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Original Article

Comparison of the skeletal and dental changes of tooth-borne vs. bone-borne expansion devices in surgically assisted rapid palatal expansion: A finite element study

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ABSTRACT

Background: The aim of this study was to compare the skeletal and dental changes of a tooth-borne (Hyrax) and a bone-borne (Smile distractor) expansion devices using three-dimensional model of a human skull.

Materials and Methods: A finite element model of human skull was generated using data from 3-D CT scans of an 11-year-old female child. Then a Hyrax expander (tooth-borne appliance) and Smile distractor (bone-borne appliance) in three different positions were adapted to the finite element model and expanded for 0.5 mm simulating the clinical situation. The 3-D pattern of displacement and stress distribution was then analyzed.

Results: The results of this study showed that screw position affects the stress and displacement pattern within the nasomaxillary complex and maxillary dental arch.

Conclusion: Closer teeth feel more stress and undergo more displacement than the farther ones. Moreover, skeletal effects of the Smile distractor were greater than of Hyrax in all different positions.

Key Words: Dental, expansion device, finite element method, skeletal

INTRODUCTION

Rapid maxillary expansion (RME) procedures have been used over the past century (Angle 1860) and have been shown to be an effective and valuable method in treatment of patients exhibiting maxillary constriction.[1] Surgically assisted rapid maxillary expansion (SARPE) is indicated in adult patients to correct maxillary deficiency.[2] It is frequently utilized to expand the maxilla in adolescents and adult patients. This technique is used because of the increasing thickness of the bony structures with simultaneous reduction in the elasticity that occurs with skeletal maturity and also the increasing ossification of the mid-palatal suture.[3]

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Different types of RME devices (i.e., Hyrax, Hass, removable appliances, acrylic-bonded appliances, and Rotterdam palatal distractor)[4] have been used by clinicians and many studies have been conducted to investigate dental and skeletal changes.[5-8] There are two major types of expansion devices: 1-Tooth-borne and 2-Skeletal-borne. Skeletal anchorage has been reported since the early 1980s[9] and dental expansion would be avoided by fixing the screws directly to the hard palate for maximizing skeletal changes.[10] This type of expansion causes less tipping of dental segments.[11,12] Tooth-borne appliances produce greater dentoalveolar effects by increasing the palatal angulation of the alveolus.[13] Hyrax appliance has been shown to exert the least force compared to Hass or other types of screws and removable appliances,[14,15] moreover it is one of the most useful appliances for maxillary expansion.[10,16-19] Smile distractor is a new reliable and safe appliance which is easy to apply and to remove by the surgeon, easy to activate twice a day by the patient and easy to be monitored by a professional.[20]

Most of the authors agree on these issues: 1-V-shape opening of the mid-palatal suture during RME[21,22] 2-More dental and skeletal expansion in the molar region than the canine.[23] 3-Greater amount of dental and skeletal relapse in the canine region than the molar.[24]

Although previous studies have provided detailed knowledge regarding the RME technique and the effects of Hyrax and skeletal expansion device, the standard position of these appliances has not been introduced, moreover most of the previous studies have focused on evaluation of stress distribution in upper skeletal structures.[1,25,26]

Stresses are induced in all bony structures of the skull during maxillary expansion, so, it can be assumed that both the level and localization of these stresses are influenced by the localization of the appliance and extent of the appliance activation.[25,27,28] Since there is no agreement on the best and standard position of the expander in the palate regarding its effect on the amount of expansion and the exact place in which it happens (various structures beneath the cranial base), identifying the most appropriate location of expansion device, would have a major impact on achieving the best results from expansion.

In order to explain the mechanical consequences of the maxillary expansion, researchers have used finite eement method (FEM) and derived useful conclusions about the stress and displacement distribution on the craniofacial complex.[16] FEM has been used to determine the displacement, internal stress, and strain in the craniofacial complex.[26]

The aim of this study was to compare the skeletal and dental changes of Hyrax and Smile distractor according to different loads and location of devices by using the FEM as applied to the three-dimensional model of a human skull.

MATERIALS AND METHODS

In this study, a three-dimensional finite element model of cranium (excluding mandible) was needed. The analytical model was developed from sequential computed tomography (CT) scan images taken at 2-mm intervals of an 11-year-old female child with neurological difficulties and no missing or malformed permanent teeth (except 2nd or 3rd molars), no gross anatomic malformations, and no discontinuity in the osseous anatomy.

As CT scans just propose the coordinate data of cloudy scatter points in the material boundaries, they may not be acceptable to directly generate FE (CAD/CAM/CAE) models. Hence, different data fitting techniques have to be employed in order to create a mathematical model. The cranium (excluding mandible) was modeled through CT-scan image processing of the anatomic data by CT-scan image control system (Mimics: Materialise Interactive Medical Image Control System; Leuven, Belgium). The external geometry from CT-scan image control system was exported in stereolithography (STL) format. As the STL file could not be further processed due to CAD/CAE inconsistency, the software of SolidView (SolidView/Pro3.53, Solid Concepts, Inc.) and SolidWorks (SolidWorks Corp, Concord, MA) were used, by taking care not to lose any important geometric information, leading to a CAD/CAE model. The midpalatal suture, periodontal ligaments and also palatal mucosa were simplified and considered to be uniform, equal to 0.5, 0.25, and 2 mm in width, respectively. As surgically assisted RPE (SARPE) was aimed, the osteotomy cuts were simulated on the maxilla model according to the literature.[29]

The expansion appliances of Hyrax (Dentaurum) and Smile distractor (Titamed, D-Series) were directly developed in SolidWorks software [Table 1] in three different positions; # 1: along canine, # 2: along the second premolar, and # 3: along the first molar.

Finally, the solid models of maxilla, teeth, mid-palatal suture, palatal mucosa, and PDLs were assembled. The natural teeth angles in three dimensions of tip, moment, and inclination reported by Andrews were considered to place teeth in the alveolar bone. Then, the Smile distractor, Hyrax and the solid models of the bands around the first premolars and the first molars in three different positions were assembled

Table 1: The dimensions of expansion devices

Expansion device	Horizontal dimension	Postero-anterior dimension	Vertical dimension
Hyrax	9.4	10.9	4.0
Smile distractor	17	1.8	1.8

separately on the model. Then, the entire models were exported to FEA software (ABAQUS V6.6-3; Simulia Corp., Providence, USA).

Material used in the models were assumed to be linear elastic, isotropic and homogeneous and were adopted from the literature [Table 2].[30,31]

The different anatomical parts were meshed with four-node tetrahedral solid elements. Each model comprised approximately 380,000 elements and 95,000 nodes. Suitable boundary conditions were imposed; a zero-displacement and zero-rotation condition was imposed on the nodes around the foramen magnum. Although application of a known force is possible with FE modeling, but for the purpose of being more close to the reality; a known laterally directed 0.5-mm displacement (activation) was applied (simulating the typical clinical first session activation of the RPE screws).

RESULTS

Table 3 shows the amounts of transverse tooth displacement in both expansion devices. Findings show that in all models central incisors were the least displaced teeth. The maximum displacement was related to first molar in all models except H1, in which first premolar had the maximum displacement [Figure 1].

Transverse displacement of mid-face skeleton [Table 4] shows that in all models, the most expansion occurred at the alveolar part and the zygomatic buttress was at the next level [Figure 2].

In all models the transverse displacement in zygomaticofrontal suture and inferior orbital rim was zero, which means no displacement occurred in these regions as well as zygomatic buttress in H1, H2, and H3 [Table 4]. Negative numbers in this table represents for areas which constriction occurred.

Maximum stress of Von-Mises in PDL of first premolar and molar teeth are shown in Table 5. Maximum stress of Von-Mises in PDL of first premolar was greater than of first molar in all models except S1, S3. There was also much greater amount of stress in all different positions of Hyrax than Smile distractor [Figure 3].

According to data from tables, paired comparisons show that with changes in expansion device position, displacement, and stress distribution pattern changes in dento-skeletal sutures and structures.

Table 2: Material properties

Material	Young's Modulus (MPa)	Poisson's Ratio
Tooth	20000	0.3
PDL	0.7	0.45
Bone	10000	0.3
Stainless Steel	193000	0.3
TMA	103400	0.33
Suture	0.7	0.45
Mucosa	10	0.4

Table 3: Displacement of the teeth (Millimeter)

Model	The central incisor	The lateral incisor	Canine	The first premolar	The second premolar	The first molar
H1	0.029	0.029	0.029	0.355	0.049	0.297
H2	0.008	0.008	0.027	0.355	0.027	0.355
H3	0.007	0.007	0.019	0.108	0.025	0.119
S1	0.0006	0.025	0.042	0.067	0.071	0.083
S2	0.088	0.093	0.124	0.144	0.164	0.184
S3	0.01	0.029	0.049	0.075	0.094	0.126

Table 4: Displacement of the mid-face skeleton (Millimeter)

Model	The alveole	The anterior part of alveole	The zygomatic buttress	The inferior orbital rim	The zygomatico frontal suture
H1	0.043	−0.015	0	0	0
H2	0.039	0.0001	0	0	0
H3	0.047	−0.0105	0	0	0
S1	0.080	−0.0121	0.011	0	0
S2	0.174	0.058	0.058	0	0
S3	0.102	−0.018	0.042	0	0

Table 5: Maximum Von-Mises stress in PDL of first premolar and molar teeth (MPa)

Model	PDL of first premolar	PDL of first molar
H1	3940	420
H2	4410	515
H3	1450	259
S1	23	26
S2	32	27
S3	9	31

DISCUSSION

Publication on the FEM-based simulations of RME in the field of orthodontics (Iseri *et al.*; Holberg *et al.*; Jafari *et al.*)[1,25,28] have been restricted until now to RME carried out without surgical assistance. Simulations with measurement of the stress-reducing

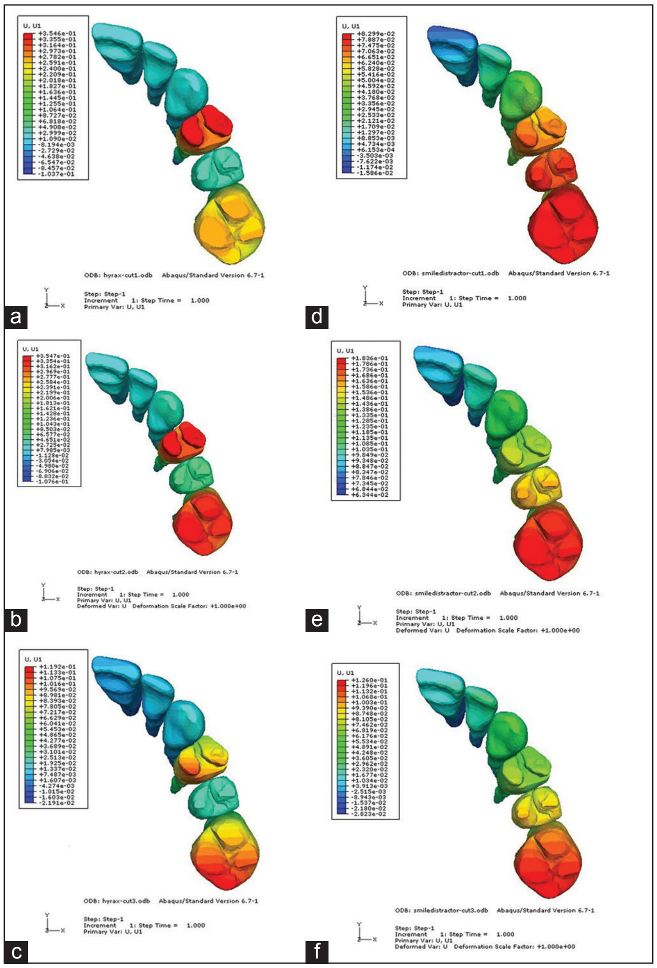

Figure 1: Teeth displacement (millimeter) (a) Hyrax 1 (b) Hyrax 2 (c) Hyrax 3 (d) Smile distractor 1 (e) Smile distractor 2 (f) Smile distractor 3

effect of surgical procedure have not been widely reported in the literature.

Several studies based on FEM used shell models[5-8,32] which can not simulate the mechanical behavior of maxillofacial skeleton properly due to histological and anatomical nature of the bone. In this study solid elements were used to give better stress transmissibility, therefore, this model is a better representation of a real human skull than the previous models.

In H1, H3, S1, and S3 models, a constriction occurred at the central incisor alveolus which could be due to determining the immediate effects of expander activation on the simulated models of facial skeleton. This is in contrast with Hass, Wertz, and Davidovitch *et al.*[5,6,8,32] findings.

In all models, there was an expansion in the posterior part of the alveolus which was greater than the anterior part in H2 and H3 models. Since Hyrax

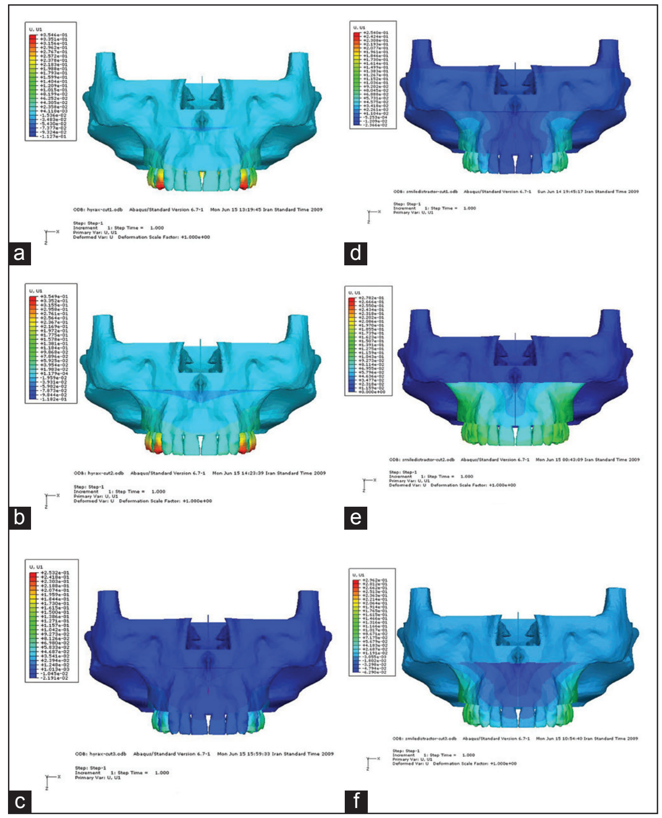

Figure 2: Transverse displacement of mid-face skeleton (millimeter) (a) Hyrax 1 (b) Hyrax 2 (c) Hyrax 3 (d) Smile distractor 1 (e) Smile distractor 2 (f) Smile distractor 3

expander is a tooth-borne appliance, the nearer its placement to posterior segment, would result in more posterior expansion. Also no displacement observed at the infra-orbital rim and ZFS in all models which could be related to reconstruction of the surgical cuts on the models. In spite of the expansion occurring at the zygomatic buttress in all S models, no expansion was observed in this area in H models. It could be explained by the bone-borne vs. tooth-borne nature of Smile distractor and Hyrax expanders. Smile distractor generates skeletal expansion which could be transmitted to upper parts of cranium through several sutures.

Our study confirms that the maximum lateral expansion was observed in the posterior area and it decreased progressively in the anterior aspect. As we mentioned before, many authors agree on the issue of V-shape opening of the suture during RME which means more dental and skeletal expansion in the molar region occur than the canine.[23] This is consistent with Gautam *et al.*, Issacson and *Ingram*, Lugravere *et al.*, and Proffit and Fields findings,[3,7,33,34] but it is in contrast with Hass, Wertz, and Davidovitch

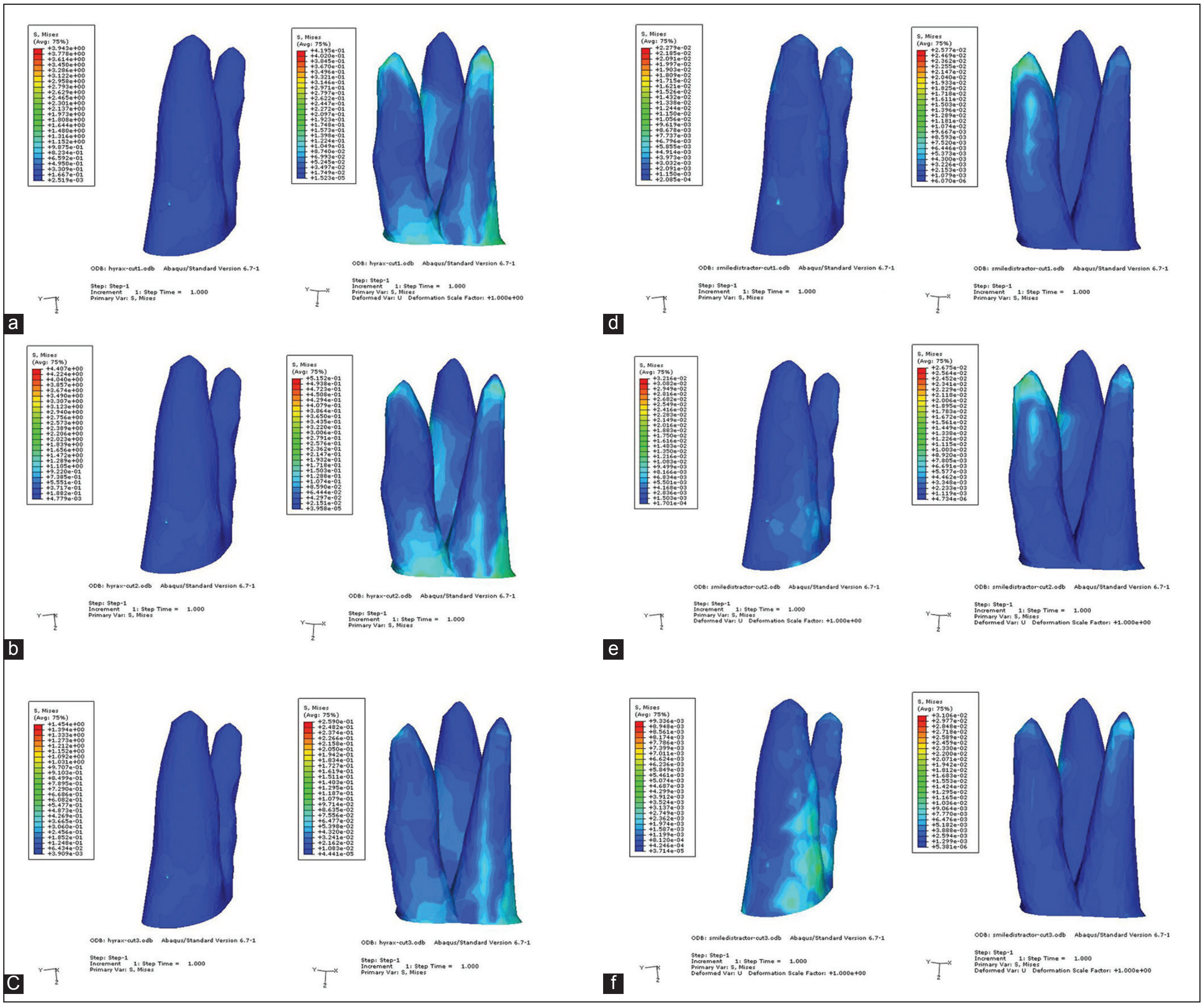

Figure 3: Stress of Von-Mises in PDL of first premolar (left) and molar (right) teeth (MPa) (a) Hyrax 1 (b) Hyrax 2 (c) Hyrax 3 (d) Smile distractor 1 (e) Smile distractor 2 (f) Smile distractor 3

et al., findings[5,6,8,32] since they did not reconstruct the surgical cuts on models.

In all models except H2 and S2 models a constriction occurred at the onset of movement which could be related to the expansion device position in H3 and S3 models and the components of the force vectors which compress the anterior area once movement begins in H1 and S1 models. This is in contrast with Hass, Wertz, and Davidovitch *et al*.,[5,6,8,32] findings due to the expansion device position and also the immediate effects of these models on the facial skeleton.

Pavlin and Vukicevic,[35] reported that in the frontal plane the center of rotation passes through the lower part of the nasal process. In our study the center of rotation was observed around the anterior nasal spine. This is in contrast with the Tausche *et al*.,[11,12] findings, who mentioned the center of rotation about the frontonasal suture. In fact, the explanation of the lower position of center of rotation in our study is that in both expanders the more anterior placement of the appliances caused the more upper position of the center of rotation in frontal view.

Ninety-five percent decrease of Von-Mises stress in Smile distractor compared to Hyrax expander in all positions, is due to the bone-borne nature of Smile distractor in which most of the stresses transfer to the bony structures primarily.

CONCLUSION

In conclusion, compared with the Hyrax expander (tooth-borne appliance), skeletal effects of the Smile distractor (bone-borne appliance) was greater whereas the amount of stress generated in PDL was less in all different positions of devices. In application of transverse forces, the expansion in frontal view was an inverted V, with more expansion in the posterior region. In all models no significant displacement observed at the structures and sutures above the surgical cut.

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