Original Article

Relationship between buccal osteotomy angulation and asymmetric expansion in surgically assisted rapid palatal expansion: a finite element analysis

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ABSTRACT

Objectives: To investigate the effects of buccal osteotomy angulation on surgically assisted rapid palatal expansion (SARPE) patterns.

Materials and Methods: A finite element analysis (FEA) model of the maxilla with Haas expander was constructed from a cone beam computed tomography (CBCT) image using Mimics, Geomagic, and solidWorks software. One-mm-thick buccal osteotomies were created with different combinations of 0°, 10°, 20°, and 30° from the horizontal plane to simulate differences in bilateral osteotomy angulation. Springs were placed at the buccal osteotomy gaps to mimic the strain of the bone callus. After applying 150 Newton of expansion force at the level of the expander jackscrew in each FEA scenario, the expansion pattern of the hemimaxillae was evaluated in Ansys software.

Results: Scenarios with 20° (0–20°; 10–30°) and 30° (0–30°) differences resulted in significant transverse asymmetric expansion. Among the groups with 10° difference, 0–10° resulted in relatively parallel expansion, while 10–20° and 20–30° experienced V-shaped expansion with more anterior widening.

Conclusions: A larger difference between the angulations of the left and right buccal osteotomies resulted in increased asymmetry in both the transverse and vertical dimensions after expansion. (*Angle Orthod*. 2025;00:000–000.)

KEY WORDS: Finite element analysis; Orthognathic surgery; Complications; Osteotomy

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INTRODUCTION

Currently, surgically assisted rapid palatal expansion (SARPE) is a standard procedure to correct significant maxillary transverse deficiencies skeletally in adult patients to achieve stable skeletal expansion.[1] It is worth noting that, although SARPE is broadly used worldwide, variations in surgical techniques occur.[2] These include differences in the angulation of the buccal osteotomy, design of the buccal osteotomy with a step at the zygomatic buttress, resection of small bony wedges from the lateral sinus wall, the inclusion of pterygomaxillary disjunction, and the inclusion of nasal septum release.[3–6] These variations in surgical techniques may lead to varying expansion outcomes of SARPE. For instance, Betts et al.[7] proposed a horizontal buccal osteotomy technique that included a step-down at the zygomatic process to prevent downward movement of the hemimaxillae which may occur in a ramped cut. Although evidence is lacking as to which technique is superior, in the literature, downward and forward movements of the maxilla have been shown after SARPE despite large variations among patients,[8] which may stem from variation in the buccal osteotomy designs.

Transverse asymmetric expansion between the left and right sides is one of the significant complications in SARPE. Drobyshev et al.[9] reported that 27 out of 665 patients experienced asymmetry in expansion, and that three of them had to go through a secondary surgery. Huizinga et al.[10] even observed asymmetric expansion of more than 3 mm in 55% of their cases. Since a significant amount of unwanted asymmetric expansion could greatly impact treatment progress and outcomes as well as lead to increased complexities in the second surgical phase or lead to additional surgeries such as recorticotomy, segmental osteotomies, or maxillary osteotomies with yaw movement,[11,12] a thorough investigation into this matter would undoubtedly aid clinicians during surgical planning and treatment. In a recent systematic review, variation in the surgical techniques of SARPE may be a contributing factor to asymmetric expansion, with a higher rate of asymmetric expansion occurring in cases without lateral nasal wall release, without nasal septum release, or with pterygomaxillary fissure release.[12] However, none of the authors of studies who reported asymmetric expansion described their design for buccal osteotomies in detail.[12] Given that buccal osteotomy is performed separately on either side of the maxilla, it can be difficult for the surgeon to maintain symmetry in the direction or angulation of the cuts. Since buccal osteotomy is an indispensable component of the SARPE procedure, understanding of its contribution to the overall results of maxillary expansion is needed.

For ethical concerns, a computer-based model is favored over in vivo trials when evaluating and comparing the effects of different surgical procedures on the expansion patterns of SARPE.[13] A novel FEA model of SARPE was constructed recently which closely simulated the clinical condition of bony callus formation at the osteotomy site and could be used to evaluate the expansion patterns of SARPE after the activation of expansion force.[14] In this study, simulations of various combinations of buccal osteotomies were set up in the novel FEA model, and the expansion outcomes were studied to investigate their impact on asymmetric expansion.

MATERIALS AND METHODS

FEA Model Setup

The FEA model was constructed step by step as described previously.[14] In brief, a three-dimensional (3D) skull model from the pre-SARPE cone beam computed tomography (CBCT) of a 47-year-old female patient who was diagnosed with maxillary transverse deficiency was imported into Mimics software version 16.0 (Materialise NV, Leuven, Belgium) for the segmentation of the maxillary complex, maxillary first premolars, and maxillary molars. The stereolithography (STL) files exported from Mimics software were then imported into Geomagic Studio version 10 (3D systems, Rock Hill, SC) for surface smoothing and creation of cancellous bone and periodontal ligament space. The constructed 3D solid model in the format of a computer-aided design (CAD) file was then imported into Solidwork version 2018 (Dassault Systèmes, Vélizy-Villacoublay, France). In the Solidwork software, the right half of the maxillary complex was retained and mirrored to create an identical left half, resulting in a perfectly symmetrical model of the maxilla that eliminated any anatomic asymmetry that could potentially affect the expansion outcome. In addition, a Haas expander was designed and banded to the maxillary first premolars and first molars.

A LeFort I osteotomy involving buccal osteotomy, the release of laterally walls of the nasal cavity, the release of nasal septum, and the release of pterygomaxillary fissure was performed to separate the hemimaxillary blocks to mimic the clinical scenarios.[15] To construct the buccal osteotomy, a 1-mm-thick plane, equivalent to the diameter of a surgical bur, was created from the corner of the piriform aperture (Alar) toward the infrazygomatic crest (IZC). Based on the suggestions from Betts et al.,[7] four different degrees of buccal osteotomy, 0°, 10°, 20°, and 30°, were created. To simulate asymmetric cuts, the four osteotomies were used in six combinations on a skeletally symmetric skull model: 0–10°, 10–20°, 20–30°, 0–20°, 10–30°, and 0–30°. Models with different buccal osteotomy angles were imported into Ansys version 2019 (Canonsburg, Pa) in Parasolid model part files for finite element analysis (FEA).

The material parameters were set in Ansys as follows: cortical bone (Young's modulus $= 1.37 \times 10^4$ MPa, Poisson's ratio $= 0.3$), cancellous bone (Young's modulus $= 1.37 \times 10^3$ MPa, Poisson's ratio $= 0.3$), premolars and molars (Young's modulus $= 2.60 \times 10^4$ MPa, Poisson's ratio $= 0.3$), periodontal ligament (Young's modulus $= 5.00 \times 10^1$ MPa, Poisson's ratio $=$ 0.49), and expander (stainless steel, Young's modulus $= 2.10 \times 10^5$ MPa, Poisson's ratio $= 0.35$). The connection properties between different parts were defined as follows: Bonded connections were established between the cancellous bone and cortical bone, between the tooth and expander, and between the periodontal ligament and tooth. Frictional connections ($\mu = 0.2$) were set between the maxillary cortical bone and skull cortical bone and between cortical bone and tooth. Frictional connections ($\mu = 0.1$) were applied between the cortical bone and nasal septum, between the periodontal ligament and cortical bone, and between the periodontal ligament and cancellous bone. Lastly, rough connections were established between the cortical bone and expander as well as between the cancellous bone and expander.

To connect the hemimaxilla blocks to the skull at the 1-mm-thick osteotomy gap, springs (1 mm long, spring constant $k = 60$ N/mm) were implemented to link and suspend the hemimaxillae at the grid nodes to simulate the tissue resistance provided by the bony callus. Lastly, an expansion force of 150 N was set along the x axis (perpendicular to the midline) on the jackscrew, and the displacements of the anatomic landmarks in all three dimensions were measured as the results of expansion as described previously.[14]

Evaluation Criteria of the FEA Model: Asymmetry Ratio

Given the variation in the osteotomy angulation and resulting resistance levels, the total activation at the expander differs even under the same predetermined activation force of 150 N. Consequently, it was impossible to compare the severity of asymmetry among groups based on the difference in displacement of their left and right landmarks. Instead, a new metric called the *asymmetry ratio* was developed, which was calculated by dividing the difference in left-right displacement at a certain landmark by the total amount of activation at the expander. This approach allowed the quantification and comparison of asymmetry levels across the different groups:

$$\text{asymmetry ratio} = \frac{\text{absolute difference between the left and right sides}}{\text{total activation at the expander}}.$$

Asymmetric expansion of 3 mm transversely was regarded as *clinically significant*, as reported by Huizinga et al.[10] The threshold for a clinically significant asymmetry ratio was determined by dividing 3 mm by 8 mm, which corresponded to the typical minimum amount of expander activation required in SARPE patients.[1] The results yielded a 37.5% transverse asymmetry ratio, which was used as an evaluation criterion for this study.

Evaluation Criteria of the FEA Model: Expansion Pattern

Another evaluation criterion applied in this study was the expansion pattern produced after activation. An unfavorable expansion pattern from the occlusal view, when both hemimaxillae rotated in the same direction, could produce a yaw of the upper jaw and result in asymmetry (Figure 1). On the other hand, unfavorable expansion from the frontal view with both hemimaxillae rotating in the same direction could produce an occlusal cant (Figure 1). Therefore, groups experiencing these movements were deemed to have unfavorable postsurgical outcomes.

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the University of Pennsylvania (Protocol 853608 and date of approval: May 2nd, 2023).

RESULTS

Asymmetry Ratio of Each FEA Scenario

The asymmetry ratios in the transverse, sagittal, and vertical dimensions of each FEA scenario are presented in Table 1. As shown in Table 1, 0–20°, 0–30°, and 10–30° scenarios all showed a transverse asymmetry ratio above 37.5% at different anatomic locations, with the 0–30° scenario showing the highest transverse asymmetry ratio. On the other hand, 0–10°, 10–20°, and 20–30° scenarios had relatively low transverse asymmetry ratios.

Expansion Pattern of Each FEA Scenario

Figures 2 and 3 show the rotation pattern of the hemimaxillae from the occlusal and frontal views, respectively. The combinations of 0–20°, 0–30°, and 10–30° were all regarded as having unfavorable rotation in both the transverse and vertical dimensions.

From the occlusal view, the combination of 0–10° resulted in a V-shaped expansion with more posterior expansion; the combinations of 10–20° and 20–30° experienced a V-shaped expansion with more anterior widening, with the 20–30° combination having a more divergent V-shaped expansion. Vertically, all 0–10°, 10–20°, and 20–30° scenarios showed V-shaped expansion with more expansion at the dental level than at

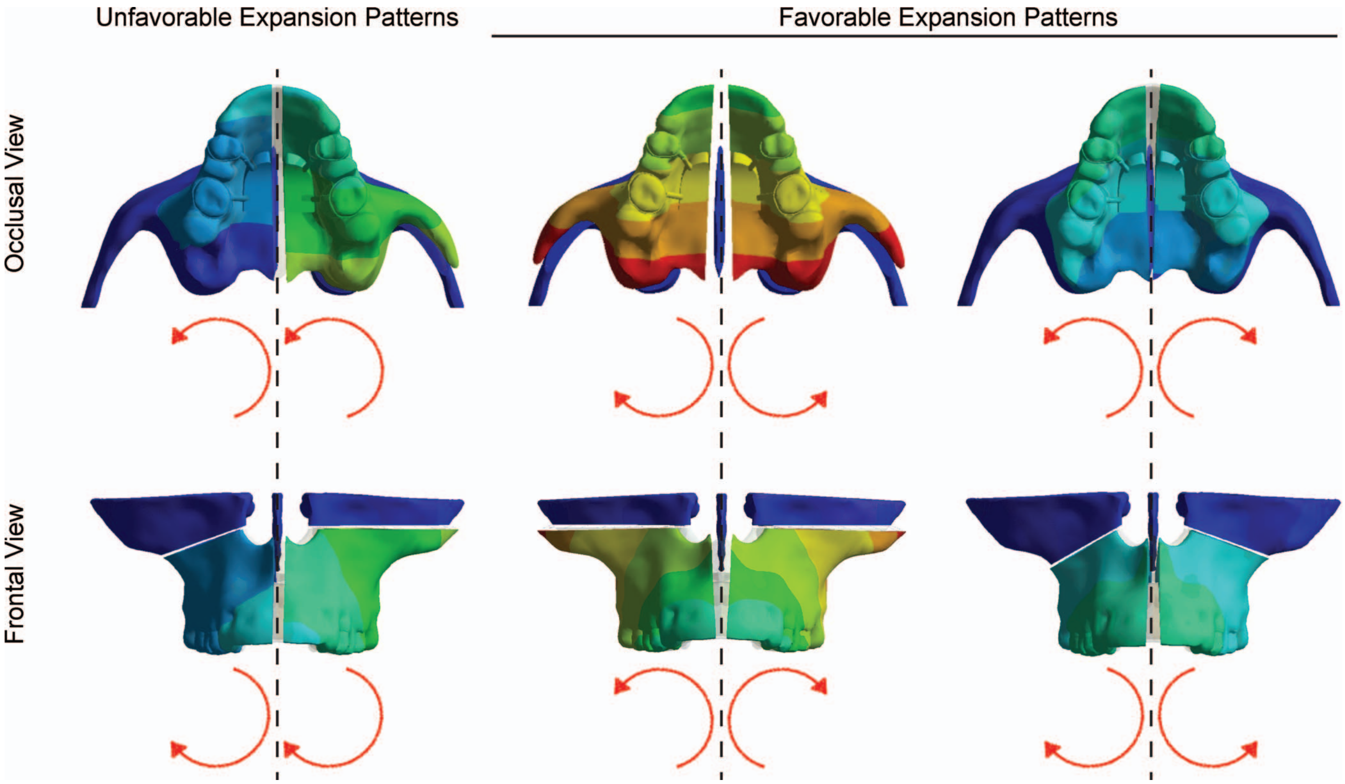

Figure 1. Demonstration of unfavorable and favorable expansion patterns from the occlusal and frontal views. The black dotted lines show the midsagittal plane. The red arrows show the rotation directions of the hemimaxillae. In the occlusal view, rotation of both the left and right hemimaxillae toward the same direction creates a yaw movement of the maxilla that is considered unfavorable. On the other hand, rotation of both left and right hemimaxillae toward opposite directions creates a more favorable fan-shaped expansion. In the frontal view, rotation of both the left and right hemimaxillae toward the same direction creates a roll movement that is considered unfavorable. Meanwhile, rotation of both left and right hemimaxillae in opposite directions creates a more favorable expansion.

the skeletal level. The 20–30° scenario had the most prominent buccal tipping of the hemimaxillary blocks.

DISCUSSION

The potential influence of buccal osteotomy on the expansion pattern of SARPE was first proposed by Betts et al.[7] as early as 1995. However, the hypothesis cannot be tested clinically due to ethical concerns. FEA is used for modeling complex structures and biomechanical analyses,[16] and its usage in dentistry has been expanding rapidly due to advantages such as the repeatability of experiments and freedom in study parameters. The FEA model used in the current study is novel in design since it evaluates the expansion pattern, providing direct visualization of treatment outcomes that benefit clinicians. In addition, the design of the 1-mm osteotomy gap filled with springs to simulate the stretching of the bony callus in both lateral and rotational movements of the hemimaxillary blocks closely mimicked the clinical condition. The model was validated when a force of 150 N, within the range of regular rapid palatal expansion,[17] was applied to a bilateral 0° osteotomy model, resulting in an 8-mm expansion.[14] As a result, the current FEA model is superior in that it resembles actual clinical scenarios. As shown in Figures 2 and 3, when the same amount of force was applied in different osteotomy scenarios, different amounts of expansion were achieved, with the side with a steeper osteotomy showing less expansion.

When observing from the frontal view of the FEA (Figure 3), more buccal tipping of the hemimaxillary blocks was noted with steeper buccal osteotomy angles. This was inconsistent with the theory of Betts et al.[7] that the hemimaxillary block would slide outward and downward along the osteotomy surface.[7] However, the findings in the current study were consistent with those of clinical studies by Chamberland and Proffit,[1] who evaluated posteroanterior cephalometric x rays, and Chung and Goldman,[18] who assessed dental models. Authors of both studies found that significant buccal tipping of the hemimaxillary blocks could occur in SARPE. In addition, while steeper osteotomy angles were correlated with greater buccal tipping of the hemimaxillary blocks, an issue prone to posttreatment relapse, in the current study, we also showed that limited expansion can be achieved with steeper osteotomy. This may also explain why no correlation was found between the amount of expander activation and the degree of relapse.[1]

Table 1. Asymmetry Ratio for All Six FEA Scenarios[a]

Left	Right	Dimension	U6 (%)	U4 (%)	IZC (%)	Alar (%)	U1 (%)	Exp (%)
0°	10°	Transverse	29.75	10.39	32.99	11.90	−9.92	26.39
		Sagittal	4.00	−0.80	23.57	−8.60	−21.19	−20.04
		Vertical	0.05	−0.35	−2.14	0.40	0.94	1.86
0°	20°	Transverse	47.74	29.23	60.52	41.87	11.11	51.44
		Sagittal	10.34	5.98	23.57	−6.20	−13.69	−15.29
		Vertical	1.77	−1.64	6.03	−2.20	−7.65	−2.69
0°	30°	Transverse	54.85	32.15	78.61	57.14	11.07	65.22
		Sagittal	1.42	−4.15	19.52	−17.50	−28.13	−29.18
		Vertical	1.21	−3.39	10.52	−5.65	−14.65	−9.31
10°	20°	Transverse	4.58	−11.62	10.52	−8.55	−31.23	3.80
		Sagittal	28.67	24.59	31.71	−0.24	2.89	−0.79
		Vertical	−4.69	−13.78	−3.70	−9.52	−16.98	−5.91
10°	30°	Transverse	19.81	−0.13	39.22	22.17	−19.27	29.30
		Sagittal	12.16	7.49	19.42	−9.69	−14.24	−18.01
		Vertical	−1.66	−8.05	4.94	−9.57	−20.42	−11.34
20°	30°	Transverse	16.57	22.33	14.57	20.07	27.35	17.04
		Sagittal	−9.78	−8.11	−10.30	−2.04	−2.22	−0.39
		Vertical	6.79	8.61	5.58	7.80	10.52	4.02

[a] FEA indicates finite element analysis; U6, mesiobuccal cusp tip of the maxillary first molar; U4, buccal cusp tip of the maxillary first premolar; IZC, infrazygomatic crest; Alar, lateroinferior corner of the piriform aperture; U1, mesioincisal line angle of the maxillary central incisor; and Exp, anterior-posterior midpoint of the medial border of the expander. In the transverse dimension, a positive value means the left side moves more laterally than the right side; a negative value means the right side moves more laterally than the left side. In the sagittal dimension, a positive value means the left side moves more anteriorly than the right side; a negative value means the right side moves more anteriorly than the left side. In the vertical dimension, a positive value means the left side moves more inferiorly than the right side; a negative value means the right side moves more inferiorly than the left side.

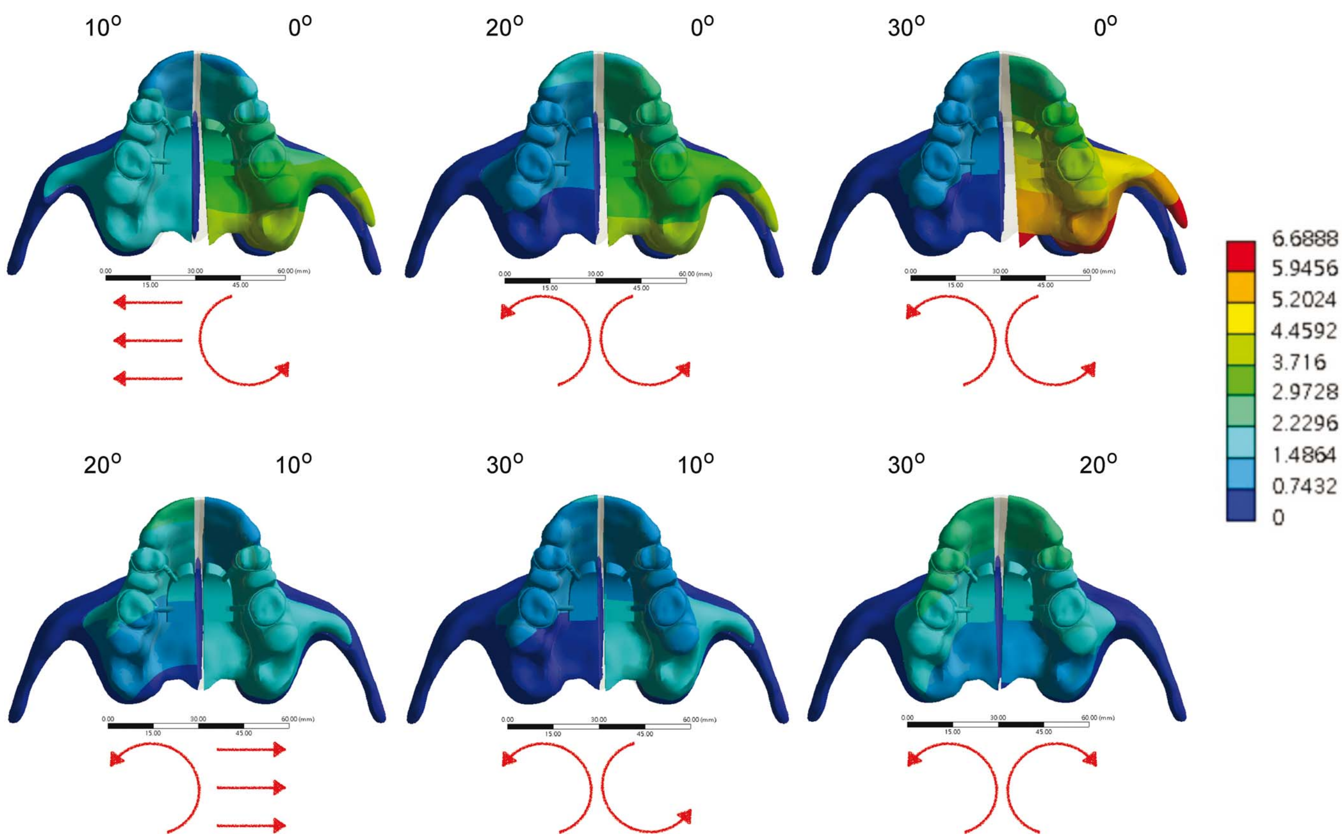

Figure 2. Transverse expansion pattern of the six combinations of buccal osteotomy on the finite element analysis (FEA) models from the occlusal view.

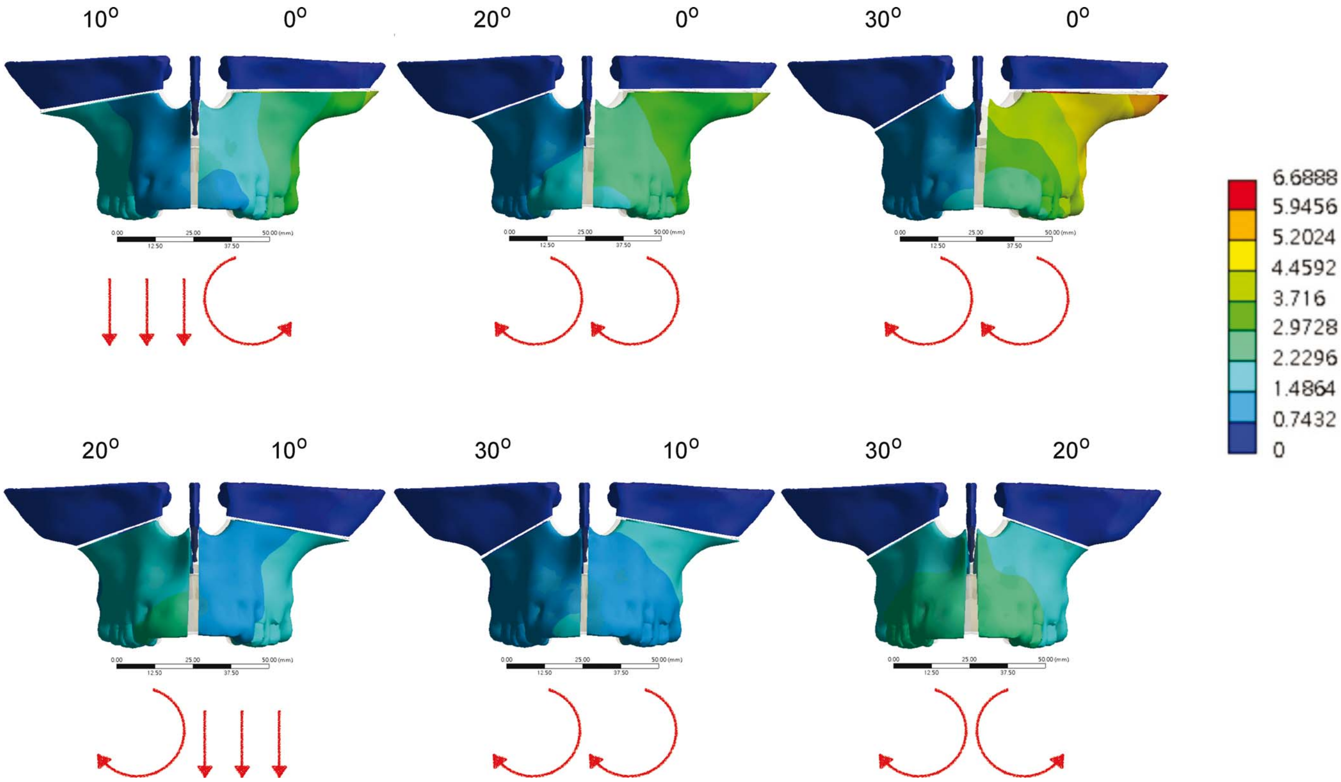

Figure 3. Expansion pattern in the vertical dimension of the six combinations of buccal osteotomy on the finite element analysis (FEA) models from the frontal view.

From the asymmetry ratio and the rotation pattern results in the FEA, it was clearly demonstrated that groups with a 20° and 30° difference had a higher degree of asymmetric expansion (Table 1, Figures 2 and 3). This was probably due to the increased difference in resistance between the left and right halves at the osteotomy site where bony collision occurred. The difference in the angulation of the cuts meant that the surface area, contact angle, and friction were different. Therefore, it was expected that groups with a larger left and right differences would show more asymmetric expansion.

The current FEA results further showed that, within the 10° difference groups, relatively more expansion could be achieved posteriorly in the 0–10° and 10–20° scenarios, while the 20–30° group resulted in a significantly anterior-posterior V-shaped expansion (Figure 2), with the smaller angulation side having more expansion. These data showed the potential importance of ensuring symmetrical and more horizontal osteotomies during SARPE procedures. To provide more precise osteotomies, generating SARPE cutting guides created from virtual surgical planning (VSP) have been reported and could be used to ensure more symmetrical osteotomies.[19] In addition, for patients with presurgical anatomic asymmetries or those who require asymmetric expansion, VSP coupled with presurgical FEA simulations may deliver more reliable results. A global collaboration is needed to standardize the FEA model construction process, enabling its use in VSP for optimized and personalized patient care.

Limitations

Certain limitations in the current study need to be considered. First, soft tissue resistance increases when it is stretched,[20] rendering it difficult to simulate in FEA. Therefore, it is disregarded in most FEA studies, including the current one, leading to an underestimation of resistance, especially around the posterior maxilla region, in an FEA environment. The presence of strong resistance from the posterior soft and hard tissue probably means that an inverted V-shaped expansion (the posterior being expanded more than the anterior), from the occlusal view, may not happen clinically. However, it is worth noting that Chung and Goldman[18] reported that, after SARPE and before orthodontic tooth movement, the expander abutment teeth exhibited rotations ranging from mesiolingual to mesiobuccal (17.2° mesiolingual to 16.5° mesiobuccal rotation for first premolars, 15.8° mesiolingual to 6.5° mesiobuccal rotation for first molars). These data indicated that both anterior-out and posterior-out rotations could occur on the hemimaxillary blocks in SARPE.

Second, the current FEA model was set up with a Haas expander on a symmetric maxilla to eliminate the possibility of anatomic influence.[14] It is worth noting that the patient's anatomy, the orientation of the expander, and the type of expander are also factors that could lead to different expansion patterns,[12,21] which could lead to the discrepancy between the current FEA outcome and the amount of asymmetric expansion for each patient.

Third, the FEA model used in the current study involved release of the nasal septum and the lateral wall of the nasal cavity and pterygomaxillary fissure which separate the hemimaxillary blocks from the superior portion of the maxillary bone that connects to other craniofacial bones through multiple circumaxillary sutures. It is worth noting that different surgical techniques with varying degrees of osteotomies have been reported with the SARPE procedure[12]; thus, the results generated from the current model may not apply to all the SARPE scenarios since variations of surgical techniques could introduce the involvement of different circummaxillary sutures when performing expansion after surgery.[22] Further studies are warranted to explore the potential roles of the circummaxillary sutures in maxillary expansion with different surgical designs of SARPE.

CONCLUSIONS

- An increase in the buccal osteotomy angle from the frontal view induced an anteroposteriorly V-shaped expansion and buccal tipping of the hemimaxillary blocks.
- A large discrepancy between the angles of the left and right buccal osteotomies resulted in increased asymmetry in both the transverse and vertical dimensions after expansion.

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DISCLOSURES

All data generated or analyzed during this study are included in this published article.

The authors declare that they have no competing interests.

J.-H.L. contributed to the design, data acquisition and interpretation, and drafted and critically revised the manuscript. G.-L.W. contributed to the design, data acquisition and interpretation, and critically revised the manuscript. C.-K.C. contributed to the design, data acquisition and interpretation, and critically revised the manuscript. S.W. contributed to data acquisition and interpretation and critically revised the manuscript. N.B. contributed to data acquisition and interpretation and critically revised the manuscript. C.-H.C. contributed to the design and critically revised the manuscript. S.C. contributed to critically revising the manuscript. D.R.M. contributed to critically revising the manuscript. A.D.L. contributed to critically revising the manuscript. C.L. contributed to the conception, design, data interpretation, drafted and critically revised the manuscript. All authors gave their final approval and agreed to be accountable for all aspects of the work.

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