Finite Element Analysis of Bone Stress After SARPE

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Purpose: This study investigated stress distribution in maxillas that underwent surgically assisted palatal expansion (SARPE).

Materials and Methods: Five maxillary models were built: no osteotomy (M1), Le Fort I osteotomy with a step in the zygomaticomaxillary buttress (M2), Le Fort I osteotomy with a step in the zygomaticomaxillary buttress and the pterygomaxillary disjunction (M3), Le Fort I osteotomy without a step (M4), and Le Fort I osteotomy with pterygomaxillary disjunction and no step (M5). Displacement coherence and maximum stress (MS) analyses were used for all models.

Results: Areas of tension spread to the maxilla and the region between the alveolar ridge and the palate and a critical point in the median suture for M2, M3, M4, and M5. In M2 and M4, MS spread farther toward and over the pterygoid process, contrary to what was found in M3 and M5. M3 had a better performance than the other models, and the tensile stress was interrupted by the posterior osteotomy, thus avoiding possible damage to the sphenoid bone or difficulties in expanding the posterior region of the maxilla.

Conclusions: The steps in the zygomaticomaxillary buttress and the pterygomaxillary disjunction seem to be important to decrease the harmful dissipation of tensions during SARPE.

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Transverse maxillary deficiency (TMD) is characterized by a narrow maxilla, a high palatal vault, crowded and rotated teeth, and a bilateral or unilateral crossbite. Its etiology may involve developmental, congenital, traumatic, or iatrogenic factors and may be genetic or environmental.5

The treatment of TMD varies according to the degree of transverse deficiency, patient age, and its association with anterior, posterior, or vertical deficiencies. It is treated to increase the maxilla transversally using orthodontic, orthopedic, or orthopedic and surgical procedures.2 Surgically assisted palatal expansion (SARPE) has shown the best results for skeletally mature patients.4 The results of expansion by orthodontic or orthopedic devices alone (non-SARPE) are inadequate because of the rigid structure of the zygomatic buttress5 and the other facial pillars. In addition, there is a direct relation between advancing age and the increase in resistance to skeletal expansion resulting from the consolidation of the skull and facial sutures.6

SARPE has been recommended to treat TMD, and the goal of surgery is to perform osteotomies that decrease the resistance resulting from the consolidation of facial and skull joints.1 Several surgical techniques and their variations have been described.7-12 Those with a larger number of osteotomies seem to be essential for the treatment of older patients.13 They are characterized by bilateral osteotomies of the anterior walls of the maxilla, extending from the piriform

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aperture up to the pterygomaxillary joint. They are combined with bilateral osteotomies for pterygomaxillary disjunction, intermaxillary suture osteotomy, and osteotomy in the lateral walls of the nose and nasal septum.\textsuperscript{2,14}

The effects of SARPE are evident not only in the maxillary dental arch but also in the nasal septum,\textsuperscript{10} nasal cavity,\textsuperscript{15} nasal floor,\textsuperscript{16} lateral nasal walls and nasal area,\textsuperscript{17} upper lip,\textsuperscript{18,19} alar base,\textsuperscript{20} and gingival sulcus.\textsuperscript{21} These effects result from the lateral movement of the maxilla and all adjacent structures and are achieved by the activation of the expander, which generates forces that dissipate in the face and the skull\textsuperscript{22-24} through the teeth and bones.

The aim of this study was to evaluate the distribution of tensions in maxillary structures caused by the expansion of the maxilla when different types of osteotomies were simulated by the finite element method (FEM).

Materials and Methods

This study was approved by the committee of ethics in research of Sagrado Coraç\~ao University (Bauru, Brazil; number 03510). Computed tomograms of Brazilian adults from the files of the Renato Archer Technology Information Center were used to build computer-aided designed maxillary models using Rhinoceros 4.0 software (McNeel North America, Seattle, WA), which generated images of the major anatomic maxillary landmarks.

The geometry of this anatomical model was imported using FEMAP 10.1.1 software (Siemens PLM Software, Inc, Plano, TX) and a tetrahedral finite element mesh was generated with 10 nodes in the pre-processing phase (Fig 1). In the postprocessing phase, the model was analyzed using NEi Nastran software (Noran Engineering, Inc, Westminster, CA), and results were sent to FEMAP 10.1.1 software.

Symmetry was assumed, and the materials simulated were elastic, isotropic, linear, and homogeneous. The axes for model displacement in space were defined as $x$, side to side (horizontal); $y$, front to back (horizontal); and $z$, top to bottom (vertical). In the areas above the osteotomies, the models were fully fixed in the $z$ axis. Table 1 lists the properties of the simulated materials.

Five different models were built: no osteotomy (M1), Le Fort I osteotomy with a step in the zygomaticomaxillary buttress (M2), Le Fort I osteotomy with a step in the zygomaticomaxillary buttress and the pterygomaxillary disjunction (M3), Le Fort I osteotomy with no step (M4), and Le Fort I osteotomy with

\begin{table}[h]
\centering
\caption{Properties of Simulated Materials}
\begin{tabular}{|l|c|c|}
\hline
Structure & Young Modulus/Elasticity (GPa) & Poisson Coefficient \\
\hline
Cortical bone\textsuperscript{25} & 17.5 & 0.3 \\
Tooth\textsuperscript{26} & 20 & 0.3 \\
Palatal soft tissue\textsuperscript{26} & 0.2 & 0.45 \\
Acrylic\textsuperscript{26} & 2.4 & 0.3 \\
Steel\textsuperscript{27} & 210 & 0.35 \\
\hline
\end{tabular}
\end{table}
pterygomaxillary disjunction and no step (M5; Fig 2); all were performed using a simulated Hass expander (Fig 1).

Expansion was limited to 1 mm, and the contacts were fixed between the orthodontic bands and the teeth and among the bone, soft tissue, and expander. Contact between the pterygoid process and the maxilla was fixed when not in the osteotomy region (M1, M2, and M4). No type of contact was applied to the surfaces that had osteotomies, which could move free of friction or contact, but were limited to the simulated 1-mm gap. Displacement coherence and

![Figure 2](image)


<table>
<thead>
<tr>
<th></th>
<th>Dark Blue</th>
<th>Light Blue</th>
<th>Green</th>
<th>Yellow</th>
<th>Orange</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (mm)</td>
<td>0.0-0.15</td>
<td>0.18-0.40</td>
<td>0.43-0.75</td>
<td>0.78-0.84</td>
<td>0.87-0.94</td>
<td>0.97-1.0</td>
</tr>
<tr>
<td>M2 (mm)</td>
<td>0.0-0.20</td>
<td>0.24-0.52</td>
<td>0.57-0.93</td>
<td>0.97-1.05</td>
<td>1.09-1.18</td>
<td>1.26-1.30</td>
</tr>
<tr>
<td>M3 (mm)</td>
<td>0.0-0.20</td>
<td>0.24-0.57</td>
<td>0.62-0.95</td>
<td>0.99-1.07</td>
<td>1.11-1.19</td>
<td>1.24-1.32</td>
</tr>
<tr>
<td>M4 (mm)</td>
<td>0.0-0.17</td>
<td>0.21-0.57</td>
<td>0.61-1.0</td>
<td>1.05-1.14</td>
<td>1.18-1.27</td>
<td>1.31-1.40</td>
</tr>
<tr>
<td>M5 (mm)</td>
<td>0.0-0.23</td>
<td>0.27-0.58</td>
<td>0.63-1.04</td>
<td>1.08-1.17</td>
<td>1.22-1.31</td>
<td>1.55-1.44</td>
</tr>
</tbody>
</table>

**Table 2. DISPLACEMENT VALUES AND COLORS THAT REPRESENT THEM IN M1 TO M5**

*Note:* Expander activation equals 1 mm.

*Abbreviations: M1, model 1; M2, model 2; M3, model 3; M4, model 4; M5, model 5.

maximum stress (MS) were determined for all 5 models. Displacements and stress analysis measurements were calculated at the same time.

Results

Analysis of Displacement Coherence

The responses of the study model and its variations to loading (1 mm) were consistent, objective, and similar to the responses seen in real life. Displacements were larger in the red areas and virtually null in the dark blue areas. Areas with intermediate colors, that is, orange, yellow, green, and light blue, represented displacements whose values were within the limits represented by red and dark blue (Table 2).

In M1, only the expander achieved total displacement, and the orthodontic band, the cusps of the first premolar, and the whole alveolar bone might have moved buccally. In M2, displacement was greater in the anterior region of the alveolar bone and for the first premolar and the medial cusp of the first molar. Displacement was smaller in the posterior region, especially for the tuberosity of the maxilla toward the pterygoid process. The displacement in M3 was greater in the anterior region and for the first premolar and the mesial and distobuccal cusps of the first molar and was smaller in the posterior region, from the tuberosity of the maxilla toward the pterygoid process, where there was a sudden change in color, which marked the end of the jaw movement at the pterygoid process osteotomy (Fig 3; Table 2).

Displacement in M4 was greater in the anterior region and smaller toward the posterior region. Displacement decreased gradually from the posterior region of the first molar to the pterygoid process, and there was greater buccal displacement of the first premolar. In M5, displacement was greater in the anterior alveolar bone and decreased gradually toward the posterior and superior regions. It also was greater at the level of the first premolar and the first molar, but smaller in the posterior region and in the maxillary tuberosity toward the pterygoid process. The sudden change of color marked the end of the maxillary movement at the pterygoid process osteotomy (Fig 3; Table 2).

MS Analysis

In M1, traction tension was more critical in the anterior region of the intermaxillary suture and over the incisive foramen, between the teeth that anchored the expander and the lingual edge of the alveolar bone. Critical tension was greater at the alveolar bone of the first premolar than at the alveolar bone of the first molar in the same model and in M2, M3, M4, and M5 (Fig 4).

In M2, MS was distributed along the maxilla, and intensity was greater in the edge of the alveolar bone and
the hard palate, particularly in the region of the first premolar and first molar; it dissipated in the posterior region toward the pterygoid process and extended along the medial aspect of this process. Dissipation of forces was greater in the alveolar bone toward the lingual edge of the premolar alveolar bone. There was a more critical point of tension in the midpalatal suture at the level of the distal face of the molar and compression in the medial aspect of the alveolar bone in the region between the teeth (Fig 4).

MS distribution in M3 was similar to that found in M2, but the dissipation of tension to the posterior region toward the pterygoid process was interrupted at the osteotomy, between the process and the maxilla. In the same way, the distribution in M4 was similar to that found in M2, but the dissipation of traction tensions was greater in the maxillary tuberosity, palatine bone, and pterygomaxillary suture compared with M3 and M5. In M5, the pattern of dissipation was the same as in M2, but there was less tension in the region of the maxillary tuberosity than in M4, and stress was concentrated in the region of the palatine bone, as in M4 (Fig 4). The values (mega pascals) that correspond to the colors in Figure 4 are listed in Table 3.

In addition, the traction tension buildup found in the intermaxillary suture in association with the palatine bone was slightly greater in M2 and M3 than in M4 and M5.

### Discussion

The goal of the FEM is to divide structures or problem domains into small fragments or subdomains, called finite elements. This simplification of elements in study models, which has been adopted in bioengineering, does not invalidate this predominantly qualitative method, also used by other investigators.

The forces applied by the expander generate tensions on the teeth, bone, and adjacent anatomic structures. The FEM can highlight levels of tension concentration in several regions of the human body, if a suitable template is created.

The surgical stage of SARPE can be performed using several techniques. Those with a larger number of osteotomies have been considered essential in the treatment of older patients, because they weaken the pillars that strengthen the face and decrease the resistance to expansion found in adults. Osteotomy variations change the expected pattern of stress dissipation. For this reason, this study evaluated 4 types of osteotomies: 2 straight and downward from the anterior to the posterior maxillary region and 2 with a step in the zygomaticomaxillary buttress. Two models (M3 and M5) had a pterygomaxillary disjunction, whereas the other 2 (M2 and M4) did not.

The analysis of displacement in M1 showed that only the expander achieved maximum displacement (1 mm), but displacements of 0.50 to 0.84 mm were found in the first premolar. The same analysis showed that the greatest displacements, represented in red, were found in M5 (1.44 mm) and M4 (1.40 mm). That color was seen only in the teeth that anchored the expander, which suggests that they underwent the greatest buccal movement. Displacement was greater in the anterior region than in the posterior region (1.08 and 1.17 mm in M5 and 1.05 and 1.18 mm in M4), in agreement with findings reported in other studies.

In M2 and M3, displacement of the anterior region was 1.14 to 1.15 mm and 1.30 to 1.32 mm, respectively, which suggests that bone displacement increased in the anterior region closest to the intermaxillary suture during the beginning of activation. The tooth with the greatest movement was the first premolar, but its displacement was proportional to the anterior opening and its displacement was smaller in M2 and M3 than in M4 and M5. It has been shown that with SARPE, only two thirds of the total activation results in skeletal movement. The other third is tooth movement only. Tooth movement in all 5 models confirmed that expectation, particularly in M4 and M5. In these 2 models, teeth movement was greater than bone expansion, despite their initial opening.

Displacement analysis also showed a change in color hues in M3 and M5, in which the maxilla and the pterygoid process were separated. M2 and M4 had a gradual and discrete change in hue, suggesting that there is greater freedom of movement of the maxilla when pterygomaxillary disjunction is used, as reported by Pereira et al.

The results of MS analysis defined the main areas of traction and compression in the structure under study. There were areas of traction tension in the zone of transition between the end of the alveolar process of the maxilla and the palate itself. This tension is a continuation of the tension from the dental alveolar bone, which results from the expansive force applied by the expander. This tension passes through the dental roots and dissipates in the palate and the maxillary sinus.
floor owing to the proximity and close contact of the apices of posterior teeth with these structures. Therefore, the change in surface direction leads to an accumulation of tension in this area, similar to the accumulation that results from the mechanical deformation (bending) of surfaces.

The more uniform distribution of tension in models with conventional osteotomies suggests that bone resistance is greater, whereas the buildup of tension at certain points suggests breakups in cases of step osteotomy, perhaps owing to lower bone resistance. This fact may be associated with a variable maxillary movement, in addition to the desired transversal movement.  

The need to perform a pterygomaxillary disjunction has been the focus of controversy because some investigators believe that maxillary expansion can be accomplished successfully without the disruption of these structures, whereas others claim that only pterygomaxillary disjunction can ensure the optimal expansion of the posterior region of the maxilla, even when there is no rupture in the intermaxillary suture in all its extension. The intermaxillary suture in all its extension.

The im-movement, in addition to the desired transversal teotomy, perhaps owing to lower bone resistance.

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mation (bending) of surfaces.

The present results are in agreement with those reported in other FEM studies and suggest that the FEM may be used as a study model. Moreover, the step in the zygomaticomaxillary buttress and in the pterygomaxillary disjunction seems to be important to decrease the harmful dissipation of tensions during SARPE.

References