

ORIGINAL RESEARCH

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A finite element analysis of the effects of different skeletal protraction and expansion methods used in class III malocclusion treatment

Serhat Ozdemir, Merve Goymen

Gaziantep University Dentistry Faculty, Department of Orthodontics, Gaziantep, Turkey

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Abstract

This study aims to carry out an in-silico examination of the different skeletal advancement methods used in the treatment of maxillary retrusion patients. Computed tomography images of a young adolescent patient with maxillary retrusion were processed using three-dimensional medical image processing software to obtain a patient-specific model. Three different treatment scenarios were envisaged for the finite element analysis. In the first scenario, rapid maxillary expansion (RME) and face mask (FM); in the second, bone-assisted maxillary advancement and RME, and in the third, hybrid hyrax+mentoplate combination method were used. The hyrax screw was activated by 0.25mm in each model, with a force of 500g in the first scenario and 250g in the second and third scenario for each side. Von Mises stresses and the initial displacements were evaluated when different maxillary protraction methods were applied. We found that similar stress distributions were observed in the skull where the methods of RME/FM model and bone-assisted maxillary advancement were used. These stresses were higher than the hybrid hyrax+mentoplate combination method. When the displacement values were compared, anterior movement was found in the maxilla in the bone-supported model to include the middle face, while maxillary anterior movement of maxilla was detected on the Le Fort 1 level with the hybrid hyrax+mentoplate combination method. Dentoalveolar anterior movement was detected in the RME/FM model. Given the obtained stress distributions and displacement values, it has been observed that the bone-assisted maxillary advancement method provides more skeletal efficiency than the RME/FM and the hybrid hyrax+mentoplate combination methods.

Keywords: Finite element, Class III, mentoplate, hybrid hyrax, facemask

Introduction

Patients with skeletal Class III anomaly are admitted to orthodontic clinics due to aesthetic problems and chewing disorders. Skeletal Class III anomaly may present as maxillary retrusion, mandibular protrusion, or a combination of both. Studies show that the prevalence of maxillary retrusion in patients with skeletal Class III anomalies is in the range of 19.5-37.5% [1]. Successful results have been obtained using facial masks (FM) in the treatment of skeletal Class III anomalies associated with maxillary retrusion. With the FM treatment, a frontward force is applied to the maxilla to promote its growth by activating the circum-maxillary sutures [2]. Frequent use of the support of the teeth in the mixed dentition period as an intraoral anchorage unit for traditional FM often poses a number of disadvantages. Undesirable effects such as mesialization of the maxillary teeth, extrusion of the maxillary molar teeth, counter-clockwise rotation in the maxilla, clockwise

rotation in the mandibula, and increase in face length are seen with dental supported FM [3-5]. The fact that this equipment requires absolute cooperation creates a separate disadvantage. Lately, investigators have been leaning towards skeletal anchorage to reduce or eliminate these unwanted effects [6,7].

In their study, De Clerck et al. placed mini-plates in the zygoma and between the mandibular canine, lateral incisor teeth on both sides and obtained protraction in the maxilla by applying inter-maxillary elastics from these plates [6]. By applying direct force to the maxilla and mandibula with this method, they argued that pure orthopedic motion was obtained without dental side effects [6]. The disadvantages of this method are the need for surgical operation when plates are inserted and removed, and the fact that it is not recommended to perform the procedure before the eruption of the lower permanent canine teeth [6]. As an alternative to this technique, Benedict Wilmes applied two mini-screws to the anterior palatal region of the maxilla and fastened the rapid maxillary expansion (RME) screw to the mini-screws in the anterior and to the molar teeth in the posterior. In the mandibula, he inserted a single plate in the menthene region in the apical of the incisor teeth, and administered intermaxillary elastics from the

Corresponding Author: Merve Goymen, Gaziantep University Dentistry Faculty
Department of Orthodontics, Gaziantep, Turkey
E-mail: mervegoymen@gmail.com

upper molars to the two incisures on both sides. He stated that fewer surgical procedures were applied by placing two mini-screws in the anterior palate and placing plates one by one instead of two at a time in the mandibular region rather than the surgical placement and removal of miniplates placed on the right and left side of the zygomatic crests in the maxilla. He argued that this results in elimination of the dental side effects of both RME and maxillary protraction and achieving an effective maxillary advancement through early treatment before the lower permanent canine eruption [8]. When examining the literature, it is seen that studies reporting the treatment of Class III skeletal anomalies with skeletal anchorage methods are limited and the effects of these new methods are not yet known. Was the force really being transferred to the skeleton structures thanks to the screws on the palate, as argued by Wilmes?

In current literature, although many new methods are suggested, no comparative results have been mentioned with conventional methods. The purpose of this study is to compare the effects of skeletal advancement methods applied to the maxilla with two different techniques (hybrid hyrax-mentoplate combination) with those of conventional FM in terms of stress and bone displacement.

Material and Methods

Computed tomography (CT) images of a young adolescent (10-year-old) patient with maxillary retrusion and Class III malocclusion (Wits: -5.8, N-A: -6.5mm) treated at the Orthodontics Department of Gaziantep University's Dentistry Faculty received in the format of Digital Imaging and Communications in Medicine (DICOM) imagery with a cross-sectional thickness of 0.625mm were processed using three-dimensional (3D) medical image processing software (Materialise's Interactive Medical Image Control System (MIMICS)) (Materialise, Leuven, Belgium) and a patient-specific 3D model was obtained. The maxilla, mandibula and teeth were separated by color assignment (mask thresholding) to all pixels in the range of specific Hounsfield Units (HU) values. HU values are defined with different limit values depending on the tissue type or whether the patient is an adult or not. With low threshold values, soft tissues (connective tissue, vessels, etc.) and with high threshold values, dense bones (teeth, cortical bone, etc.) can be masked.

When constructing the periodontal ligament, the dental roots were given a thickness of 0.30 mm and then the PDL was created by obtaining the original shape of the teeth from this 3D model [9]. Later, all of the teeth were cut one by one according to their boundaries from the collum dentis and their PDL structures were obtained.

On the raw CT images, the HU value was set to -1024/315 and the Temporomandibular Joint (TMJ) model was obtained roughly by creating a point cloud of the condyle head and glenoid fossa. Then, the exact TMJ model was obtained through checks according to the coronal, axial and sagittal sections and determining the incision lines. The regions where the condyle head and glenoid fossa were located were removed by Boolean operation to obtain the TMJ model that overlaps with the boundary anatomies. Drawings were made of the expanders, screws, mini-plates and bands using the Computer Aided Three-Dimensional Interactive Application (CATIA) (Dassault Systemes Simulia Corp.,

Providence, RI, USA) run on a professional CAD/CAM-based software. All parts were prepared for the analysis model. The face mask was scanned using the Steinbichler Comet 5 4MP (Carl Zeiss Optotechnik GmbH Neubeuern, Germany) system method and transferred to the computer for finite element analysis. The Altair Hypermesh (Altair Engineering, Inc., Michigan, USA) software was used to make all the components interoperate and the analysis program Dassault Sytemes Abaqus 6.14 was utilized. A model of skull finite elements consisting of 4,250,445 tetrahedral elements and 828,747 nodes was obtained. Each of the models forming the structure was given a material (elastic modulus and Poisson's ratio) value describing their physical properties to define the dental structures of the created model, the bone and other regions in the software. (Table 1)

Table 1. Material Specifications (17, 34)

Material	Young Module	Poisson Ratio
Cortical bone	$1,37 \times 10^4$	0.26
Cancellous bone	33×10^3	0,30
Teeth	$1,96 \times 10^4$	0.30
Periodontal Ligament	$2,70 \times 10^4$	0.45
Miniplate, screw, expander, molar band 1	$1,05 \times 10^5$	0.35

The model needs to be fixed for a finite element analysis to be carried out. For this reason, the degrees of freedom on the appropriate parts of the model should be restricted. In our study, the same basic model was fixed at the foramen magnum [10], three different installations were planned, and the study was carried out on three models.

In the first model, a hyrax screw was used, which received support from the maxillary second deciduous molar tooth and the first permanent molar tooth on the model. Together with the RME, a force of 500g was given to each side so as to make an angle of 30° downward from the occlusal plane from the FM and the canine region in the buccal [11]. Simultaneously, the RME was activated at 0.25mm. In the second model, a hyrax screw was applied to the model supported by the first permanent molar tooth and the second deciduous molar tooth in a similar way to the first model. Four plates were placed on the infrazygomatic crest of the maxilla between lateral incisor teeth in the mandibula and the canine teeth [12]. The plaques were secured to the bone with two screws on the lower jaw and three screws [20] on the upper jaw, which are 5mm long with a diameter of 2.3 mm. A force of 250g [13] was applied to each side. Simultaneously, the RME was activated at 0.25mm. On the third model, two mini-screws were placed on the model on the anterior of the palate, 2mm in width and 9mm in length, parallel to each other and adjacent to the median suture with 2mm in alignment with the premolar teeth [8, 14]. The hyrax was adapted to these two screws and molar bands on the first molar tooth (Table 2) (Figure 1).

One mini-plate was inserted into the lower jaw horizontally into the apical region of the incisor teeth with four screws [14], 2 mm wide and 5 mm long. At the mucogingival level, the incisures were extended through the canine lateral teeth and a force of 250g [14]

was applied to these incisures from the upper molars for one side. The RME was activated at 0.25 mm. (Table 2) (Figure 1)

Table 2. Identification of treatment modalities

Scenario No.	Treatment Model	Force Application	Force Direction
1	Rapid Maxillary Expansion + Facemask	500g	30° to occlusal plane
2	Rapid Maxillary Expansion + Bone-Assisted Maxillary Advancement	250g	from miniplate to miniplate
3	Expansion with Hybrid Hyrax + Maxillary Advancement using Mentoplate	250g	from molar band to mentoplate

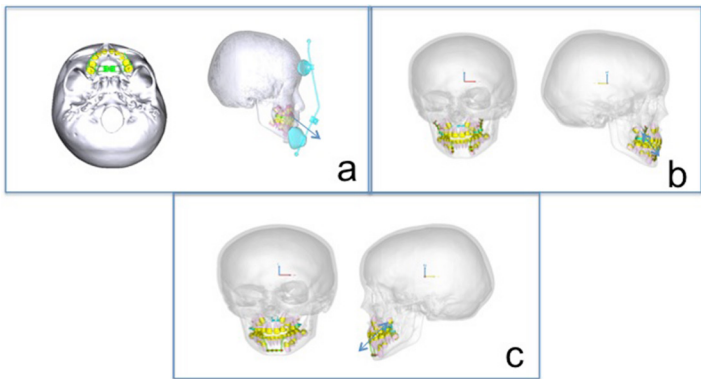


Figure 1. Treatment modalities and directions of force application (a) treatment scenario 1 (b) treatment scenario 2 (c) treatment scenario 3

RESULTS

In our study, the Von Mises stresses on the maxillary complex were evaluated when three different maxillary protraction methods were applied. In addition, movements in three planes of space in maxilla (X-axis represent the transversal plane, Y-axis the sagittal plane and Z-axis the vertical plane) were evaluated.

The results of all the measurements were given as colored figures. In these images, each color corresponds to a numerical value. The color corresponding to each value was indicated on the left side of the figures. Stresses in our study were referred to as MPa and displacements as mm.

The results of the analysis made in treatment model 1 showed von Mises stress in the buccal region of the maxillary posterior teeth. The von Mises values gradually decreased upwards, forwards and backwards, and ended in alignment with the glabella and frontozygomatic suture above, in the pterygoid processes in the posterior, and in the anterior nasal spinal region in the anterior. The von Mises values varied between 10-17.5MPa zygomaticomaxillary and frontonasal suture (Figure 2-a). Following a frontal examination and analysis, the highest von Mises stress value was measured as 136.5MPa in the maxillary cortical bone in the mesial of the second left deciduous molar tooth. The von Mises stress values were particularly concentrated in areas where the FM was applied (the region from the first permanent molar to the canine

tooth). The high von Mises stress values measured here decreased towards the zygomatic arc and the glabella and ended in the frontal bone (Figure 2-b).

An analysis of treatment model 2 showed that von Mises stress values were the highest in the second deciduous molar mesial alveolar crest. Decreasing upwards, forwards and backwards, they reached a value of 15-20 MPa in the frontonasal suture in the infra-zygomatic area and in the zygomaticotemporal region in the fronto-zygomatic area (Figure 2-c). The highest von Mises stress value in the cortical bone was measured as 135.2MPa in the maxillary bone in the mesial of the left deciduous second molar tooth. The von Mises stress values in the buccal cortical bone region were high in the maxillary buccal bone region located between the canine tooth and the permanent first molar tooth. The high von Mises stress values measured here decreased towards the zygomatic arc and the glabella and ended in the frontal bone (Figure 2-d).

When treatment 3 model was examined, it showed that the von Mises values were high in the alveolar crest in the buccal of the posterior teeth and in the zygomatic crest as they decreased upwards and forwards. The Von Mises values ended at the zygomatic protrusion of the glabella frontal bone. The values were measured at approximately 10MPa in the frontonasal suture and zygomaticofrontal suture and the infraorbital area. In the lateral examination, the highest stress was measured at 40MPa in the mesial of the permanent first molar tooth socket. The value decreased forward and upward, while it increased again in the alveolar crest in the canine area. It was in the region of 10-15MPa around the zygotico-maxillary suture and the frontonasal suture (Figure 2 d-e).

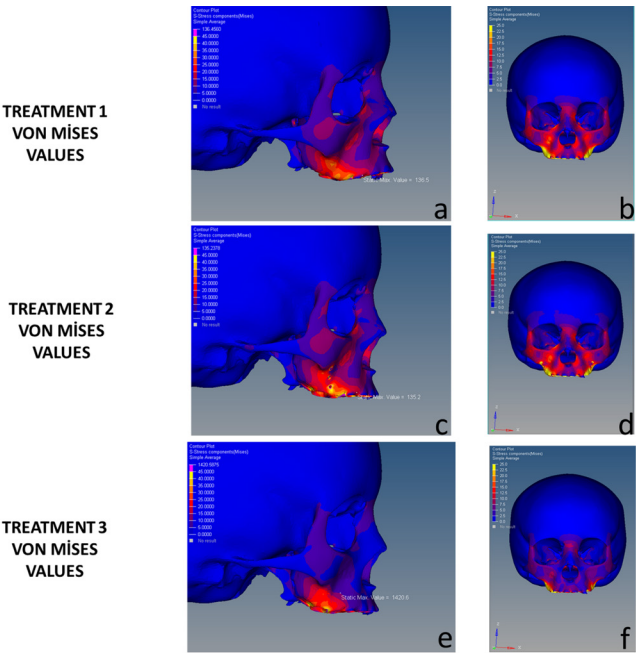


Figure 2. Von Mises stress values of treatment types (a) lateral view of treatment scenario 1 (b) frontal view of treatment scenario 1 (c) lateral view of treatment scenario 2 (d) frontal view of treatment scenario 2 (e) lateral view of treatment scenario 3 (f) frontal view of treatment scenario 3

In the treatment 1 model, the displacements observed on the X-axis, the highest value being 12529x10⁻⁵mm, occurred in the alveolar crest aligned with the permanent molar tooth and the

second deciduous molar. The movement on the X-axis gradually decreased towards the anterior, posterior, and superior, ending in the lateral tooth socket in the front, in the zygomatic diaphysis above and the pterygoid process behind. In the anterior, the X-axis displacement value was measured as zero (Figure 3-a). Looking at the displacement from the Y-axis, it was observed that the maximum movement was 63×10^{-5} mm in the posterior region of the alveolar crest. Anterior motion was observed in the frontal exit of the maxillary bone and in the zygomatic diaphysis with gradual decrease in the value upwards, forwards and backwards. In ANS and PNS, the amount of anterior movement was equal and measured as approximately 20×10^{-5} mm (Figure 3-b). In the treatment model 1, there was a vertical downwards movement in the anterior, posterior and alveolar of the maxillary complex. The highest value was measured as 70560×10^{-5} mm at the ANS point and the anterior region of the maxillary. The amount of downward motion in the posterior region was 1291×10^{-5} mm. The vertical movement reached up to the frontonasal suture (Figure 3-c).

In the treatment 2 model, the transversal displacement in the maxillary complex was made to decrease gradually forwards, backwards and upwards where the molar region became the alveolar crest center as in the treatment 1 model and the highest value was measured as 12544×10^{-5} mm in the molar alveolar crest. In the anterior maxilla, the value was zero (Figure 3-d). It was observed that the displacement movement in the sagittal plane spread more than the maxillary complex. The forward maxillary movement showed a gradual decrease from the alveolar upwards, extending to the suture naso-maxillary above in the anterior and to the upper border of pterygoid processes behind. The highest values were 63×10^{-5} mm in the alveolar crest and decreased to as low as 13×10^{-5} mm in the upper limit (Figure 3-e). In the vertical displacement assessment, treatment model 2 showed a great similarity to model 1. The highest values were 7017×10^{-5} mm in the vicinity of the anterior nasal spine and downwards and 1291×10^{-5} mm in the posterior (Figure 3-f).

In the treatment model 3, displacement values on the X-axis started at 15481×10^{-5} mm with the molar tooth taking the central location and continued downwards, forwards and backwards, extending to the frontal exit of the zygomatic bone. The anterior value was zero (Figure 2-g). At the Y-axis a forward motion in the maxilla caught our attention at Le Fort 1 level with almost a homogeneous intensity. The highest value was 63×10^{-5} mm (Figure 2-h). For the Z-axis displacement values, there were equal values in the anterior and posterior of the maxilla and it was downwards at about 1291×10^{-5} mm. The anterior vertical movement was limited only to the area under the nasal floor (Figure 3-i).

Discussion

According to Wolff's Law, bones will adapt to the stresses under which they are placed [15]. The functional changes in the bone are related to changes in the internal and external structures of the bones. Depending on the stress, the bones may become elongated, shortened or stretched [15,16].

In a study, Lee et al. [17] evaluated the application of protraction with two different methods using the finite element analysis via two mini-plates, one of which was inserted into the infra-zygomatic crest, and the other into the outer edge of the nasal wall for the maxilla. They found a forward and downward maxillary movement in the simulation with the mini-plate placed outside the nasal wall, while the maxilla was found to rotate counterclockwise in the maxillary protraction on the infra-zygomatic area. Yan et al. [18] compared a maxillary protraction performed with skeletal and dental anchorage support using a finite element analysis. The dental anchorage was taken from the permanent first molar tooth and the skeletal anchor was taken from the infra-zygomatic region. The effects of the protraction forces applied at 0° , 10° , 20° and 30° angles on the two models downward from the occlusal plane were evaluated and as a result, it was found that the maxilla moves forward and downward without rotation through the application of a proximal force applied downwards for the skeletal support by 20° from the occlusal plane and by 30° for the dental support. In a finite element analysis, Tanne et al. [19] exerted force with a magnitude of 1000g on the maxillary through the first molar teeth and another force within the range of $+90^\circ$ to -90° downward and upward from the occlusal plane and they determined that the rotation was removed when a force of 30° was applied downward from the occlusal plane. Katada et al. [20] conducted a finite element analysis when they applied a force of 1000g on the maxilla to be parallel to the occlusal plane from the permanent first molar tooth, and as a result, they found that the maxilla rotated counterclockwise. In a finite element analysis, Yu et al. [21] found that the counter-clockwise rotation of the maxilla was minimal when force was applied from the first premolar tooth with an angle of 20° downward from the occlusal plane. In a finite element analysis, Gautam et al. [10] performed maxillary protraction with a force of 1000g applied at the level of the canine teeth with an angle of 30° from the occlusal plane and they found that the maxilla rotated counter-clockwise.

In this study, a downward movement of the maxilla was observed in the anterior and posterior regions on the Z-axis where vertical direction movements were evaluated under treatment model 1. The amount of downward movement around the spina nasalis anterior was less than that of the posterior, and therefore there was

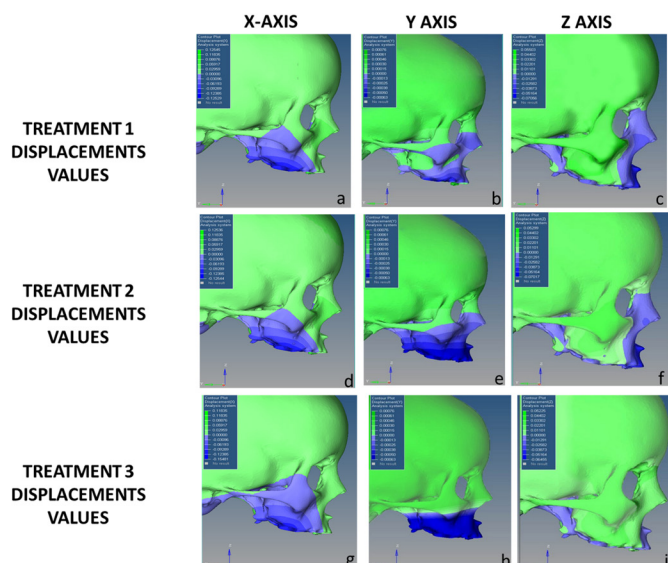


Figure 3. Displacement values of treatment types (a) x-axis of treatment scenario 1 (b) y-axis of treatment scenario 1 (c) z-axis of treatment scenario 1 (d) x-axis of treatment scenario 2 (e) y-axis of treatment scenario 2 (f) z-axis of treatment scenario 2 (g) x-axis of treatment scenario 3 (h) y-axis of treatment scenario 3 (i) z-axis of treatment scenario

clockwise movement on the maxillary plane. Results similar to the first treatment model were obtained from the second treatment model. For the first model, there was little difference in the amount of movement (39×10^{-5} mm), while in the second model there was clockwise rotation on the maxillary plane. In the third model, the amount of motion in the anterior and posterior regions was equal and there was no rotation on the maxillary plane. It was thought that this result was due to the fact that the skeletal anchorage is greater in the third model.

We found that the maxilla rotated clockwise in the model where the FM was applied downwards from the occlusal plane at an angle of 30° and that the maxilla also rotated clockwise with the bone-assisted maxillary protraction method and that the maxilla did not rotate with the hybrid hyrax mentoplate combination method. When evaluated in terms of the rotation of the maxillary plane, the hybrid hyrax/mentoplate model can be considered to be more advantageous than the other two methods.

In the comparison of displacement values in our study, transversal changes occurred at very similar boundaries and the values on the X-axis for treatment models 1 and 2, while the changes in the third model extended to the upper and lower parts of the skull and the value at the center of motion (the circumference of the permanent molar teeth in model 3, the circumference of the second molar deciduous teeth, and the permanent molar teeth in the first two models) was greater in model 3. The transversal movement ended at the front of the maxilla. From these data, it can be said that the hybrid hyrax is more efficient for the transversal expansion process.

Different distributions have taken place for the three models on the Y-axis, on which the forward movement of the maxilla has been evaluated. In the first treatment model, the highest motion occurred at the top of the alveolar crest and was concentrated in the crest in the canine tooth region. While the anterior movement reached the end of the frontal protrusion of the maxillary, it did not extend above the processus alveolaris in the posterior region. When these movements in the first model are examined, it is thought that molar teeth are exposed to motion and dragged forward, and that skeletal effect is more intense at the dentoalveolar level. It was seen that the forward movement of the maxilla in the second treatment model was more homogeneous in the alveolar process and that the first model had the highest value. It decreased gradually upwards, and in contrast to the first model, a more homogeneous movement occurred in the posterior maxilla. In the second model, the forward skeletal movement of the maxilla was much higher than that of the first model. The absence of localized areas of motion in the bone surrounding the teeth suggests that the movement in the teeth is only parallel to the maxillary motion. The maxilla's forward movement was deep enough to cover the middle front. The amount of anterior movement of the maxilla in the third treatment model was equal in all areas under the zygomatic bone of the maxilla and was found to be the highest value and the same as the highest value of the first two models. The motion was homogeneous and higher, though lower than the first two models, and there was no separate density in the bones around the teeth. Although there were no dental side effects, the movement at Le Fort 1 level suggests that the positive effect on the middle front was lower compared with the second model.

Tanne et al. [19] applied a protraction force of 1000g over the permanent first molar teeth from different directions and they found that the stress distributions were scattered. They reported that the most uniform distribution in the sutures was obtained at an angle of 30° to the occlusal plane. In another finite element analysis, Tanne et al. [22] applied force on the maxilla in alignment with the molar teeth and in parallel to the occlusal plane downwards at an angle of 30° and found that the stress distribution in the sutures was not uniform for both cases. In a finite element analysis, Tanne and Sakuda [23] applied a protraction force of 1000g in parallel to the occlusal plane from the region of the first permanent large molar teeth and they found stress in the bones around the zygomatico-maxillary, and the fronto-zygomatic and frontonasal sutures, as well as in the zygomatic maxillary and the frontonasal sutures. At the same time, they reported seeing high levels of strain on the maxillary bone side of the zygomatic-maxillary suture. Gautam et al. [24] found that the highest von Mises stress values were in the sphenozygomatic, zygomatico-maxillary and zygomatico-temporal sutures, respectively, in a finite element analysis study with RME and RME performed with a 30° angle and a protraction force of 1000g. The lowest stresses were found in internasal and nasomaxillary sutures. According to the authors, the different pushing and pulling strains in the sutures are the horizontal protraction force applied on the maxillary. Yan et al. [18] compared a maxillary protraction performed with skeletal and dental anchorage support using a finite element analysis. The dental anchorage was taken from the permanent first molar tooth and the skeletal anchor was taken from the infra-zygomatic region. The effects of the protraction forces applied at 0° , 10° , 20° and 30° angles on the two models downward from the occlusal plane were evaluated and higher values of straining were seen in the zygomatico-maxillary, zygomatico-temporal and pterygopalatine sutures in the skeletal supported model with the same force vector in comparison to the tooth supported model. The opposite was true in the case of the nasion and nasal ala. Based on these findings, the authors stated that there was stress that would induce growth in the sutures of the maxilla posterior with the skeletal-supported maxillary protraction and as for dental-assisted protraction, more osteogenesis activity occurred in the nasal region, and the profile reflection was better. In a limited element analysis in 2012, Lee and Baek [25] performed protraction with mini-plates placed in the maxillary aperturapiriformis and the infra-zygomatic region and as a result, the stress in the frontonasal and frontomaxillary and zygomatico-maxillary and pterygomaxillary sutures was found to be higher in the model with the infrazygomatic plate than in the model supported by the aperture piriformis region. Similarly, in parallel with the findings of Tanne and Sakuda [23] and Gautam et al. [10], the highest von Mises stress values in both models were seen in the pterygomaxillary, zygomatico-temporal, zygomatico-maxillary and frontonasal sutures, respectively.

The stress distributions for the three models in our study were very similar to these studies, and were focused in the bones around the frontonasal, frontozygomatic, and zygomaticomaxillary sutures. Contrary to these studies, we think that excessive accumulation of stress in the buccal alveolar bone emanates from the RME.

In our study, it was observed that the stress distribution in the first and second treatment simulations were very close to each other. In particular, the similar stress distribution in the areas directly

affected by the RME showed consistency with the same amount of activation for the same expansion system. Stress distribution was almost the same for models 1 and 2, but at some points (in the zygomatic bone, frontonasal suture, frontozygomatic suture and zygomatic bone), a more intense stress distribution occurred in the bone-supported proximal model. The stress distributions in the hybrid hyrax model were lower than those in the first and second models. Especially striking were the lower stress levels in the frontonasal suture, the zygomatic bones and around the zygomatico-maxillary sutures compared to other models. The fact that the stress increased in model 3 in the mesiobuccal socket of the permanent molar tooth suggests that the protraction force was not indirectly transmitted to the maxillary bone, with the hyrax screw concentrating instead in the alveolar crest.

The limitation of this study is that the study was carried out in the laboratory and only gives the stress distribution and displacement values when force was first applied. Clinical randomized controlled studies to be performed in the future may better clarify this issue.

Conclusion

In the RME + FM model, anterior movement occurred mostly in the alveolar protrusion and the frontal region of the maxillary bone, while maxillary advancement at Le Fort 2 level occurred in the bone-assisted maxillary advancement model. Hybrid hyrax mentoplate combination model showed progress at Le Fort 1 level.

It was seen that the undesired mesialization movement of the posterior teeth in the maxilla occurred in the RME + FM group and not in the other two models.

In the RME + FM model and in the bone-assisted maxillary advancement model, the maxillary plane rotation was clockwise, while there was no rotational movement in the hybrid hyrax mentoplate combination model.

Considering the maxillofacial complex, it was found that the stress values in the RME + FM model were similar to the bone-supported maxillary advancement model and at higher levels than in the hybrid hyrax mentoplate model.

Given the obtained stress distributions and displacement values, it seems that the bone-assisted maxillary advancement method may provide more skeletal efficiency than the rapid upper jaw expansion/face mask and the hybrid hyrax + mentoplate combination methods. It is considered that the hybrid hyrax mentoplate combination method cannot be as effective as the bone-assisted maxillary advancement method on the middle front because of the anterior movement being limited to the lower parts of the maxilla.

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Competing interests

The authors declare that they have no competing interest

Financial Disclosure

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Ethical approval

Before the study, permissions were obtained from local ethical committee.

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