Title:

Numerical study of the impact of osteotomies and distractor location in surgically assisted rapid palatal expansion for transverse maxillary deficiency.

STATEMENT OF CLINICAL RELEVANCE

SARPE procedures (distractor and osteotomy positions) can be tailored based on desired outcomes. Higher lateral osteotomies lead to increased displacements, and more posterior distractors to more parallel expansion. Pterygomaxillary disjunction reduces stress in the maxillofacial complex.

HIGHLIGHTS

- Performance of a pterygomaxillary disjunction results in reduced posterior stress
- The higher the lateral osteotomy the larger the displacements
- Moving the palatal distractor more posteriorly results in more a parallel expansion

ABSTRACT

Introduction: This paper employs finite element analysis to assess the biomechanical behavior of surgically assisted rapid palatal expansion (SARPE) with a bone-borne transpalatal distractor (TPD) by varying surgical parameters.

Material and Methods: Nine models were constructed to scrutinize the effects of pterygomaxillary disjunction (PMD), lateral osteotomy positioning, and TPD placement on displacement profiles and Von Mises stresses. These models encompassed variations such as no, unilateral or bilateral PMD, asymmetrical lateral osteotomy, and five TPD locations.

Results: Performing a PMD reduces posterior resistance to transverse expansion, resulting in 10-20% stress reduction around the maxillofacial complex. No significant changes in horizontal tipping were observed post-PMD. The asymmetric lateral osteotomy model exhibited larger displacements on the side with a more superiorly positioned osteotomy. Reduced stresses were observed at the maxillary body and medial pterygoid plate (superiorly), while increased stresses were observed at the medial (inferiorly) and lateral pterygoid plates. More posterior TPD placement facilitated more parallel expansion thus less horizontal tipping, albeit with increased vertical tipping.

Discussion: SARPE procedures (distractor and osteotomy positions) can be tailored based on desired outcomes. PMD reduces stress within the maxillofacial complex but doesn't significantly affect tipping. Higher lateral osteotomies lead to increased displacements, more posterior distractors to more parallel expansion.

Keywords: Maxillary expansion, SARPE, Transverse maxillary deficiency, FEA, Bone-borne transpalatal distractor

Abbreviations: FEA (finite element analysis), SARPE (surgically assisted rapid palatal expansion), PMD (pterygomaxillary disjunction**),** TPD (Transpalatal Distractor), ORPE (orthodontic rapid palatal expansion), CT (computed tomography), STL (stereolithography)

1. INTRODUCTION

Transverse maxillary deficiency (TMD) is a common facial deficiency characterized by a narrow maxilla, a high palatal vault, crowded maxillary teeth and a uni- or bilateral crossbite. The deficiency may contribute to the development of persistent mouth breathing, crowding of the maxillary teeth, nose breathing problems and sleep apnea syndrome (1, 2). To correct these deficits, two types of maxillary expansion treatments are used: orthodontic rapid palatal expansion (ORPE) and surgically assisted rapid palatal expansion (SARPE) (1, 2). A transpalatal distractor (TPD) can be either tooth or bone born. Both are based on expansion of the midpalatal suture. The ossification and interdigitation process of the latter, varies greatly with age and sex of the patient. Mostly around the age of fifteen years, the midpalatal suture has matured, resulting in an increased resistance against transversal expansion (3). This decreases the elasticity of the facial skeleton and the possibility for orthodontic expansion. When the midpalatal suture has matured, nonsurgical orthodontic treatment would result in unpredictable expansion and a series of unwanted effects: lateral tipping of the teeth (tooth-borne expansion), alveolar bone bending, instability of the expansion among other complications (1, 4).

In skeletally mature patients, SARPE is required to temporarily interrupt the key resisting elements (facial buttresses) of the midfacial skeleton. In this way, the maxilla can be expanded in a more predictable manner with the use of lower forces (6). The piriform aperture pillars (anterior support), the ossified midpalatal suture (median support), the zygomaticomaxillary (lateral support) and pterygomaxillary (posterior support) buttresses form the main resistances to the transversal displacement of the maxilla (7). The optimal SARPE treatment modality is patient specific and depends on the personal experiences of the clinician, the maturation stage of the sutures and the magnitude of the required expansion (5).

There is no consensus in literature on the optimal set of osteotomies, neither on the exact influence each osteotomy has on the expansion profile (8). Due to mechanical complexity of the stomatognathic system, ethical issues, and inability to examine the mechanical properties of the human skeleton in vivo, it is very difficult to gain more insight in the biomechanical behavior of the maxillofacial complex. Therefore, finite element analysis (FEA) has been embraced in maxillofacial surgery research (9). No FEA has yet been performed on the use of an asymmetric surgery, such as a one-sided pterygomaxillary disjunction (PMD) or superoinferior variations of the lateral osteotomy, although these variables could impact the success of the procedure.

We aimed to evaluate the influence of surgical variations of the SARPE procedure using a TPD device. The influence of the position of the osteotomies, the position of the TPD and the addition of a pterygomaxillary osteotomy on the expansion profile and stress distribution in the craniofacial complex is investigated.

2. MATERIALS AND METHODS

A 3D model was constructed from a computed tomography (CT) scan of a skull from an anonymized patient who required the SARPE procedure. Segmentation of the CT scan was performed using MIMICS software (version 23.0; Materialise, Leuven, Belgium). The segmented anatomical structures were exported in 3-MATIC software (version 15.0; Materialise, Leuven, Belgium) in the STL format. A cephalometric analysis was performed according to the definitions of Swennen (10) to obtain the correct maxillofacial landmarks and the anatomical planes, which were required to define the different osteotomies. Locally at the maxilla, the sphenoid bone and the frontal part of the facial bones, a surface mesh with elements of 1 mm was chosen. The other parts of the cranium were meshed with elements of 4 mm in size, to preserve the computational efficiency. Using this surface mesh, a high-quality volumetric mesh (10-node quadratic tetrahedral elements C3D10) was created, which resulted in a dense mesh consisting of over 2.3 million elements. A mesh convergence study confirmed the proper choice of element type and size. Next, the material properties were assigned according to Lee and al. (11). The thickness of the cortical shell of the maxilla was determined according to the study by Peterson (12). All materials were assumed to be linear elastic, isotropic, and homogeneous.

A coordinate system was set up to refer to all displacements. This coordinate system has an origin at the posterior nasal spine. The x-axis was defined along the midpalatal suture (anteroposterior direction), the y-axis was then constructed in the transversal direction (laterolateral direction) perpendicular to the x-axis and parallel to the posterior border of the palatal bone. Finally, the z-axis was constructed in the superoinferior direction perpendicular on the x and y axes. Positive values were defined in the anterior, right, and superior direction respectively. Using this newly defined coordinate system, the displacements could be transformed from the general coordinate system to this user-defined local coordinate system.

In all the simulations, a TPD was simulated based on the TPD NEO distractor designed by Surgi-Tec (Sint-Denijs-Westrem, Belgium). The TPD was mimicked in ABAQUS (DASSAULT SYSTEMES, Velizy- Villacoublay, France) using an axial connector with constraints constructed between indicated reference points on the alveolar ridge, corresponding to the fixation of the TPD to the alveolar bone. The reference points were connected to each other with a wire feature, allowing to attribute an axial connector, which can model the expansion process. The axial connector results in a force if a displacement is imposed (spring behavior) (Figure 1).

The connection between these reference points and the alveolar ridge was constructed using a MPC – beam constraint. This type of constraint provides a rigid beam between nodes to constrain the displacement and rotation at the first node (palatal distractor) to the displacement and rotation of the secondary nodes (positioned at the alveolar ridge). The nodes at the alveolar ridges were chosen such that the area is corresponding to the area of a fixation plate.

The distractor (wire feature) was activated 5 mm in a latero-lateral direction (Y). As suggested by Gautam et al. (12), several nodes around the foramen magnum were completely fixed in all directions."

Multiple osteotomy variants and combinations are performed on the models. In Figure 2, the different possible osteotomy lines are demonstrated schematically. The lateral (red), vertical (blue), median (yellow) and pterygoid (white) osteotomies can be performed on the model. Using this set of osteotomies, several models can be created, depending on the required analysis.

The obtained FEA model was first validated by recreating finite element studies found in literature by Lee and al. (11) and Möhlenrich (13). The model was then further verified by comparing the obtained results to the contemporary literature. After validation of our FEA model, the effect of three variables was analyzed: the influence of the PMD, the presence of a more superior located lateral osteotomy on one side, and the variation of TPD location.

Pterygomaxillary disjunction models: In total, three models were analyzed: a model without a pterygomaxillary disjunction, a model with a unilateral PMD (left side) and a model with bilateral PMDs. On all models, the lateral, vertical, and median osteotomies were performed as well. The TPD was modeled between the second premolars and an expansion of 5 mm was simulated.

Superior lateral osteotomy models: The location where the lateral osteotomy can be positioned is restricted by several limitations. The osteotomy needs to be at least 5 mm superior of the apex of the canine, to avoid damaging the teeth and at least 5 mm inferior of the infraorbital foramen. Taking these limitations into account, a model was created where the most inferior location was chosen on one side (left) and on the most superior location on the other side (right). These osteotomy lines are theoretical rather than practical surgical osteotomy lines. In Figure 3, both the symmetrical and asymmetrical lateral osteotomy are illustrated. The palatal distractor was modeled between the second premolars, and again an expansion of 5 mm was simulated.

Variation in the TPD location models: Five models were constructed. Four symmetric expansions were performed where the distractor is installed at four different locations: both at the first and second premolar and at the first and second molar (Figure 3). Next to these four symmetrical simulations, another simulation was performed where the distractor was installed at the second premolar site with a small inferior deviation of 2 mm with respect to the symmetric case. This model was created to check if the accuracy of the surgeon during positioning of the TPD has a significant impact on results and outcome. Again, a transverse displacement of 5 mm was imposed for all simulations.

Using these models, the influence of the pterygoid disjunction, the presence of asymmetries in the lateral osteotomies and the effect of the TPD location could be analyzed. The net displacements in millimeters and Von Mises stresses were evaluated at each tooth position on the palatal side of the alveolar bone. Tooth position T1 was given to the position at the central incisor running up to T7 at the position of the second molar (Figure 4). Furthermore, tipping behavior in the frontal and axial plane was evaluated. Horizontal tipping (axial plane) can be defined as a transverse expansion where expansion is lesser or greater in the anterior part compared to the posterior part of the maxilla, resulting in a V-formed expansion profile. Similar for vertical tipping (frontal plane), unequal expansion in the upper and lower region of the maxilla results in a V-formed expansion. Von Mises stresses are a theoretical value which allows to make a comparison between a multi-axial stress and a uniaxial tensile stress.

3. RESULTS

A. Pterygomaxillary disjunction

The results measured at the alveolar bone are shown in Table I. On average, the expansion on the right side was 52.3%, 51.3% and 56.3% for respectively the symmetric, unilateral and bilateral PMD models. More pronounced differences for the unilateral pterygoid disjunction model were present for the most posterior measurement point. By performing the PMD, posterior resistance against the expansion was removed, and more expansion occurred.

Subsequently, the influence of the pterygoid disjunction on the horizontal tipping behavior was measured. Small opening angles were measured in all models. The smallest opening angle was 5.82°, obtained when the PMD was performed bilaterally, without the PMD an opening angle of 5.86° was obtained. The horizontal tipping was the largest when the PMD was only performed unilaterally, with an opening angle of 6.71°. Vertical tipping increased as the pterygoid plates were disjuncted, with values ranging from 6.13° for the model without PMD, 6.68° for the unilateral PMD and 7.42° for the bilateral PMD.

Next to the displacement measurements, the stresses were also measured at several maxillofacial landmarks. The model with the unilateral PMD had comparable stresses to the model without PMD on the side without the disjunction and to the model with bilateral PMD on the side with the disjunction. In this way, the results could be omitted from the analysis. By performing the PMD, a different stress distribution was observed. The anteriorly positioned maxillofacial landmarks (maxillary body, infraorbital margin, frontonasal suture) all showed reduced stresses, with reductions of 10 to 20%. At the maxillary tuberosity a reduction of 67% was observed, and an increase of 47.5% at the medial pterygoid plate (inferiorly measured). By performing the PMD, the stresses at the cranial foramina were lowered, with reductions of up to 32.1% at the optic foramen.

B. Superior lateral osteotomy

The results measured at the alveolar bone are shown in Table II. The total expansion was quite similar between the two models. However, due to the asymmetry in the lateral osteotomy, an imbalance was created in the amount of expansion on each side. The average relative amount of expansion on the right side was 52 % for the base model, and 60 % for the asymmetric lateral osteotomy model.

In the asymmetrical model more horizontal tipping was observed compared to the symmetrical model with an opening angle of 7.3° and 5.85° respectively. Considering vertical tipping, a smaller opening angle of 5.4° was observed in the asymmetric model compared to the symmetric model that had an opening angle of around 6.1°.

In Figure 5, the stresses at the several maxillofacial landmarks are reported. Large differences were observed between both models. A significant reduction (-87%) of the stresses at the body of the maxilla was observed. Slightly higher stress values were observed at the infraorbital margin. The zygomatic arch and the frontonasal suture showed reduced stresses. The views of the lateral pterygoid plates on both sides are shown in Figure 6. Together with the results depicted in Figure 5, the results show higher stresses at the pterygoid plates of the superiorly located osteotomy than those observed at the inferior osteotomy, especially at the lateral pterygoid plates.

C. TPD location

Changing the position of the palatal distractor resulted in different expansion profiles in transversal, horizontal and superoinferior direction. When taking a vector sum of these displacements the largest expansion was obtained when the distractor was positioned at the first molar. A V-shaped expansion in both the axial (horizontal tipping) and frontal plane (vertical tipping) occurred in all the models as illustrated in Table III. The opening angle in the axial plane was calculated by indexing the expansion at the level of the posterior nasal spine (PNS) and at the incisive foramen (For.Inc.) against the length of the palatum between these points. Parallelism was calculated using the following formula: $1 - \Delta u/u_{For.Inc.}$. ($u_{For.Inc.}$ the displacement at the For.Inc. and Δu the difference in displacement at the For.Inc. and PNS).

No difference between the tipping behavior was observed if the distractor was positioned at the first or second premolar. However, from this point on, if the device was positioned more posteriorly, the transversal expansion occured more parallel in the axial plane, thus less horizontal tipping was observed. Especially in the case where the device was positioned at the second molar, a higher degree of parallelism was obtained when compared to the other cases, with a profound reduction of difference in measurement at the incisive foramen and PNS.

Similar measurements and observations could be made for vertical tipping of the maxillary halves. To analyze the vertical tipping behavior, measurements of the transverse expansion were made at both the anterior nasal spine (ANS) and the central incisor (C.I.) (Table III). Vertical tipping of the maxillary halves was smaller than horizontal tipping. When the distractor was positioned at the first or second premolar or the first molar, similar results were obtained for the parallelism of the expansion. When the palatal distractor was positioned at the second molar, the opening angle increased and a more pyramidal shaped expansion in the frontal plane occurred.

The influence of a 2 mm deviation in inferior direction on one side of the alveolar bone was analyzed. No significant differences were reported between the two cases for displacements in the anterior and transversal directions and a similar overall expansion profile was obtained. The model with the inferior deviation showed smaller superior displacements, 0.02 mm less at the second molar position running up in anterior direction to 0.1 mm less at the central incisor position when compared to the base symmetric case.

Similar stress patterns occured for the premolar and molar 1 models, where the highest stresses occurred in the body of the maxilla. If the distractor was positioned at the second molar, the posterior maxillofacial landmarks showed higher stresses (lateral pterygoid plate, maxillary tuberosity …). The stresses in the body of the maxilla were then significantly reduced. The model with the small 2mm deviation inferiorly at the second premolar site showed no significant differences when compared to the model at the second premolar.

4. DISCUSSION

In literature different methods and outcomes have been described to surgically widen the maxillary complex as treatment for TMD (8). There is no clear consensus on the optimal set of osteotomies and their influence on the expansion profile (8). Using FEA, we created an in vitro model to evaluate different intra operative and surgical factors (with or without PMD, TPD location, asymmetrical surgery, and location of osteotomies) in order to unravel the biomechanical behavior of distraction movement.

The main rationale in literature to perform the PMD is to lower the horizontal tipping. The obtained results show small differences in this tipping behavior, which may be clinically irrelevant. These findings are in accordance with Möhlenrich et al. (14), who reported a more parallel transverse expansion when PMD was performed, however with few statistical differences. A FEA study performed by Holberg et al. (15) showed that the pterygoid disjunction generally reduced stresses at most anatomic structures of the midface. This is confirmed by the simulations performed in this FEA. With reduced stresses, the procedure might lead to an increased stability and more stable long-term results. For the maxillofacial landmarks considered in the study, a reduction of –0 - 20% was observed by Holberg et al. (15). In the models obtained in this simulation, the PMD led to a 15% decrease of stresses, with exceptions at the maxillary tuberosity (67%) and the medial pterygoid plate, measured inferiorly (47%).

The study by Holberg et al. (15) also showed significantly reduced stresses at the foramina of the cranial base after the PMD is performed, with significant reductions at the optic foramen. Lower stresses at the foramina of the cranial base, reduces the possibility of (mini)fractures and can avoid severe complications (15). In this study a reduction of 32.1% is observed at the optic foramen in the PMD model, whereas Holberg et al. (15) measured reductions up to 75%. Nevertheless, the same conclusion can be drawn: PMD allows for lower stresses at the cranial base, reducing the risk for (mini)fractures at the skull base.

Since the total expansion is the same in all the PMD models, the models can be compared to each other. In literature, the exact influence of the PMD remains unknown. Bays & Greco (16) reported a larger posterior expansion when the PMD was performed, whereas Han et al. (17) reported the opposite behavior. This indicates the uncertainty in literature concerning the exact influence of the PMD. Multiple variables such as sex, age, position of the distractor, distractor type and patient anatomy could influence the effect of PMD on the expansion. In this study only one anonymized CT-scan of a patient, who required the SARPE procedure, was selected (to reflect clinical relevance). Further research on multiple CT-scans could shed light on the effect of individual variations.

The model without PMD showed that a small asymmetry (52.3%) in expansion profile occurred on the right side. According to Koudstaal (18), this signifies a pre-existing imbalance in the equilibrium of the resisting forces of the maxillary segments. Different positions of the palatal distractor and/or the lateral osteotomy, as well as the presence of soft tissues, such as muscles and ligaments, can affect the resistance on each side. In this study, the influence of the surrounding soft tissues on maxillary expansion were not considered thus this asymmetry must solely be caused by asymmetries in maxillary segments and TPD placement. In our model with unilateral PMD, 51.3% of the expansion occurred at the right side; therefore, the effects for the unilateral PMD are small and may be clinically irrelevant.

In the model where the lateral osteotomy is positioned more superiorly, the total expansion at the midpalatal suture remains unchanged but a larger displacement was obtained at that side compared to the model with symmetrical lateral osteotomies. As the maxilla is osteotomized at a more superior location, a larger part of the maxilla is osteotomized, resulting in a lowered resistance against the transversal expansion and increased displacements at that side. According to Möhlenrich et al. (13), who investigated the influence of several osteotomies, the largest stress reduction is found when performing the lateral osteotomy. This indicates that the anterior piriform aperture pillars and the lateral zygomatic buttresses show the largest resistance against the transversal expansion. One could argue that variations in this lateral osteotomy could also lead to significant changes in the stress distribution. The results obtained in this study also confirm this.

The superoinferior placement of the lateral osteotomy has a significant influence on the stress distribution. Higher stress concentrations are observed at most of the pterygoid plates. A recommendation is made to separate the pterygoid plates if a more superiorly positioned lateral osteotomy is planned. In this way, the stresses at the pterygoid plates and the cranial foramina are reduced, and possible fractures at the pterygoid plates could be avoided. The interaction of the pterygoid plate disjunction together with the superior located lateral osteotomy is outside of the scope of this study and requires further research.

Only one study in literature describes the asymmetry between left and right maxillary segments in patients with a bone-borne distractor with PMD (19). Some factors that could influence the asymmetric behavior are mentioned: differences in the resistance of the soft tissues and alveolar bone, the placement of distractor and the orientation of the distractor in the frontal plane. According to Huizinga et al. (19), transversal asymmetry may occur when the palatal distractor is positioned obliquely in the frontal plane.

Moving the device more posteriorly to reduce horizontal tipping was suggested by Braun et al. (20), this theory is corroborated in our models with different TPD locations. By moving the palatal distractor more posteriorly, the moment-to-force ratio is reduced by decreasing the distance to the center of resistance, resulting in less rotational movement (20). Furthermore, Möhlhenrich et al. (13) found that the opening angle decreases with a more posterior placement of the distractor. However, no significant changes in the opening angle were reported in this study. An anterior V-shaped pattern resulted at the level of the premolars regardless of the surgical procedure (PMD) or the distractor position, which is in accordance with the results found in this study.

In our study an increase in opening angle and pyramidal shaped expansion in the frontal plane is found when the distractor is positioned at the second molar. Similar vertical tipping behavior is reported in literature, where Chamberland and Profitt (21) and Zandi et al. (22) observed similar behavior. According to Pinto et al. (23), the vertical tipping can be decreased by placing the distractor as cranially against the roof of the palatal vault as possible to decrease the moment lever arm.

The influence of a small deviation in the superoinferior direction was also modelled in our study. A deviation of 2 mm resulted in maximally 0.1 mm difference in superior displacement at the alveolar bone, which is clinically negligible. Ideally, the surgeons should try to position the implant as symmetrical as possible, however small deviations do not have a large influence on the general displacement profile.

This study was designed to evaluate the effect of surgical variations and TPD position on maxillary expansion by performing a SARPE procedure. Therefore, we chose to start with and focus on one patient and thoroughly document variations in one patient. Consequently, the study design has several limitations. Firstly, only one anonymized CT was analyzed, thus the effects of individually different maxillofacial segment dimensions are unclear as these could have influenced stress distribution. Secondly, our models were designed in the absence of correct (viscoelastic) material properties, as of right now, no reliable viscoelastic finite element model can be created since there are no viscoelastic properties for the maxilla and/or skull in the literature. The absolute values of the stresses therefore must be treated with care as some of the stresses in this study are above the yield strength of both cortical and trabecular bone. This can be attributed to viscoelasticity and gradual application of expansion forces not being considered in this model (in reality steps of 0.5 mm/day with in between relaxation are applied whereas in this model expansion was imposed in one step). As such, the results concerning the stresses can only be used to compare different cases against each other. Thirdly, soft tissue forces and the temporomandibular joint resisting expansion were not considered in our models (24, 25). In the palatal expansion location models, a direct comparison of the stress distribution cannot be made, as the different models represent a different physical expansion due to different distractor positions, resulting in different absolute displacements. The time dependency (and stress relaxation) of the distraction phase and the inclusion of soft tissues to the models could improve the quality of the simulations. The opportunity to expand on these limitations show the requirement for further research.

Three possible factors that influence the expansion profile were analyzed. By performing a uni- or bilateral PMD, (posterior) resistance against the transversal expansion is removed and stress reductions in the maxillofacial complex are achieved. A unilateral PMD increases the transversal expansion at this side while a bilateral PMD increases the total amount of expansion. PMD also decreases horizontal tipping but not significantly. The more superior positioned lateral osteotomy tends to increase the displacement of the alveolar bone at that side, however also increasing the stresses at the lateral pterygoid plates. Based on these results, a PMD on that side is advised. The optimal distractor position depends on the required expansion profile. Moving the distractor more posteriorly results in a more parallel expansion (less V-shaped). Small deviations in the superoinferior direction will only result in negligible superoinferior displacements at the alveolar bone.

5. ACKNOWLEDGEMENTS

Conflicts of interest:

The author(s) declare no conflict of interest concerning research, authorship and publication. No personal or financial conflicts can be identified.

Funding:

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethical Approval:

Ethical approval was not required for this study, no patients were recruited, no patient material was used.

Author contributions

- Conceptualization: Renaat Coopman & Wim Van Paepegem
- Methodology: Tomas Verplanken
- Software: Tomas Verplanken & Wim Van Paepegem
- Formal analysis: Tomas Verplanken: Wim Van Paepegem
- Writing—original draft preparation: Tomas Verplanken, Robin Vanroose
- Writing—review and editing: Matthias Ureel, Renaat Coopman, Wim Van Paepegem
- Visualization: Tomas Verplanken, Robin Vanroose
- Supervision: Renaat Coopman, Wim Van Paepegem

6. REFERENCES

1. Nowak R, Strzalkowska A, Zawiślak E. Treatment Options and Limitations in Transverse Maxillary Deficiency. Dental and Medical Problems. 2015;52:389-400.
2. Menon S, Manerikar R, Sinha R. Surgical management of transverse maxillary deficiency in adults. J Maxillofac Oral Surg. 2010;9(3):241-6.
3. Angelieri F, Cevidanes LH, Franchi L, Gonçalves JR, Benavides E, McNamara JA, Jr. Midpalatal suture maturation: classification method for individual assessment before rapid maxillary expansion. Am J Orthod Dentofacial Orthop. 2013;144(5):759-69.
4. Suri L, Taneja P. Surgically assisted rapid palatal expansion: a literature review. Am J Orthod Dentofacial Orthop. 2008;133(2):290-302.
5. Agarwal A, Mathur R. Maxillary Expansion. Int J Clin Pediatr Dent. 2010;3(3):139-46.
6. Andrucioli MCD, Matsumoto MAN. Transverse maxillary deficiency: treatment alternatives in face of early skeletal maturation. Dental Press J Orthod. 2020;25(1):70-9.
7. Shetty V, Caridad JM, Caputo AA, Chaconas SJ. Biomechanical rationale for surgical-orthodontic expansion of the adult maxilla. J Oral Maxillofac Surg. 1994;52(7):742-9; discussion 50-1.
8. Kapetanović A, Theodorou CI, Bergé SJ, Schols J, Xi T. Efficacy of Miniscrew-Assisted Rapid Palatal Expansion (MARPE) in late adolescents and adults: a systematic review and meta-analysis. Eur J Orthod. 2021;43(3):313-23.
9. Shyam Sundar S, Nandlal B, Saikrishna D, Mallesh G. Finite Element Analysis: A Maxillofacial Surgeon's Perspective. J Maxillofac Oral Surg. 2012;11(2):206-11.
10. Swennen G. 3D Virtual Treatment Planning of Orthognathic Surgery. A Step-by-Step Approach for Orthodontists and Surgeons2016.
11. Lee SC, Park JH, Bayome M, Kim KB, Araujo EA, Kook YA. Effect of bone-borne rapid maxillary expanders with and without surgical assistance on the craniofacial structures using finite element analysis. Am J Orthod Dentofacial Orthop. 2014;145(5):638-48.
12. Peterson J, Wang Q, Dechow PC. Material properties of the dentate maxilla. Anat Rec A Discov Mol Cell Evol Biol. 2006;288(9):962-72.
13. Möhlhenrich SC, Modabber A, Kniha K, Peters F, Steiner T, Hölzle F, et al. Simulation of three surgical techniques combined with two different bone-borne forces for surgically assisted rapid palatal expansion of the maxillofacial complex: a finite element analysis. Int J Oral Maxillofac Surg. 2017;46(10):1306-14.
14. Möhlhenrich SC, Ernst K, Peters F, Kniha K, Chhatwani S, Prescher A, et al. Immediate dental and skeletal influence of distractor position on surgically assisted rapid palatal expansion with or without pterygomaxillary disjunction. Int J Oral Maxillofac Surg. 2021;50(5):649-56.
15. Holberg C, Steinhäuser S, Rudzki I. Surgically assisted rapid maxillary expansion: midfacial and cranial stress distribution. Am J Orthod Dentofacial Orthop. 2007;132(6):776-82.
16. Bays RA, Greco JM. Surgically assisted rapid palatal expansion: an outpatient technique with long-term stability. J Oral Maxillofac Surg. 1992;50(2):110-3; discussion 4-5.
17. Han UA, Kim Y, Park JU. Three-dimensional finite element analysis of stress distribution and displacement of the maxilla following surgically assisted rapid maxillary expansion. J Craniomaxillofac Surg. 2009;37(3):145-54.
18. Koudstaal MJ, Smeets JB, Kleinrensink GJ, Schulten AJ, van der Wal KG. Relapse and stability of surgically assisted rapid maxillary expansion: an anatomic biomechanical study. J Oral Maxillofac Surg. 2009;67(1):10-4.

19. Huizinga MP, Meulstee JW, Dijkstra PU, Schepers RH, Jansma J. Bone-borne surgically assisted rapid maxillary expansion: A retrospective three-dimensional evaluation of the asymmetry in expansion. J Craniomaxillofac Surg. 2018;46(8):1329-35.
20. Braun S, Bottrel JA, Lee KG, Lunazzi JJ, Legan HL. The biomechanics of rapid maxillary sutural expansion. Am J Orthod Dentofacial Orthop. 2000;118(3):257-61.
21. Chamberland S, Proffit WR. Short-term and long-term stability of surgically assisted rapid palatal expansion revisited. Am J Orthod Dentofacial Orthop. 2011;139(6):815-22.e1.
22. Zandi M, Miresmaeili A, Heidari A. Short-term skeletal and dental changes following bone-borne versus tooth-borne surgically assisted rapid maxillary expansion: a randomized clinical trial study. J Craniomaxillofac Surg. 2014;42(7):1190-5.
23. Pinto PX, Mommaerts MY, Wreakes G, Jacobs WV. Immediate postexpansion changes following the use of the transpalatal distractor. J Oral Maxillofac Surg. 2001;59(9):994-1000; discussion 1.
24. Leonardi R, Caltabiano M, Cavallini C, Sicurezza E, Barbato E, Spampinato C, Giordano D. Condyle fossa relationship associated with functional posterior crossbite, before and after rapid maxillary expansion. Angle Orthod. 2012;82(6):1040-6.
25. Koudstaal MJ, Wolvius EB, Schulten AJ, Hop WC, van der Wal KG. Stability, tipping and relapse of bone-borne versus tooth-borne surgically assisted rapid maxillary expansion; a prospective randomized patient trial. Int J Oral Maxillofac Surg. 2009;38(4):308-15.

7. FIGURES

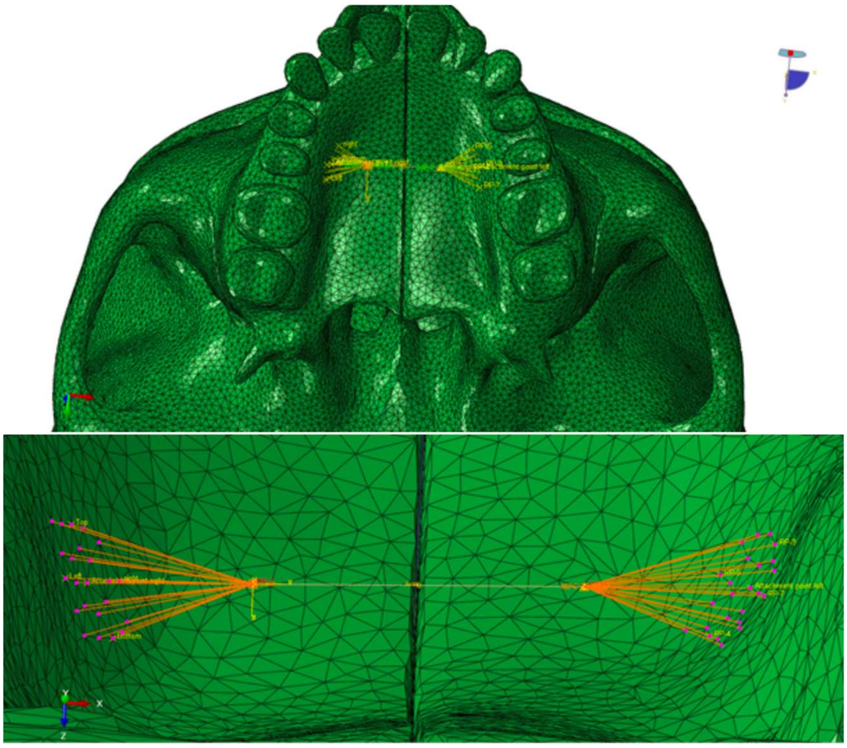

Fig. 1: Up: Axial connector between reference points on the alveolar ridge of the maxilla. Below: detailed view of the transpalatal wire, connected with beam elements (orange lines). Black line in the middle indicates the palatal suture.

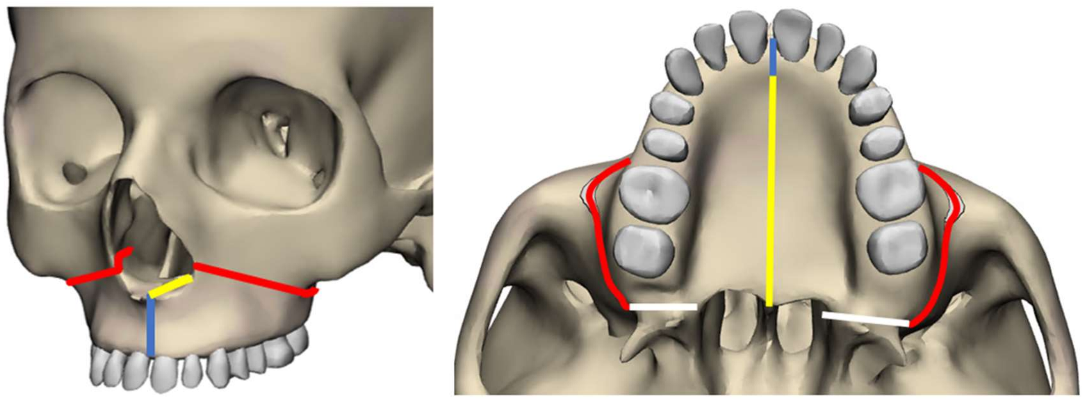

Fig. 2: Schematic representation of the osteotomy lines on the 3D finite element model. Lateral (red), vertical (blue), median (yellow) and pterygomaxillary (white)

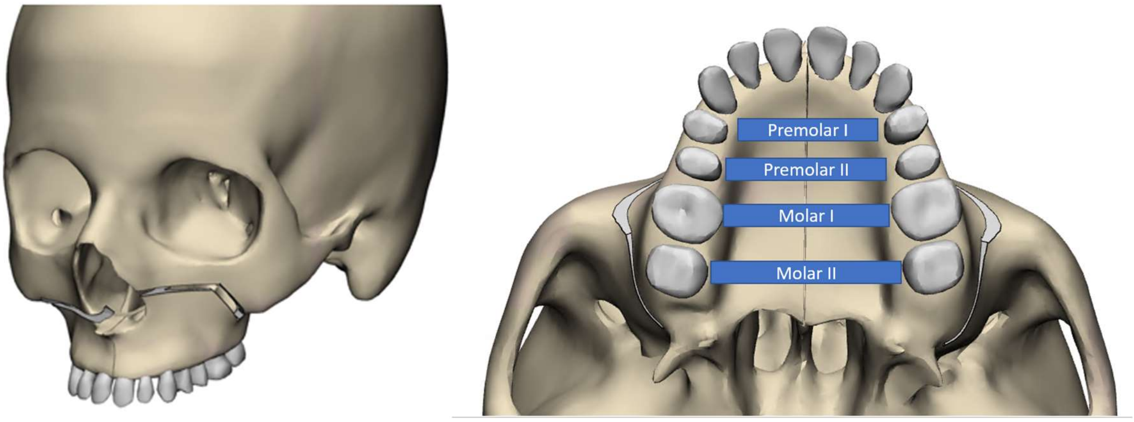

Fig. 3: Left: asymmetric lateral osteotomy (inferior osteotomy 5 mm superior of the apex of the incisor and superior osteotomy 5 mm inferior of the infraorbital foramen). Right: Four different positions of the palatal distractor in horizontal direction.

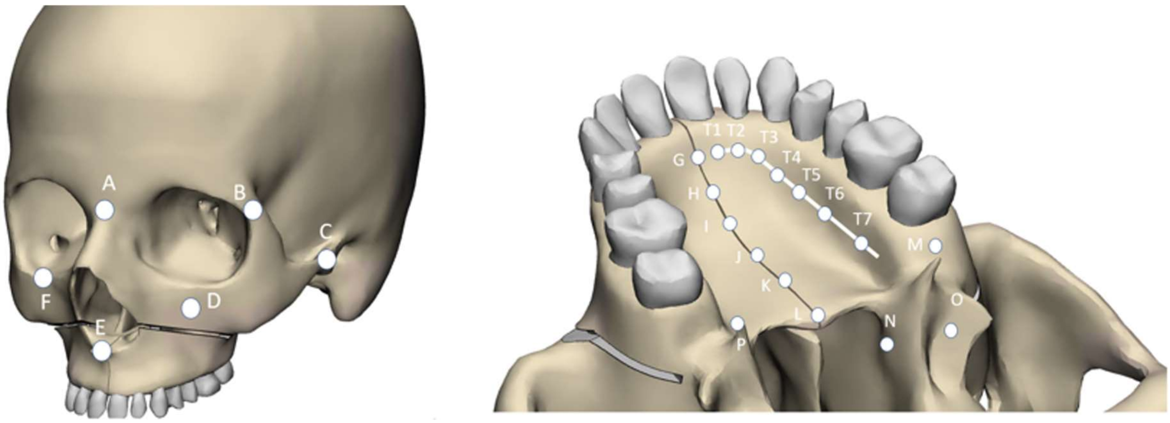

Fig. 4: Left: anatomical cephalometric landmarks of stress measurements. Right: anatomical maxillary landmarks of stress measurements.

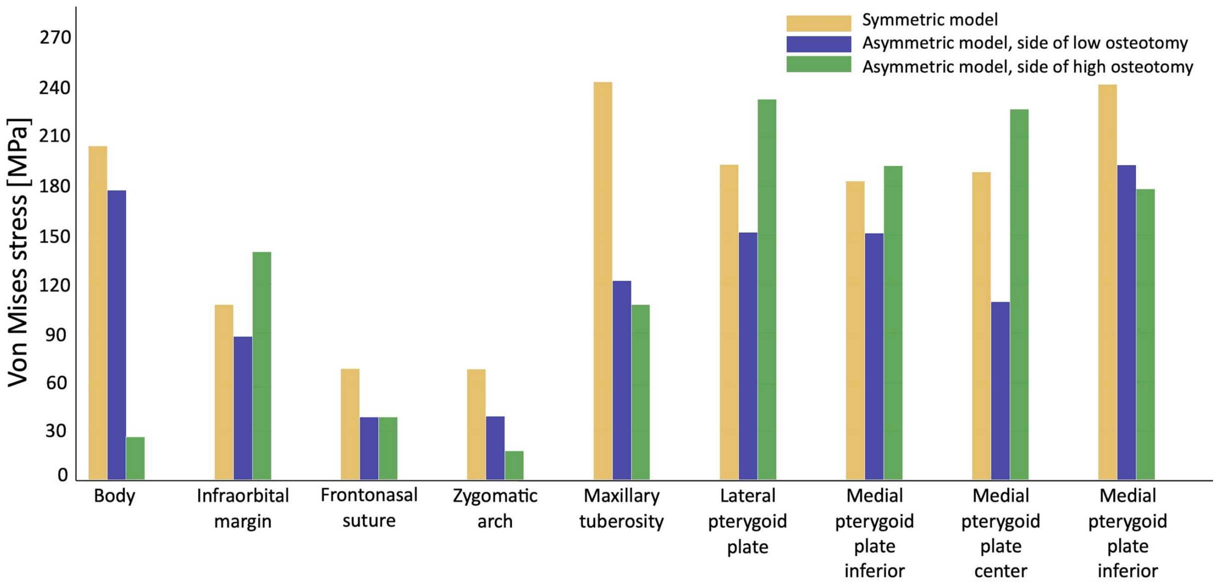

Fig. 5: Stress distribution in the maxillofacial complex - Lateral osteotomy variation models

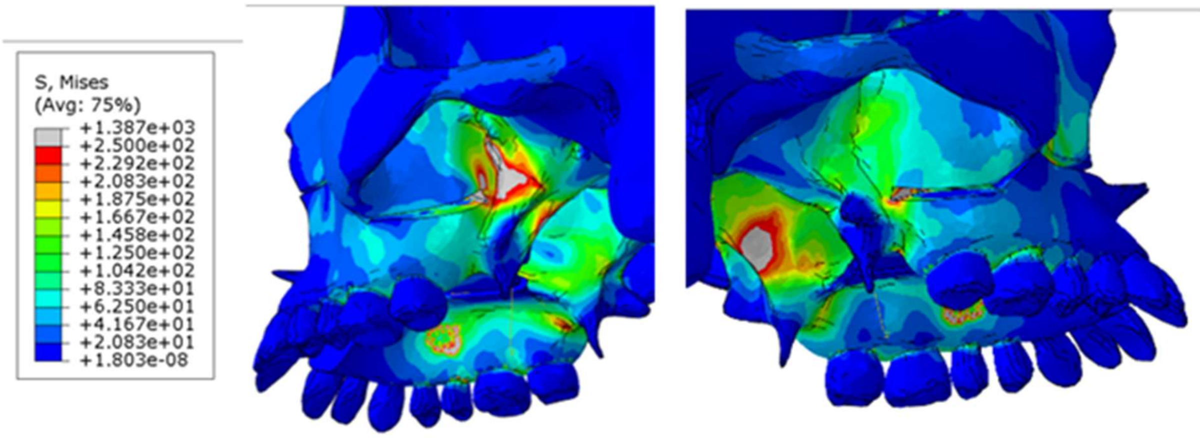

Fig. 6: Stresses at the lateral pterygoid plates, left (asymmetric) and right (symmetric) side of the model

8. TABLES

TABLE I: Displacements at the level of the alveolar bone - PMD models

Vector Sum	Orientation	T1	T2	T3	T4	T5	T6	T7
No PMD [mm]	Left	3.32	3.22	3.01	2.82	2.62	2.03	1.44
	Right	3.62	3.49	3.27	3.12	2.81	2.23	1.65
Unilateral PMD [mm]	Left	3.42	3.31	3.09	2.89	2.67	2.07	1.15
	Right	3.56	3.42	3.21	3.06	2.75	2.19	1.62
Bilateral PMD [mm]	Left	3.27	3.13	2.86	2.67	2.47	1.92	1.39
	Right	4.00	3.89	3.73	3.47	3.12	2.60	1.89

TABLE II: Displacements at the level of the alveolar bone – Lateral osteotomy variation models

Vector Sum	Orientation	T1	T2	T3	T4	T5	T6	T7
Symmetric lateral osteotomy [mm]	Left	3.32	3.22	3.012	2.82	2.615	2.03	1.43
	Right	3.62	3.49	3.27	3.12	2.81	2.23	1.65
Asymmetric lateral osteotomy [mm]	Left	2.75	2.68	2.51	2.34	2.18	1.72	1.25
	Right	4.18	4.02	3.78	3.60	3.23	2.59	1.94

TABLE III: Horizontal tipping (axial plane) and vertical tipping (frontal plane) - Palatal distractor models

	Premolar 1		Premolar 2		Molar 1		Molar 2	
	Axial	**Frontal**	**Axial**	**Frontal**	**Axial**	**Frontal**	**Axial**	**Frontal**
$u_{For.Inc.}$ [mm]	7.9	-	8.2	-	8.36	-	7.03	-
u_{PNS} [mm]	1.93	-	1.9	-	2.91	-	3.80	-
$u_{C.I}$ [mm]	-	4.28	-	4.63	-	5.34	-	4.45
u_{ANS} [mm]	-	3.13	-	3.42	-	3.91	-	2.85
Δu [mm]	5.97	1.15	6.31	1.20	5.45	1.42	3.23	1.60
Opening angle [°]	8.28	5.28	8.75	5.52	7.57	6.52	4.49	7.33
Parallelism [%]	0.24	0.73	0.23	0.74	0.35	0.73	0.54	0.64