgery. 1991;6(1):7-18.
3. Donatsky O, Bjorn-Jorgensen J, Holmqvist-Larsen M, Hillerup S. Computerized cephalometric evaluation of orthognathic surgical precision and stability in relation to maxillary superior repositioning combined with mandibular advancement or setback. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 1997;55(10):1071-9; discussion 9-80.
4. Joss CU, Vassalli IM. Stability after bilateral sagittal split osteotomy advancement surgery with rigid internal fixation: a systematic review. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2009;67(2):301-13.
5. Bianchi A, Muyldermans L, Di Martino M, Lancellotti L, Amadori S, Sarti A, et al. Facial soft tissue esthetic predictions: validation in craniomaxillofacial surgery with cone beam computed tomography data. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2010;68(7):1471-9.
6. Liebregts J, Xi T, Timmermans M, de Koning M, Berge S, Hoppenreijs T, et al. Accuracy of three-dimensional soft tissue simulation in bimaxillary osteotomies. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery. 2015;43(3):329-35.
7. Liebregts JH, Timmermans M, De Koning MJ, Berge SJ, Maal TJ. Three-dimensional facial simulation in bilateral sagittal split osteotomy: a validation study of 100 patients. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2015;73(5):961-70.
8. Shafi MI, Ayoub A, Ju X, Khambay B. The accuracy of three-dimensional prediction planning for the surgical correction of facial deformities using Maxilim. International journal of oral and maxillofacial surgery. 2013;42(7):801-6.
9. Liebregts J, Baan F, de Koning M, Ongkosuwito E, Berge S, Maal T, et al. Achievability of 3D planned bimaxillary osteotomies: maxilla-first versus mandible-first surgery. Sci Rep. 2017;7(1):9314.
10. Semaan S, Goonewardene MS. Accuracy of a LeFort I maxillary osteotomy. The Angle orthodontist. 2005;75(6):964-73.
11. Resnick CM, Dang RR, Glick SJ, Padwa BL. Accuracy of three-dimensional soft tissue prediction for Le Fort I osteotomy using Dolphin 3D software: a pilot study. International journal of oral and maxillofacial surgery. 2017;46(3):289-95.
12. Peterman RJ, Jiang S, Johe R, Mukherjee PM. Accuracy of Dolphin visual treatment objective (VTO) prediction software on class III patients treated with maxillary advancement and mandibular setback. Progress in orthodontics. 2016;17(1):19.

13. Pektas ZO, Kircelli BH, Cilasun U, Uckan S. The accuracy of computer-assisted surgical planning in soft tissue prediction following orthognathic surgery. Int J Med Robot. 2007;3:64-71.
14. Marchetti C, Bianchi A, Muyldermans L, Di Martino M, Lancellotti L, Sarti A. Validation of new soft tissue software in orthognathic surgery planning. International journal of oral and maxillofacial surgery. 2011;40(1):26-32.
15. Khambay B, Ullah R. Current methods of assessing the accuracy of three-dimensional soft tissue facial predictions: technical and clinical considerations. International journal of oral and maxillofacial surgery. 2015;44(1):132-8.
16. Ullah R, Turner PJ, Khambay BS. Accuracy of three-dimensional soft tissue predictions in orthognathic surgery after Le Fort I advancement osteotomies. The British journal of oral & maxillofacial surgery. 2015;53(2):153-7.
17. Terzic A, Combescure C, Scolozzi P. Accuracy of computational soft tissue predictions in orthognathic surgery from three-dimensional photographs 6 months after completion of surgery: a preliminary study of 13 patients. Aesthetic plastic surgery. 2014;38(1):184-91.
18. Vittert L, Katina S, Ayoub A, Khambay B, Bowman AW. Assessing the outcome of orthognathic surgery by three-dimensional soft tissue analysis. International journal of oral and maxillofacial surgery. 2018;47(12):1587-95.
19. Haas Jr OL, Becker OE, de Oliveira RB. Computer-aided planning in orthognathic surgery-systematic review. International journal of oral and maxillofacial surgery. 2014.
20. Stokbro K, Aagaard E, Torkov P, Bell RB, Thygesen T. Virtual planning in orthognathic surgery. International journal of oral and maxillofacial surgery. 2014;43(8):957-65.
21. Gaber RM, Shaheen E, Falter B, Araya S, Politis C, Swennen GRJ, et al. A Systematic Review to Uncover a Universal Protocol for Accuracy Assessment of 3-Dimensional Virtually Planned Orthognathic Surgery. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2017;75(11):2430-40.
22. Baan F, Sabelis JF, Schreurs R, van de Steeg G, Xi T, van Riet TCT, et al. Validation of the OrthoGnathicAnalyser 2.0-3D accuracy assessment tool for bimaxillary surgery and genioplasty. PloS one. 2021;16(1):e0246196.
23. Ritto FG, Ritto TG, Ribeiro DP, Medeiros PJ, de Moraes M. Accuracy of maxillary positioning after standard and inverted orthognathic sequencing. Oral Surg Oral Med Oral Pathol Oral Radiol. 2014;117(5):567-74.
24. Ayoub AF, Trotman CA, Stirrups DR, Wilmot JJ. Stability of bimaxillary osteotomy following surgical correction of class II skeletal deformities: a two-centre study. The British journal of oral & maxillofacial surgery. 1997;35(2):107-15.
25. Xi T, van Luijn R, Baan F, Schreurs R, de Koning M, Berge S, et al. Three-dimensional analysis of condylar remodeling and skeletal relapse following bimaxillary surgery: A 2-year follow-up study. Journal of cranio-maxillo-facial surgery : official publication of the European Association for Cranio-Maxillo-Facial Surgery. 2017;45(8):1311-8.

26. Ayoub AF, Stirrups DR, Moos KF. The stability of bimaxillary osteotomy after correction of skeletal Class II malocclusion. The International journal of adult orthodontics and orthognathic surgery. 1993;8(3):155-70.
27. Moen K, Wisth PJ, Skaale S, Boe OE, Tornes K. Dental or skeletal relapse after sagittal split osteotomy advancement surgery? Long-term follow-up. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 2011;69(11):e461-8.
28. Arpornmaeklong P, Shand JM, Heggie AA. Skeletal stability following maxillary impaction and mandibular advancement. International journal of oral and maxillofacial surgery. 2004;33(7):656-63.
29. Schwartz K, Rodrigo-Domingo M, Jensen T. Skeletal Stability after Large Mandibular Advancement (> 10 mm) with Bilateral Sagittal Split Osteotomy and Skeletal Elastic Intermaxillary Fixation. J Oral Maxillofac Res. 2016;7(2):e5.



Summary

In the past decades, numerous technological advances have had their influence on modern medicine. In orthognathic surgery, evolution in digital imaging technology has brought us the capability to visualize soft tissue, bony tissue, and dentition of a patient's head in 3D. With this ability come many advantages, most substantially regarding 3D preoperative planning and 3D postoperative evaluation. In this thesis, the main objective is to investigate how 3D planning in orthognathic surgery can optimize the surgical outcome and predictability. In **Chapter 1**, a general introduction to the clinical and technical fundamentals of contemporary 3D orthognathic planning is provided. In order to create a virtual 3D head model, bony structures, soft tissue, and dentition need to be visualized. Different 3D imaging techniques are being used and the information from separate imaging modalities are combined using image fusion algorithms in dedicated software programs. Cone-beam computed tomography (CBCT) serves as the basis of a 3D virtual head model, as it provides information about the bone structures and thickness of overlying soft tissue. Combined with stereophotogrammetry, a 3D color photo of the soft tissue, an intra-oral scan of the dentition, an augmented 3D virtual head can be rendered. Virtual osteotomies can be performed (Le Fort 1, bilateral sagittal split-osteotomy (BSSO), genioplasty) upon this 3D augmented head model, in which all jaw segments can be moved in any desired direction. The soft tissue outcome of a virtual osteotomy can be simulated in real-time by using different biomechanical models.

In **Chapter 2**, the accuracy of the Mass Tensor Model (MTM) algorithm in Maxilim® software (Medicim NV, Mechelen, Belgium) is assessed. Pre- and postoperative CBCT scans of 100 patients that were treated with a BSSO were registered on the anterior cranial base. 3D distance maps and 3D cephalometric analyses were used to calculate the differences between the soft tissue simulation and the actual postoperative soft tissue results. For the entire face, the mean absolute error was found to be 0.9±0.3 mm and the mean absolute 90th percentile was 1.9 mm. The chin area was the most predictable area, with a mean absolute error of 0.8±0.5 mm, whereas the lower lip area was the least predictable, with a mean absolute error of 1.2±0.5 mm. It is important to realize that the lip area may be the most difficult area to predict. The presence of orthodontic appliances, or absence thereof, and the difficulty in maintaining the same amount of tension in patients' lips in pre- and postoperative CBCTs might have a role in the pre- and postoperative discrepancy.

In **Chapter 3**, a similar study was conducted on the accuracy of soft tissue prediction in bimaxillary osteotomies. Sixty patients who underwent bimaxillary surgery were enrolled in this study. Using a similar methodology, a mean absolute error of 0.81±0.22 mm was found for the face as a whole. The accuracy of the soft tissue simulation in the upper lip region was the highest (1.2 ± 0.6 mm), whereas the lower lip region was found to be the least predictable (1.4 ± 0.5 mm). In general, the accuracy of the soft tissue simulation decreased in patients when a larger surgical advancement was planned.

In **Chapter 4**, the influence of Le Fort I osteotomy on the width of the nose at the alar base was assessed in 60 patients that underwent bimaxillary surgery. Despite using different closing sutures, the VY closure and alar cinch technique, widening of the alar base width was perceived, with an absolute mean of 1.6 ± 1.1 mm. The 3D cephalometric analysis of the simulation versus the actual postoperative results showed a mean absolute error of 1.0 ± 0.9 mm. A lack of correlation between the simulation error of alar widening and maxillary advancement was found, which seems to indicate that the MTM model used in this study was unable to simulate the correct relationship between postoperative alar changes and maxillary displacement and is therefore unsuitable for soft tissue prediction of the nasal region.

In 2014, a new 3D photogrammetry-based automated method for quantifying variations in soft tissue facial profiling using principal component analysis (PCA) was developed in the department of oral and maxillofacial surgery at Radboudumc to evaluate surgical related facial soft tissue changes. PCA is applied to reduce complex data in simplified structured patterns and is a commonly used tool in modern data analysis. It is based on statistical simulation rather than biomechanical models. The model is presented in **Chapter 5**. The PCA model can automatically quantify the facial appearance of the chin region of dysgnathic patients compared to a large group of controls. In this way, the effects of orthognathic surgery on the soft tissue facial profile can be evaluated. The effect of BSSO advancement surgery on the facial profile of Class II patients in comparison to a control sample of the Dutch population with a Class I facial profile was assessed using PCA. 3D photographs of 25 female patients that underwent a BSSO and 70 female controls were acquired. The specific facial variations were defined as unique variations and the effect of each unique variation (UV) on the soft tissue facial profile was investigated. The UVs that described the variations in the retrusion of the mandible were used to distinguish patients with mandibular hypoplasia from the control population. A clockwise rotation of the mandible and a shortening of the lower part of the face were the most prominent differences between the two groups (UV1). A protrusion of the upper lip and a retrusion of the mandible were observed among the preoperative BSSO patients compared to the control group. Consequently, an over-accentuation of the labial-mental fold was present in the preoperative BSSO patient group compared to the control group. This morphological variation was defined as UV2. For all subjects the scores for UV1 and UV2 were calculated, the effect of BSSO advancement surgery was evident. The postoperative group of BSSO patients had shifted towards the control group compared to the preoperative situation. However, the postoperative group did not overlap the control group completely, indicating that many BSSO patients maintained some characteristics of Class II facial profile despite having had the surgery.

In the past, cephalometric landmarks were used to evaluate the accurate transfer of 2D and 3D planned bony movements to the actual postoperative result. However, this method is based on identifying the same landmarks multiple times which leaves room for error. It therefore impedes a correct interpretation of the analysis and the actual difference between the preoperative (3D) planning and postoperative outcome. **Chapter 6** presents the OrthoGnathicAnalyser (OGA), a novel tool to quantify the displacement of bony segments in orthognathic surgery. Pre- and postoperative CBCT scans of ten patients who underwent bimaxillary surgery were acquired. To calculate the skeletal discrepancies between the 3D planning and the actual surgical outcome, the jaws were segmented and superimposed upon the postoperative maxillary and mandibular segments using voxel-based registration. This innovative method of quantifying the surgical displacement of jaw segments in six degrees of freedom (sagittal, vertical, and transverse translations, and pitch, roll, and yaw) was highly reproducible (intraclass correlation coefficients > 0.97). By using the OGA, the skeletal discrepancies between 3D planning and the surgical outcome can be objectified, which eliminates the need to identify cephalometric landmarks multiple times.

Using the OGA, the effect of sequencing on the predictability of bimaxillary surgery could be objectively assessed. In **Chapter 7**, 116 patients undergoing bimaxillary surgery were appraised, where 58 patients were operated on with a maxilla-first approach, and 58 patients had the mandible surgical procedure before the maxillary surgical procedure. It was found that the achievability of the anterior displacement of the maxilla was significantly higher in the maxilla-first group (0.5±2.5 mm) than in the mandible-first group (2.0±1.9 mm, $p<0.01$). **Chapter 8** evaluates the postoperative skeletal stability one year following bimaxillary surgery in the same study cohort between the maxilla-first and mandible-first approaches. No significant differences were found in relapse between the maxilla-first or mandible-first groups. The study showed that the mean sagittal, vertical, and transverse relapse was less than 1.8 mm, which is consistent with previous findings.

Chapter 9 evaluates the effects of sequencing in bimaxillary osteotomies in the study population of chapters 7 and 8 pooled with similar data from the Oral and Maxillofacial Surgery Research Unit at the University of Southern Denmark in Odense. The main conclusions of the chapter were that the maxilla-first sequencing was generally centered closer around the planned reposition than the mandible-first, while the mandible-first approach resulted in a significantly better AP position of the maxilla when an impaction of the maxilla was planned. Surgical accuracy of the maxilla for CCW or CW rotation was not statistically significantly influenced by sequencing.

This thesis investigates the additional value of 3D preoperative planning and the postoperative 3D evaluation of the achieved surgical results. With 3D simulation, orthognathic surgery has become more accurate and predictable. Throughout this thesis, it became more and more clear that 3D simulation has become indispensable in orthognathic surgery, and indeed has now become the gold standard.

Samenvatting

Talloze technologische ontwikkelingen hebben de afgelopen decennia de moderne geneeskunde beïnvloed. Een van de belangrijkste ontwikkelingen binnen de orthognatische chirurgie is de mogelijkheid om het gehele hoofd, in verschillende lagen, in 3D te visualiseren. Deze technologie brengt een aantal voordelen met zich mee, waarvan 3D preoperatieve planning en 3D postoperatieve evaluatie de meest relevante zijn. Het hoofddoel van deze thesis is om te onderzoeken hoe 3D planningen binnen orthognatische chirurgie de voorspelbaarheid en chirurgische resultaten hiervan kunnen verbeteren.

In **hoofdstuk 1** worden in een algemene introductie de klinische en technologische aspecten binnen de huidige 3D orthognatische planning besproken. Om een virtueel 3D hoofd te creëren moeten benige structuren, weke delen en dentitie gevisualiseerd worden. Hiervoor worden verschillende 3D beeldvormingstechnieken gebruikt. De verkregen informatie wordt gecombineerd met *image fusion techniques* in orthognate softwareprogramma's. De basis van het virtuele model wordt gelegd met cone-beam computed tomography (CBCT), deze techniek geeft informatie over de benige structuren en de dikte van de weke delen. Wanneer CBCT gecombineerd wordt met stereophotogrammetry - een 3D kleurenfoto van de weke delen - en een eventuele intra-orale scan van de tanden, kan een virtueel 3D hoofd gecreëerd worden. Op dit virtuele hoofd kunnen virtuele osteotomieën (Le Fort 1, bilaterale sagittale splijtings-osteotomie (BSSO), genioplastiek) uitgevoerd worden waarin alle segmenten van de kaken in elke richting verplaatst kunnen worden. Met het gebruik van verschillende biomechanische modellen kunnen deze virtuele osteotomieen en de gevolgen ervan op de weke delen real-time gesimuleerd worden.

In **hoofdstuk 2** wordt de nauwkeurigheid van het Mass Tensor Model (MTM) algoritme, dat gebruikt wordt in Maxilim® software (Medicim NV, Mechelen, België) onderzocht. Van 100 patiënten die behandeld zijn met een BSSO zijn pre- en postoperatieve CBCT-scans verzameld. 3D distance-maps en 3D cephalometrische analyses zijn gebruikt om verschillen tussen de simulatie en de werkelijk behaalde postoperatieve uitkomsten van de weke delen te berekenen. Voor het volledige gezicht werd een gemiddeld absolute fout van 0.9±0.3 mm gevonden, het gemiddelde absolute 90^{e} percentiel was 1.9 mm. Het meest voorspelbare deel van het gezicht was de kin met een gemiddelde absolute fout van 0.8±0.5 mm. De onderlip is het minst voorspelbare gebied van het gezicht, met een gemiddelde absolute fout van 1.2±0.5 mm. Zoals ook blijkt uit eerdere studies zijn de lippen het gebied dat het moeilijkst te voorspellen is.

De aan- of afwezigheid van orthodontische apparatuur en de moeilijkheid om bij de pre- en postoperatieve CBCT's dezelfde hoeveelheid lipspanning te krijgen bij patiënten, kunnen een verklaring zijn voor de pre- en postoperatieve verschillen.

In **hoofdstuk 3** wordt een vergelijkbare studie beschreven. Bij 60 patiënten die een bimaxillaire osteotomie ondergingen werd de nauwkeurigheid van het voorspellen van de weke delen verplaatsing met het MTM-algoritme ten opzichte van de postoperatieve resultaten onderzocht. De methodologie van hoofdstuk 2 volgend, werd voor het volledige gezicht een gemiddelde absolute fout van 0.81±0.22 mm gevonden. De simulatie van de weke delen bleek het meest nauwkeurig in de regio van de bovenlip (1.2±0.6 mm) en het minst nauwkeurig in de regio van de onderlip (1.4±0.5 mm). Een belangrijke conclusie van de studie was dat bij een grotere verplaatsing de uitkomsten minder voorspelbaar zijn.

In **hoofdstuk 4** wordt een ander centraal esthetisch deel van het gezicht, de alar basis, beoordeeld in hetzelfde studie cohort. Ondanks het gebruik van verschillende sluitingstechnieken - de VY closure and alar cinch technique - werd bij alle patiënten de alar basis breder, met een absoluut gemiddelde van 1.6±1.1 mm. De gemiddelde absolute fout van de 3D chephalometrische simulatie ten opzichte van de postoperatieve resultaten bedroeg 1.0±0.9 mm. Dit lijkt erop te wijzen dat het in deze studie toegepaste MTM algoritme niet in staat is om de relatie te leggen tussen de postoperatieve verandering van de alar basis en de maxillaire verplaatsing. Het is daarmee ongeschikt om de verandering van de weke delen in het gebied van de neus te voorspellen.

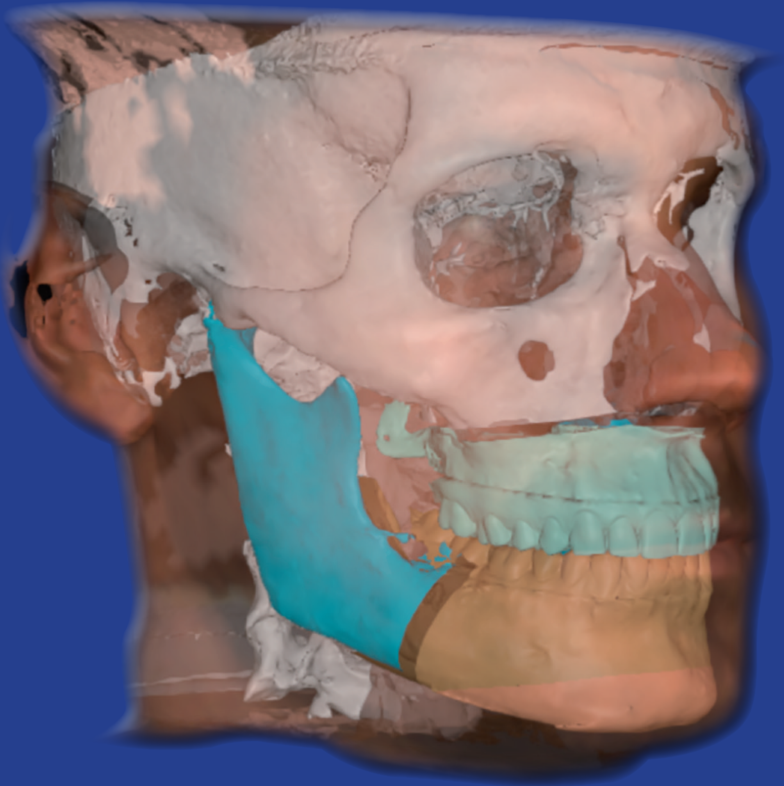
In 2014 werd op de afdeling Mond-, Kaak- en Aangezichtschirurgie van het Radboudumc een nieuwe methode ontwikkeld voor het kwantificeren van variaties in het weke delen profiel van het gezicht op basis van 3D-fotografie. In deze methode wordt principal component analysis (PCA) gebruikt om complexe data te reduceren naar versimpelde gestructureerde patronen, dit wordt veelvuldig toegepast in moderne data-analyse. PCA is gebaseerd op statistische simulatie, in plaats van op biomechanische modellen, zoals bijvoorbeeld het eerder gebruikte MTM. In **hoofdstuk 5** wordt dit model gepresenteerd. Het effect van BSSO-chirurgie op het profiel van het gezicht in klasse II patiënten wordt vergeleken met een controlegroep van klasse I proefpersonen middels PCA. 3D foto's van 25 vrouwelijke patiënten die een BSSO hadden ondergaan en van 70 vrouwelijke controles zijn gemaakt. Het effect van BSSO-chirurgie op het gezichtsprofiel werd geëvalueerd en gekwantificeerd met behulp van PCA. De methode was in staat de behandelde patiënten te onderscheiden van de controlegroep. Op basis van deze toegepaste PCA-methode werd zichtbaar dat patiënten die een BSSO hadden ondergaan in de meeste gevallen slechts een suboptimale verbetering van het gezichtsprofiel hadden gekregen.

Cephalometrische oriëntatiepunten zijn voorheen het meetinstrument geweest waarmee de geplande benige verplaatsing postoperatief kon worden geëvalueerd ten opzichte van het werkelijk behaalde resultaat. Deze methode is gebaseerd op het meerdere keren identificeren van hetzelfde oriëntatiepunt, waarna het oriëntatiepunt wordt bepaald op basis van het gemiddelde hiervan, wat ruimte laat voor onnauwkeurigheid binnen de methode zelf. Het hindert de correcte analyse van het daadwerkelijke verschil tussen preoperatieve (3D) planning en postoperatieve uitkomsten. In **hoofdstuk 6** wordt de OrthoGnathic Analyser (OGA) gepresenteerd; een nieuwe tool om de verplaatsing van benige structuren in orthognatische chirurgie te kwantificeren. Van tien patiënten welke een bimaxillaire osteotomie ondergingen, werden pre- en postoperatieve CBCT-scans vergaard. De kaken werden gesegmenteerd en gesuperponeerd op postoperatieve maxillaire en mandibulaire segmenten, gebruik makend van voxel-based registration, om de benige verschillen tussen 3D planning en werkelijke chirurgische uitkomst te berekenen. Deze innovatieve methode van het kwantificeren van chirurgische verplaatsingen in *six degrees of freedom* (sagitaal, verticaal en transversale translaties, en pitch, roll en jaw) heeft een hoge intraclass-correlation coefficient van >0.97. De hoge reproduceerbaarheid van OGA maakt het een betrouwbare manier om benige verschillen tussen 3D planning en chirurgische uitkomsten te objectiveren en maakt hiermee het gebruik van cephalometrische oriëntatiepunt identificatie overbodig.

Door gebruik van deze nieuwe methode kon het effect van volgorde van kaakverplaatsing (maxilla eerst versus mandibula eerst) in bimaxillaire chirurgie objectief onderzocht worden. Een cohort van 116 patiënten (58 maxilla-eerst, 58 mandibula-eerst geopereerd) dat bimaxillaire chirurgie onderging wordt onderzocht met OGA in **hoofdstuk 7**. De haalbaarheid van de anterieure verplaatsing van de maxilla bleek significant hoger te zijn in de maxilla-eerst groep ten opzichte van de mandibula-eerst groep, 0.45±2.52 mm versus 1.97±1.86 mm ($p<0.01$). In **hoofdstuk 8** wordt hetzelfde cohort één jaar postoperatief met OGA geanalyseerd om de verschillen in benige stabiliteit te onderzoeken. Er werden geen significante verschillen gevonden in stabiliteit tussen de mandibula-eerst en de maxilla-eerst groep. De studie liet een gemiddelde sagittale, verticale en transversale terugval zien van minder dan 1.8 mm, wat een vergelijkbare uitkomst is met eerdere studies.

Hoofdstuk 9 beschrijft de effecten van volgorde van kaakverplaatsing in bimaxillaire osteotomieën van de gebruikte data in hoofdstukken 7 en 8, samengevoegd met vergelijkbare data van de afdeling Mond-, Kaak- en Aangezichtschirurgie van de Odense Universiteit in Denemarken. Een belangrijke conclusie van het artikel is dat het postoperatieve resultaat van maxilla-eerst verplaatsen over het algemeen dichter bij de geplande repositie lag dan wanneer mandibula-eerst werd geopereerd. De mandibula-eerst benadering is echter significant beter in anterieure en posterieur positie van de maxilla wanneer impactie van de maxilla gepland werd. Wanneer een mandibula-eerst of maxilla-eerst benadering gekozen moet worden, moet dit altijd besloten worden op basis van de geplande verplaatsing.

In deze thesis is de toegevoegde waarde van 3D preoperatieve planning en postoperatieve 3D evaluatie op basis van uitkomsten van uitgevoerde ingrepen onderzocht. Met de komst van 3D simulatie is orthognatische chirurgie nauwkeuriger en voorspelbaarder geworden en dit biedt de patiënt betere functionele en esthetische chirurgische uitkomsten. Gedurende de totstandkoming van deze thesis werd steeds duidelijker dat 3D simulatie onmisbaar zal worden in orthognatische chirurgie en ondertussen eigenlijk al geldt als de gouden standaard.



Dankwoord

Dankwoord

Geen enkel proefschrift wordt enkel en alleen geschreven. Iedereen die in meer of mindere mate heeft bijgedragen aan dit proefschrift wil ik graag via deze weg bedanken.

Ik ben Prof. dr. S. Bergé en Prof. dr. T. Maal, mijn promotoren, en dr. T. Xi co-promotor, erkentelijk voor hun begeleiding en bijdrage om dit proefschrift tot een goed einde te brengen. Daarnaast dank ik ook alle co-auteurs voor hun bijdragen.

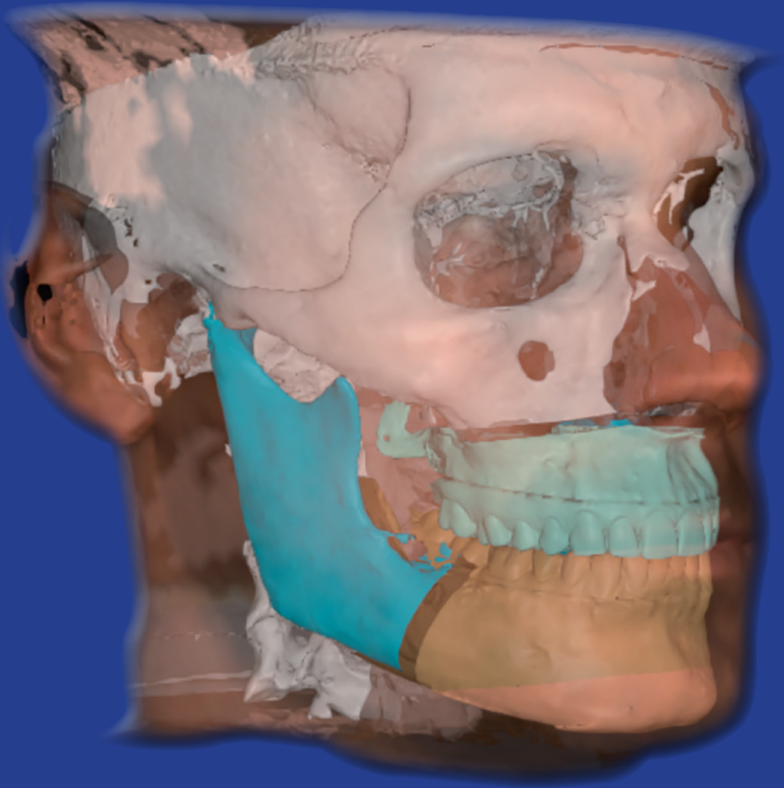
Mijn paranimfen drs. Baan en dr. Klijn hebben mij bijgestaan tijdens de laatste loodjes van dit proefschrift, waar ik hun erg dankbaar voor ben.

Tevens ben ik dankbaar voor alle steun van mijn partner, familie, vrienden en collega’s, die mij mogelijk met enige regelmaat hebben moeten ontberen tijdens het maken van dit proefschrift.

Tot slot wil ik in het bijzonder de MKA en het 3Dlab van het Radboudumc bedanken, zonder hun inzet was dit onderzoek niet mogelijk geweest.

Curriculum Vitae

Jeroen Henricus Franciscus Liebregts werd geboren op 15 februari 1987 in Oisterwijk, waar hij ook opgroeide. Na het behalen van zijn VWO-diploma aan 2College Durendael te Oisterwijk in 2006 begon hij aan de opleiding tandheelkunde aan de Radboud Universiteit Nijmegen, die hij in 2011 voltooide. Hij startte aansluitend met de opleiding geneeskunde, eveneens aan de Radboud Universiteit Nijmegen, waarna hij in 2015 zijn artsendiploma behaalde. In het voorjaar van 2016 startte hij met de specialisatie Mondziekten, Kaak- en Aangezichtschirurgie en deze opleiding werd eind maart 2020 afgerond. Opeenvolgend werd hij staflid van de afdeling MKA in het Radboudumc en sinds 1 april 2021 is hij benoemt tot hoofd van het Centrum voor Bijzondere tandheelkunde van het Radboudumc. Al tijdens de opleiding geneeskunde werd gestart met het promotietraject met de titel "3D Surgical Planning in Orthognathic Surgery" onder begeleiding van prof. Bergé, prof. Maal en dr. Xi. De resultaten van zijn promotietraject resulteerden in tientallen wetenschappelijke publicaties in peer-reviewed journals. Tevens zijn de onderzoeksresultaten door Jeroen gepresenteerd op verschillende nationale en internationale congressen.



Portfolio

LIST OF PUBLICATIONS

DM. Beek, F. Baan, J. Liebregts, S. Bergé, T. Maal, T. Xi. Surgical accuracy in 3D planned bimaxillary osteotomies: intraoral scans and plaster casts as digital dentition models, International Journal of Oral and Maxillofacial Surgery, 2021, doi.org/10.1016/j.ijom.2021.11.016.

Vinayahalingam S, Claeys G, Liebregts J, Maal T, Bergé S, Xi T. Does distractor design influence the risk of asymmetric palatal expansion?" *Submitted and in revision: Orthodontics and Craniofacial Research 2020*

Stokbro K, Liebregts J, Baan F, Bell RB, Maal T, Thygesen T, Xi T. Does Mandible-First Sequencing Increase Maxillary Surgical Accuracy in Bimaxillary Procedures? J Oral Maxillofac Surg. 2019 Sep;77(9):1882-1893. doi: 10.1016/j.joms.2019.03.023. Epub 2019 Apr 4.

Liebregts J, Baan F, van Lierop P, de Koning M, Bergé S, Maal T, Xi T. One-year postoperative skeletal stability of 3D planned bimaxillary osteotomies: maxilla-first versus mandible-first surgery. Sci Rep. 2019 Feb 28;9(1):3000. doi: 10.1038/s41598-019-39250-x.

Van den Bempt M, Liebregts J, Maal T, Bergé S, Xi T. Toward a higher accuracy in orthognathic surgery by using intraoperative computer navigation, 3D surgical guides, and/or customized osteosynthesis plates: A systematic review. J Craniomaxillofac Surg. 2018 Dec;46(12):2108-2119. doi: 10.1016/j.jcms.2018.10.012. Epub 2018 Oct 21.

Liebregts J, Baan F, de Koning M, Ongkosuwito E, Bergé S, Maal T, Xi T. Achievability of 3D planned bimaxillary osteotomies: maxilla-first versus mandible-first surgery. Sci Rep. 2017 Aug 24;7(1):9314. doi: 10.1038/s41598-017-09488-4.

Baan F, Liebregts J, Xi T, Schreurs R, de Koning M, Bergé S, Maal T. A New 3D Tool for Assessing the Accuracy of Bimaxillary Surgery: The OrthoGnathicAnalyser. PLoS One. 2016 Feb 22;11(2):e0149625. doi: 10.1371/journal.pone.0149625. eCollection 2016.

Liebregts J, Xi T, Schreurs R, van Loon B, Bergé S, Maal T. Three-dimensional virtual simulation of alar width changes following bimaxillary osteotomies. Int J Oral Maxillofac Surg. 2016 Oct;45(10):1315-21. doi: 10.1016/j.ijom.2016.05.012. Epub 2016 Jun 3.

Meulstee J, Liebregts J, Xi T, Vos F, de Koning M, Bergé S, Maal T. A new 3D approach to evaluate facial profile changes following BSSO. J Craniomaxillofac Surg. 2015 Dec;43(10):1994-9. doi: 10.1016/j.jcms.2015.08.007. Epub 2015 Sep 12.

Liebregts J, Xi T, Timmermans M, de Koning M, Bergé S, Hoppenreijs T, Maal T. J Accuracy of three-dimensional soft tissue simulation in bimaxillary osteotomies. Craniomaxillofac Surg. 2015 Apr;43(3):329-35. doi: 10.1016/j.jcms.2014.12.012. Epub 2014 Dec 30.

Liebregts JH, Timmermans M, De Koning MJ, Bergé SJ, Maal TJ. Three-dimensional facial simulation in bilateral sagittal split osteotomy: a validation study of 100 patients. J Oral Maxillofac Surg. 2015 May;73(5):961-70. doi: 10.1016/j.joms.2014.11.006. Epub 2014 Nov 20.

Presentations and lectures

Sept. 2018: 3D planned bimaxillary osteotomies: maxilla first or mandible first? EACMFS congress Munich-Germany.

Okt. 2016: TEDtalk nauwkeurigheid van 3D weke delen simulatie na bimaxillaire osteotomie. NVMKA-congres Utrecht.

Okt. 2016: 3D evaluatie van bimaxillaire osteotomie: mandible of maxilla first?

Mei 2015: 3D Gezichtssimulatie bij een BSSO; een validatie studie van 100 patiënten. NVMKA-congres Rotterdam.

April 2018: Symposium; MKA chirurg als MKB ondernemer

Feb. 2019: European Rhinoplasty Course

April 2019: Updates and controversies in Advanced Oral and Maxillofacial Surgery, S.O.R.G.

Nov. 2019: Facial reconstruction, Arnett, Gunson

Training and Teaching activities

	Year(s)	ECTS
TRAINING ACTIVITIES		
a) Courses & Workshops		
– eBROK Course	2015	1.5
– Introduction Day Radboudumc	2016	0.25
– Scientific Integrity Course (all PhD’s)	2016	1
– Radiation Safety Course – Level 4A/M	2016	2
– Optimisation in CMF trauma care	2016	1
– Cursus Hoofdzaken	2016-2019	2
– Hands- on Workshop Saggitale Ramus osteomie	2018	0.4
– Biennial Symposium Surgical Orthodontics	2019	1
– Hands- on Workshop: anatomie van het hoofd- halsgebied	2019	1
– MKA junior implantologie studieclub	2019	1
– EAO congress	2019	1
– ALS course Radboudumc	2020	0.2
b) Seminars & lectures		
– Radboud Research Rounds	2016-2018	0.2
– Research meetings of the Department of OMF surgery	2015-2021	1
c) Symposia & congresses		
– Annual conference NVMKA*	2015-2018	2
– 9th Congres of the European Pain federation (Wien)	2015	2
– EACMFS congress Munich-Germany*	2018	2
– Update in Advanced Oral and Maxillofacial Surgery S.O.R.G.	2019	4.5
– European Rhinoplasty Course	2019	2
– Facial reconstruction Arnett, Gunson USA	2019	4.5
d) Other		
– Peer Review Scientific Papers	2019-2020	0.1
– Teaching	2016-2021	1
TEACHING ACTIVITIES		
e) Lecturing		
– Onderwijs LOVAH	2020	0.1
– KIO orthognathic surgery	2020	0.1
f) Supervision of internships / other		
– Pieter van Lierop	2017	1
– Jacelyn Rooyer	2018	1
– Theresa Leow	2019	1
– Shankeeth Vinayahalingam	2020	1
– Guido Kielenstijn	2021	1
TOTAL		**36.65**

Research and data management

Various studies in this thesis used patient data. Those studies were conducted in accordance with the principles of the Declaration of Helsinki. Patient consent was obtained if required. The medical ethics committee on Research Involving Human Subjects region Arnhem-Nijmegen has given approval to conduct the studies (file number: #181/2005).

The projects are stored on the Radboudumc department servers of the mond-, kaak- en aangezichtschirurgie. The privacy of the participants in this study is warranted by use of encrypted and unique individual subject codes. The software code that was developed and used in this thesis was stored separately from the study data on the department server. The data will be saved for 15 years after termination of the study concerned. The data sets analysed during these studies are available from the corresponding author on reasonable request.