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"Comparative evaluation of stress distribution, displacement pattern and buccolingual angulation between four different bone-borne rapid palatal expanders in bilateral cleft lip and palate patients:A three-dimensional Finite Element Analysis".

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ABSTRACT

Background: Bilateral cleft lip and palate (BCLP) patients commonly present with maxillary transverse deficiency requiring palatal expansion. Conventional tooth-borne expanders often produce undesirable dentoalveolar effects such as buccal tipping and periodontal stress. Bone-borne rapid palatal expanders have been developed to enhance skeletal expansion while minimizing these adverse effects. However, limited evidence is available comparing the biomechanical performance of different bone-borne and bone and tooth borne rapid palatal expander designs in terms of stress distribution, displacement pattern, and buccolingual angulation in BCLP patients using three-dimensional finite element analysis (FEA).

Aim: To comparatively evaluate stress distribution, displacement pattern, and buccolingual angulation among four different bone-borne rapid palatal expanders in bilateral cleft lip and palate patients using three-dimensional finite element analysis.

Materials and Methods: A three-dimensional finite element model of the maxilla of a bilateral cleft lip and palate patient was constructed from cone-beam computed tomography (CBCT) data. Four rapid palatal expansion designs—Hybrid Hyrax, MARPE No-DS, MARPE DS with three miniscrews, and MARPE DS with four miniscrews—were virtually adapted to the model. Standardized expansion forces were applied under identical simulation conditions, and von Mises stress distribution, displacement pattern, and buccolingual angulation were analyzed.

Results: All four expansion systems demonstrated distinct biomechanical responses. The Hybrid Hyrax appliance produced the highest stress concentration, displacement, and buccolingual angulation, indicating predominantly dentoalveolar effects. MARPE No-DS exhibited the lowest stress, negligible displacement, and no measurable tooth angulation, suggesting predominantly skeletal expansion. Both MARPE DS designs produced intermediate responses, with the four miniscrew configuration demonstrating more uniform stress distribution, controlled displacement, and symmetrical tooth angulation than the three-miniscrew design, indicating superior biomechanical stability.

Conclusion: The biomechanical performance of rapid palatal expanders varied according to the anchorage design. Bone-borne expanders, particularly the MARPE DS with four miniscrews, provided a more favourable balance between skeletal expansion and controlled dentoalveolar effects compared with the Hybrid Hyrax appliance. Three-dimensional finite element analysis proved to be a valuable method for evaluating appliance biomechanics and may assist clinicians in selecting the most appropriate expander for patients with bilateral cleft lip and palate....

INTRODUCTION

Cleft lip and palate (CLP) is one of the most common congenital craniofacial anomalies, affecting approximately 1 in 700 live births. Patients with CLP frequently present with maxillary transverse deficiency due to congenital deformity and the restrictive effects of surgical repair, making transverse expansion an essential component of orthodontic treatment.[1]

Bilateral cleft lip and palate patients commonly exhibit a constricted maxillary arch, posterior crossbite and dental crowding. Scar tissue following surgical repair further restricts transverse maxillary growth, making correction of transverse deficiency an important objective of orthodontic treatment.[2]

Conventional rapid palatal expansion (RPE), such as Hyrax and Haas appliances.

They effectively corrects maxillary constriction but may produce undesirable dentoalveolar effects such as buccal tipping, periodontal stress and root resorption, particularly in cleft patients.[3]

In order to minimize these undesirable dental effects and enhance skeletal expansion, bone-borne and miniscrew-assisted rapid palatal expansion devices have been introduced.This biomechanical advantage makes bone-borne expansion particularly beneficial in patients with cleft lip and palate, where skeletal correction of maxillary constriction is often more desirable than dentoalveolar compensation.[4]

Despite the increasing clinical use of bone-borne expanders, the biomechanical response of the craniofacial skeleton during expansion remains complex and not fully understood. The distribution of stresses generated during expansion and the resulting displacement patterns of the maxillary segments may vary depending on factors such as appliance design, number and position of miniscrews, and magnitude of the applied forces. Additionally, evaluation of bucco-lingual angulation changes during expansion is important, as excessive dental tipping may negatively affect periodontal health and long-term stability of orthodontic treatment. Understanding these biomechanical responses is therefore essential for optimizing appliance design and improving treatment outcomes in patients with cleft lip and palate.[5]

Finite Element Analysis (FEA) has emerged as an effective and reliable computational method for evaluating the biomechanical behavior of craniofacial structures under orthodontic forces. This technique enables the construction of three-dimensional digital models of anatomical structures and allows detailed simulation of stress distribution, displacement patterns, and deformation of tissues when mechanical forces are applied.[6]

Previous finite element studies have demonstrated characteristic stress and displacement patterns during rapid palatal expansion. However, comparative evidence regarding different bone-borne rapid palatal expanders in bilateral cleft lip and palate patients remains limited.[7]

Therefore, a comprehensive biomechanical evaluation of various bone-borne rapid palatal expanders is necessary to better understand their effects on the craniofacial skeleton in cleft patients. Three-dimensional finite element analysis provides an ideal platform to investigate these biomechanical responses and to compare the performance of different expander designs under standardized conditions. Hence, the present study aims to comparatively evaluate the stress distribution, displacement pattern, and bucco-lingual angulation produced by four different bone-borne rapid palatal expanders in patients with bilateral cleft lip and palate using three-dimensional finite element analysis.[8]

MATERIALS AND METHODS

2.1 CBCT data from a 16-year-old patient with complete bilateral cleft lip and palate were converted into a three-dimensional finite element model using HyperMesh (Version 11). Segmentation of cortical bone, cancellous bone, enamel, dentin and periodontal ligament was performed, and the model was analyzed in ANSYS (Version 18.1).

2.2 Force Application

A transverse expansion force of 6 N was applied through the expansion screw. The force was distributed equally between the right and left sides (3 N each). In models with three miniscrews, the load was distributed according to the number of supporting miniscrews.

2.3 Defining the boundary condition

The superior aspect of the maxilla was fixed in all three directions. Materials were assumed to be homogeneous, isotropic and linearly elastic. Material properties were obtained from published literature **(Table 1)**. All interfaces were considered

bonded, and the expander screw contact was defined as rigid.

Table 1. Material properties

Material properties	Material Elastic modulus (MPa)	Poisson ratio
Cortical bone	13700	0.3
Cancellous bone	1370	0.3
Dentine	18600	0.3
Enamel	84600	0.3
PDL	50	0.45
Expander and Band (Stainless steel)	200000	0.3
Miniscrew (Titanium)	110 000	0.33

2.4 Virtual Models

Four virtual rapid palatal expansion models were constructed and analyzed under identical simulation conditions:

Model 1: Hybrid Hyrax appliance (2 × 9 mm) banded to the maxillary first molars.

Model 2: MARPE No-DS, supported by three palatal miniscrews (1.8 mm diameter × 5.4 mm length) without dental anchorage.

Model 3: MARPE DS with three palatal miniscrews (1.8 mm diameter × 5.4 mm length) and dental anchorage involving the maxillary second premolars and first molars.

Model 4: MARPE DS with four palatal miniscrews (1.8 mm diameter × 5.4 mm length) and dental anchorage.

In all models, the bands were bonded to the teeth and connected to the expansion screw using a 1.5-mm stainless steel wire.

2.5 Meshing

Meshing was performed using tetrahedral elements. The four models consisted of 3,012,193 nodes and 1,647,510 elements (Table 2).

Table 2. Number of nodes and elements

NUMBER OF NODES AND ELEMENTS			
S.No.	MODELS	NODES	ELEMENTS
1	Hybrid Hyrax	748551	410667
2	MARPE No-DS	742184	407214
3	MARPE DS (3 miniscrew)	760558	414788
4	MARPE DS (4 miniscrew)	760900	414841

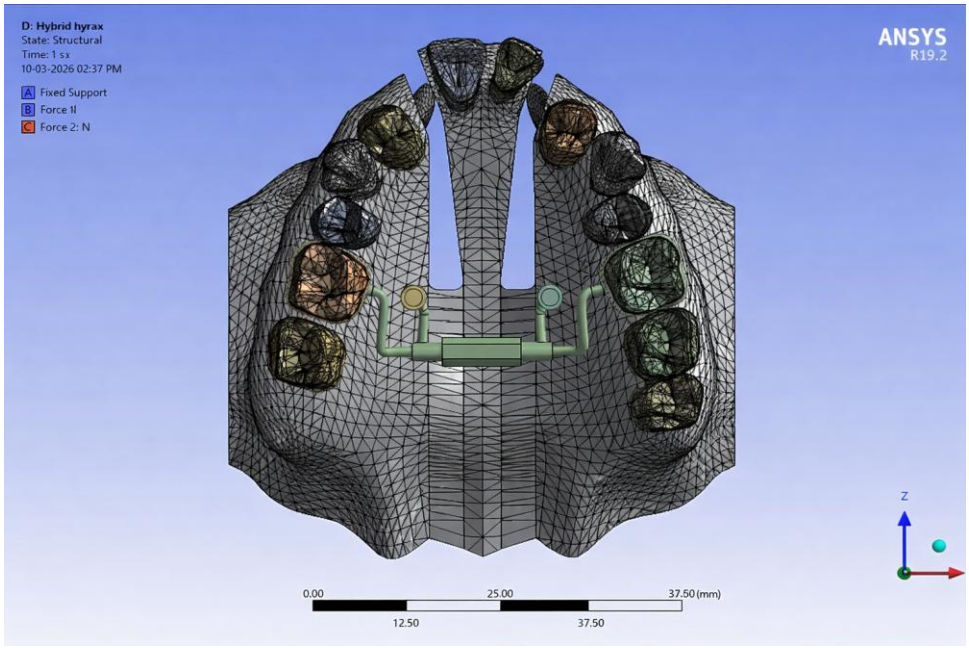

Fig 1. Three-dimensional finite element model of the Hybrid Hyrax appliance illustrating dental anchorage on the maxillary arch with meshed craniofacial structures

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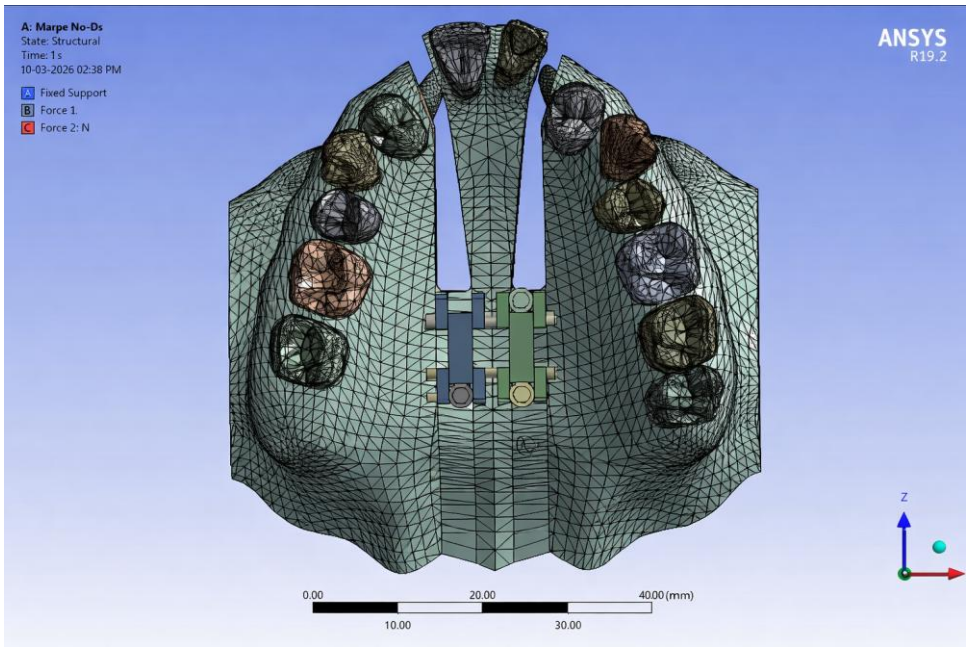


Fig 2. Three-dimensional finite element model of the MARPE No-DS appliance supported by three miniscrews, demonstrating skeletal anchorage and meshed maxillary structures.

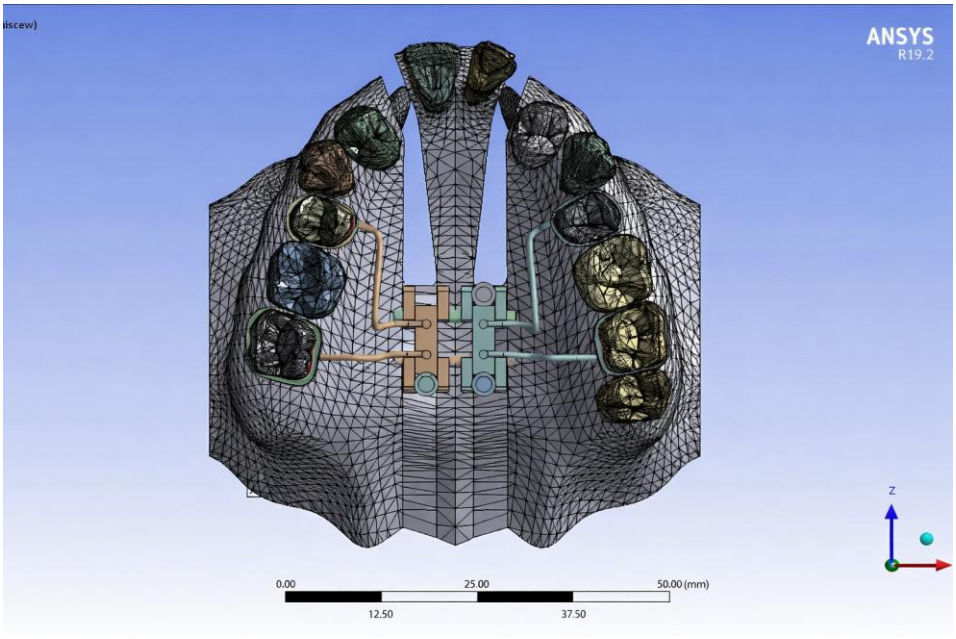


Fig 3. Three-dimensional finite element model of the MARPE DS appliance with three miniscrews and dental anchorage.

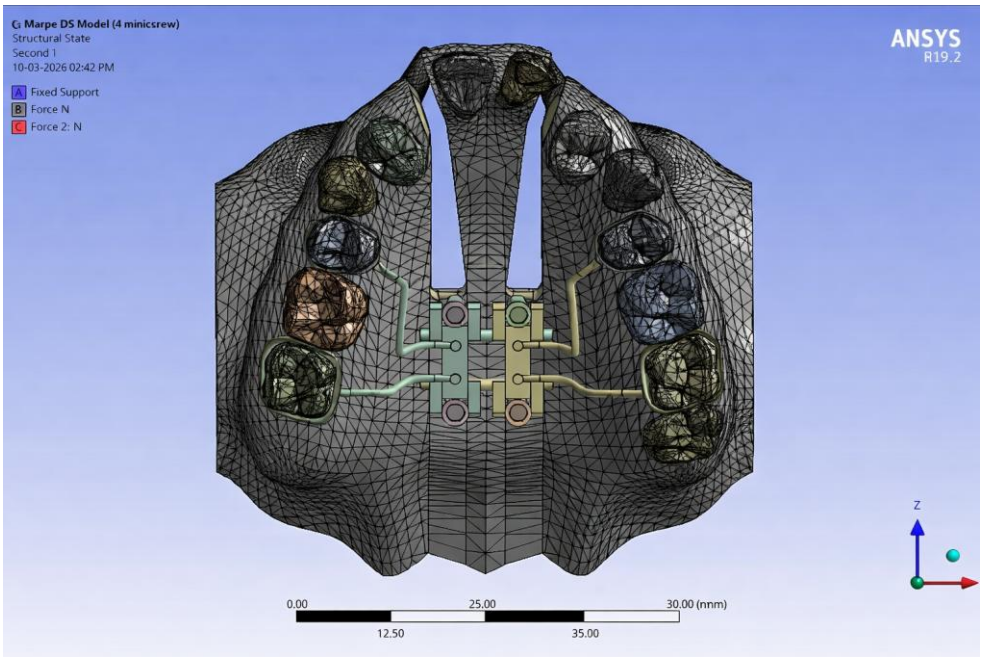


Fig 4. Three-dimensional finite element model of the MARPE DS appliance with four miniscrews, illustrating enhanced skeletal anchorage with meshed maxillary structure.

3.RESULTS

3.1 STRESS DISTRIBUTION AMONG MODELS

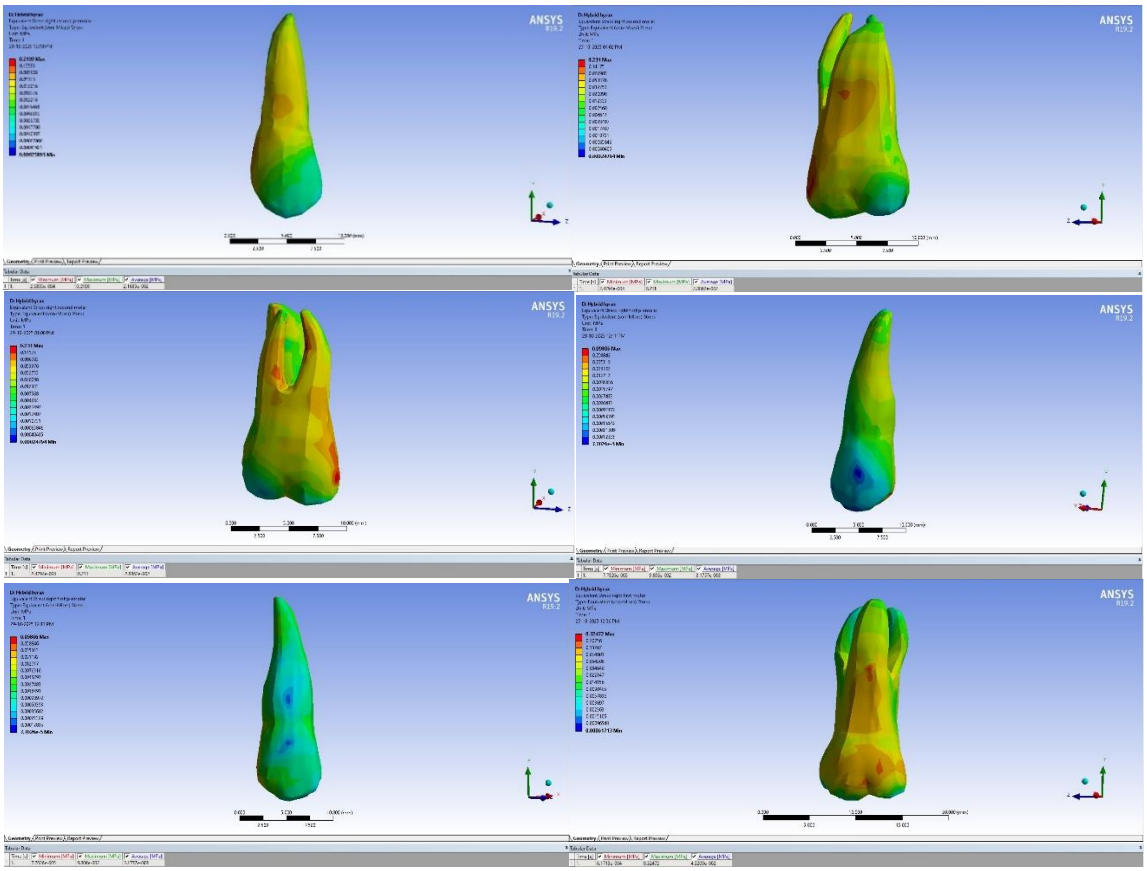
Finite element analysis demonstrated differences in von Mises stress distribution among the four expansion models. The Hybrid Hyrax appliance exhibited the highest stress concentration, whereas MARPE No-DS showed the lowest stress values. Both MARPE DS models demonstrated intermediate stress levels, with the four-miniscrew configuration producing a more

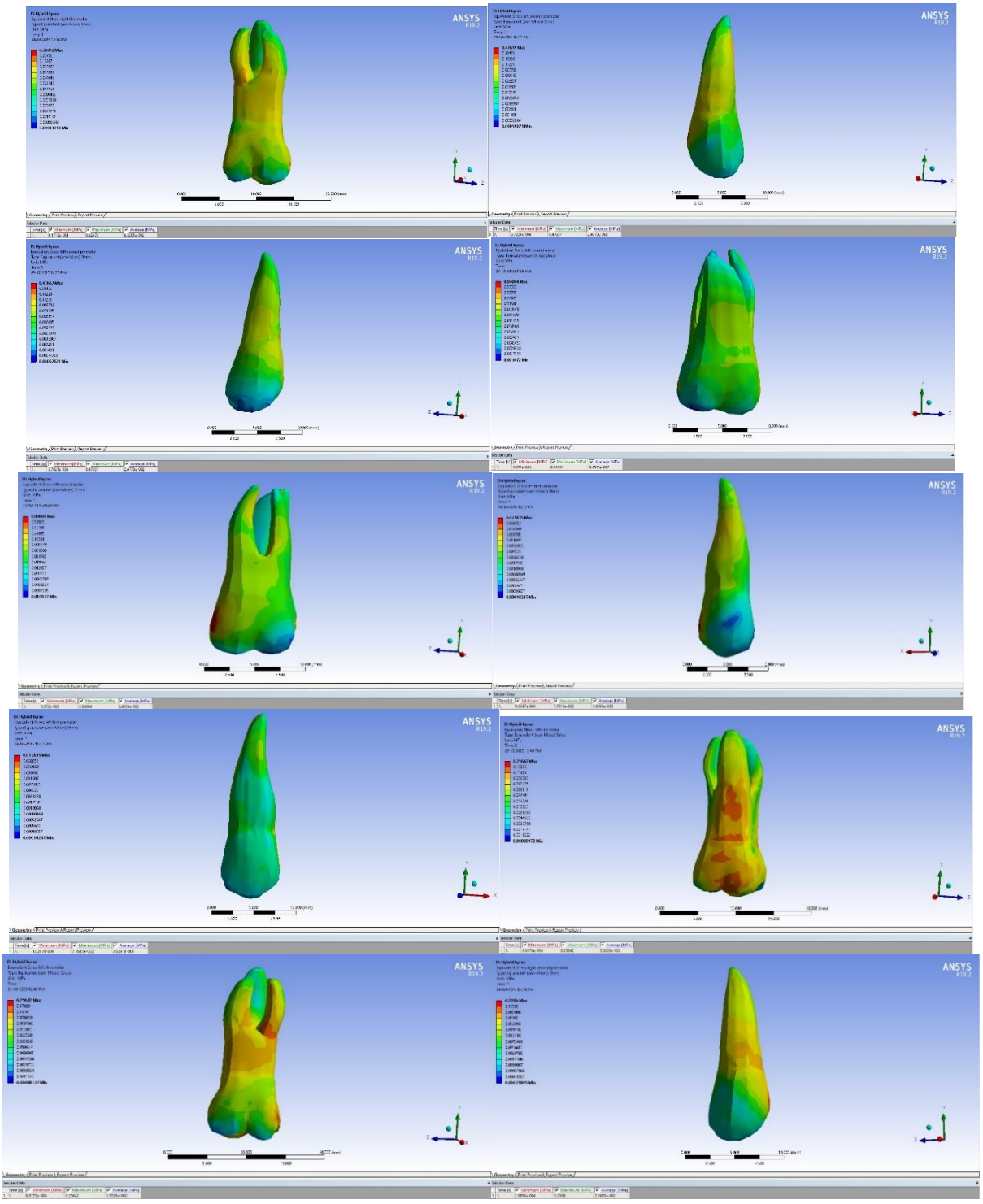
symmetrical stress distribution than the three-miniscrew design **(Table 3; Figs. 5–8).**

Table 3. Average Equivalent von Mises Stress (MPa) Distribution in Premolar and Molar Regions

Tooth	MARPE No-DS	MARPE DS (3 Miniscrews)	MARPE DS (4 Miniscrews)	Hybrid Hyrax
Right 1st Premolar	0.00027533	0.0028419	0.0030178	0.0031757
Left 1st Premolar	0.00024696	0.0026113	0.0025972	0.0030291
Right 2nd Premolar	0.00026207	0.040763	0.044401	0.021685
Left 2nd Premolar	0.00017506	0.047008	0.045822	0.024775
Right 1st Molar	0.0011306	0.024145	0.026342	0.043209
Left 1st Molar	0.00082094	0.029184	0.026889	0.055029
Right 2nd Molar	0.0011023	0.025853	0.02407	0.028862
Left 2nd Molar	0.0009892	0.018944	0.022424	0.034555

Hybrid Hyrax exhibited the highest stress concentration, whereas MARPE No-DS showed the lowest stress values. The four-miniscrew MARPE demonstrated a more symmetrical stress distribution than the three-miniscrew design.

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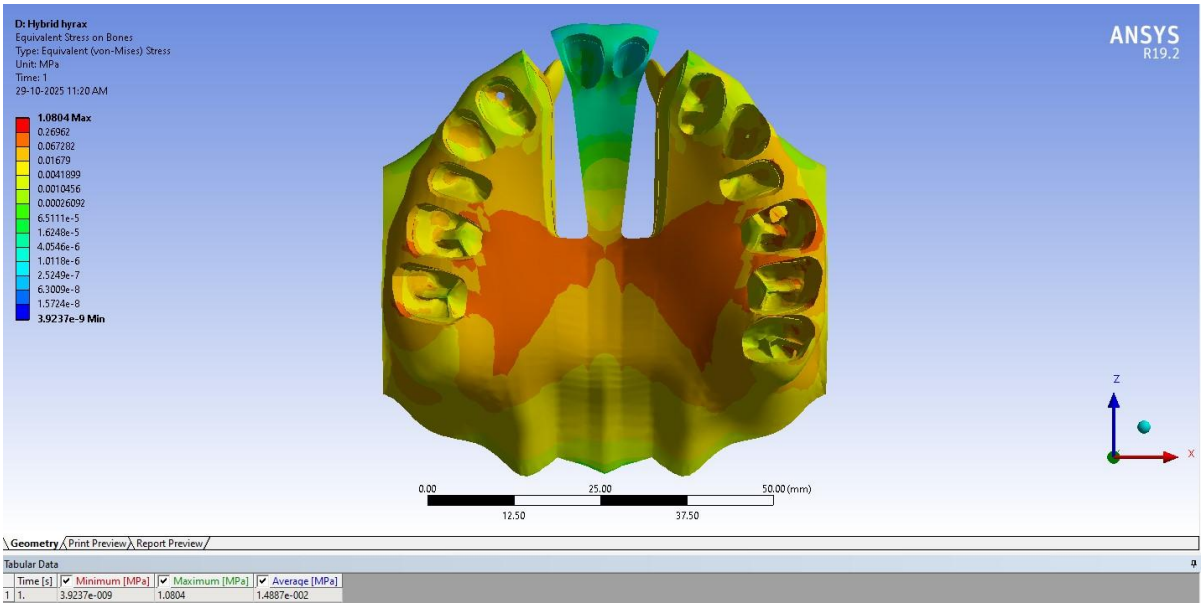
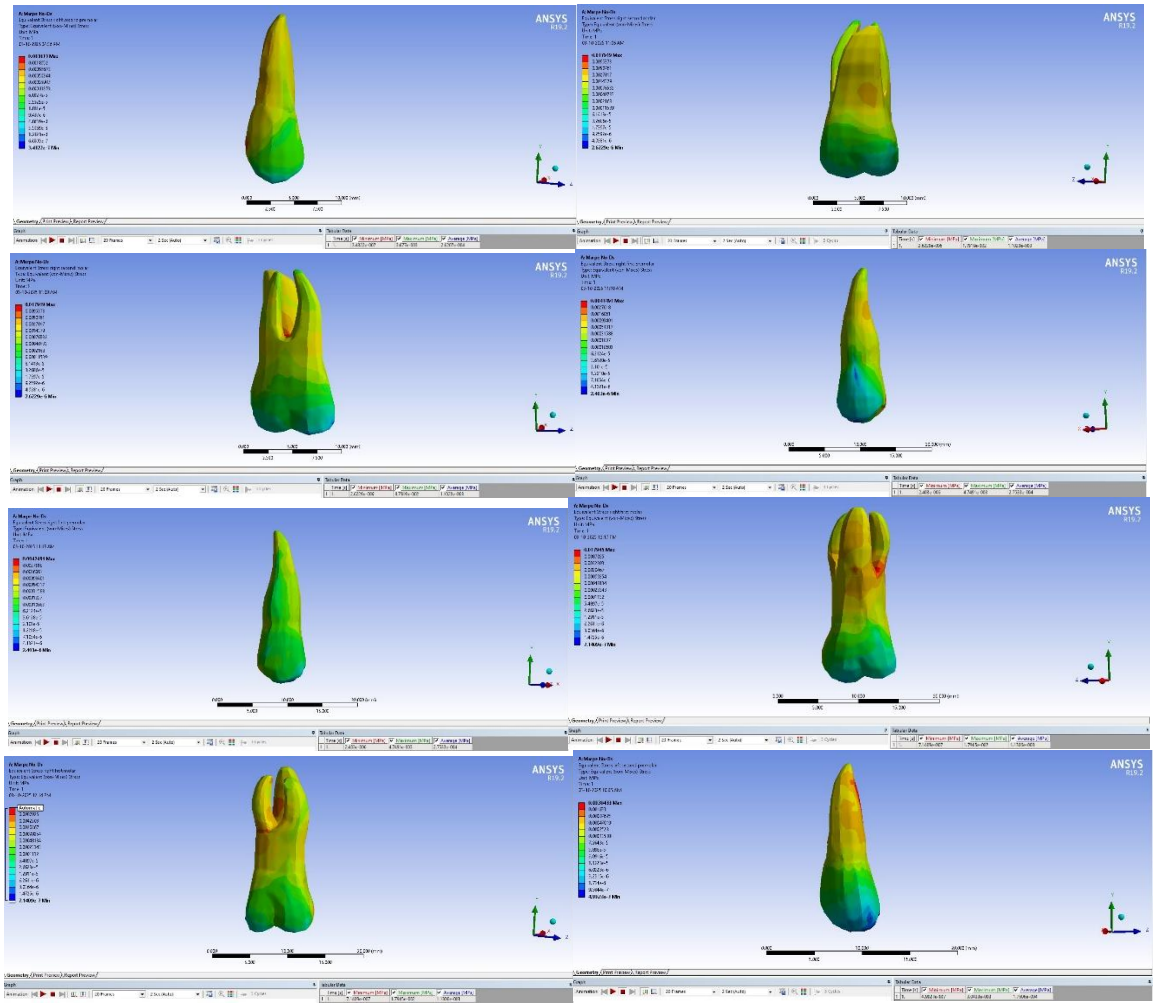


Fig 5. Von Mises stress distribution in the Hybrid Hyrax model showing stress concentration in the premolar and molar regions following application of transverse expansion forces.



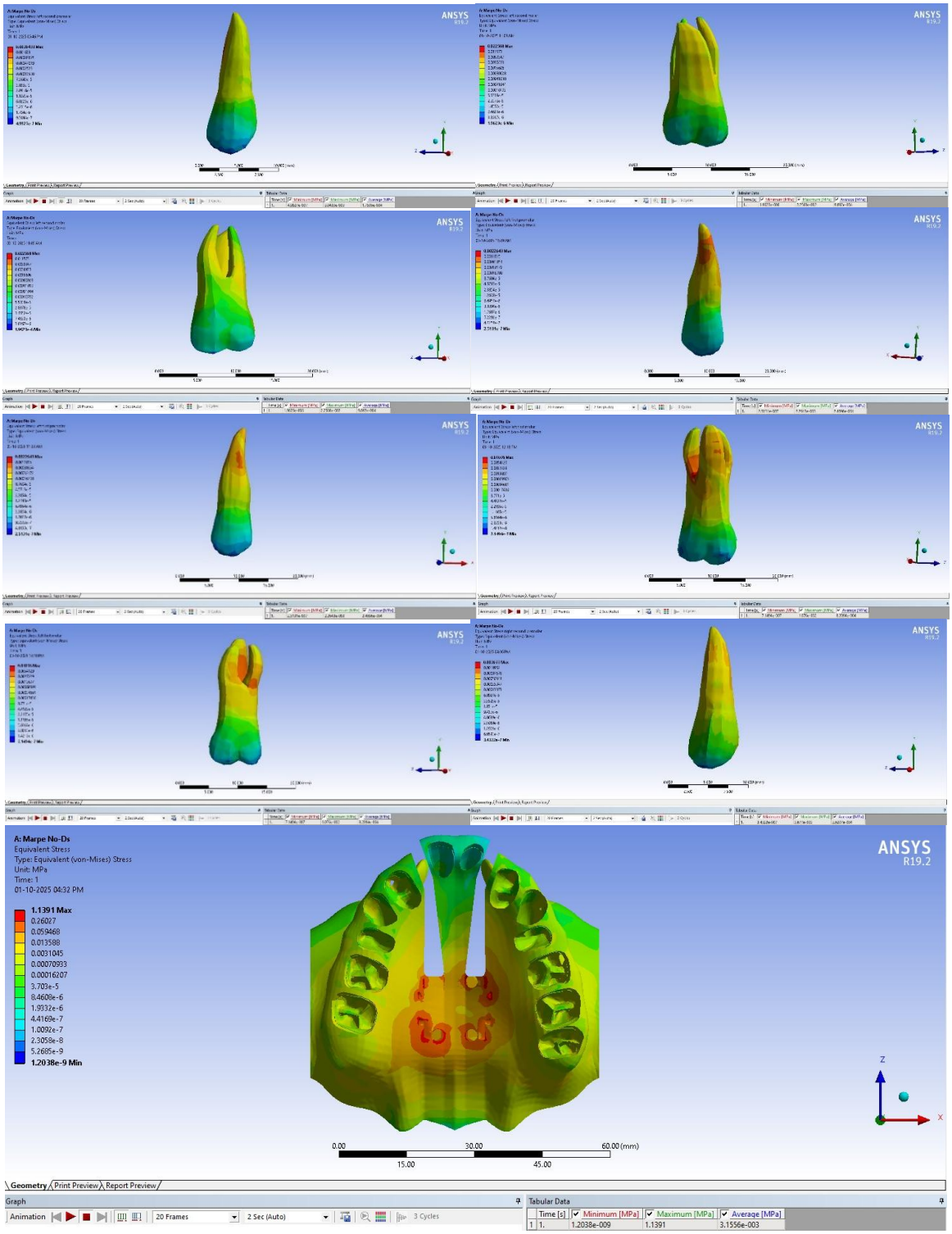
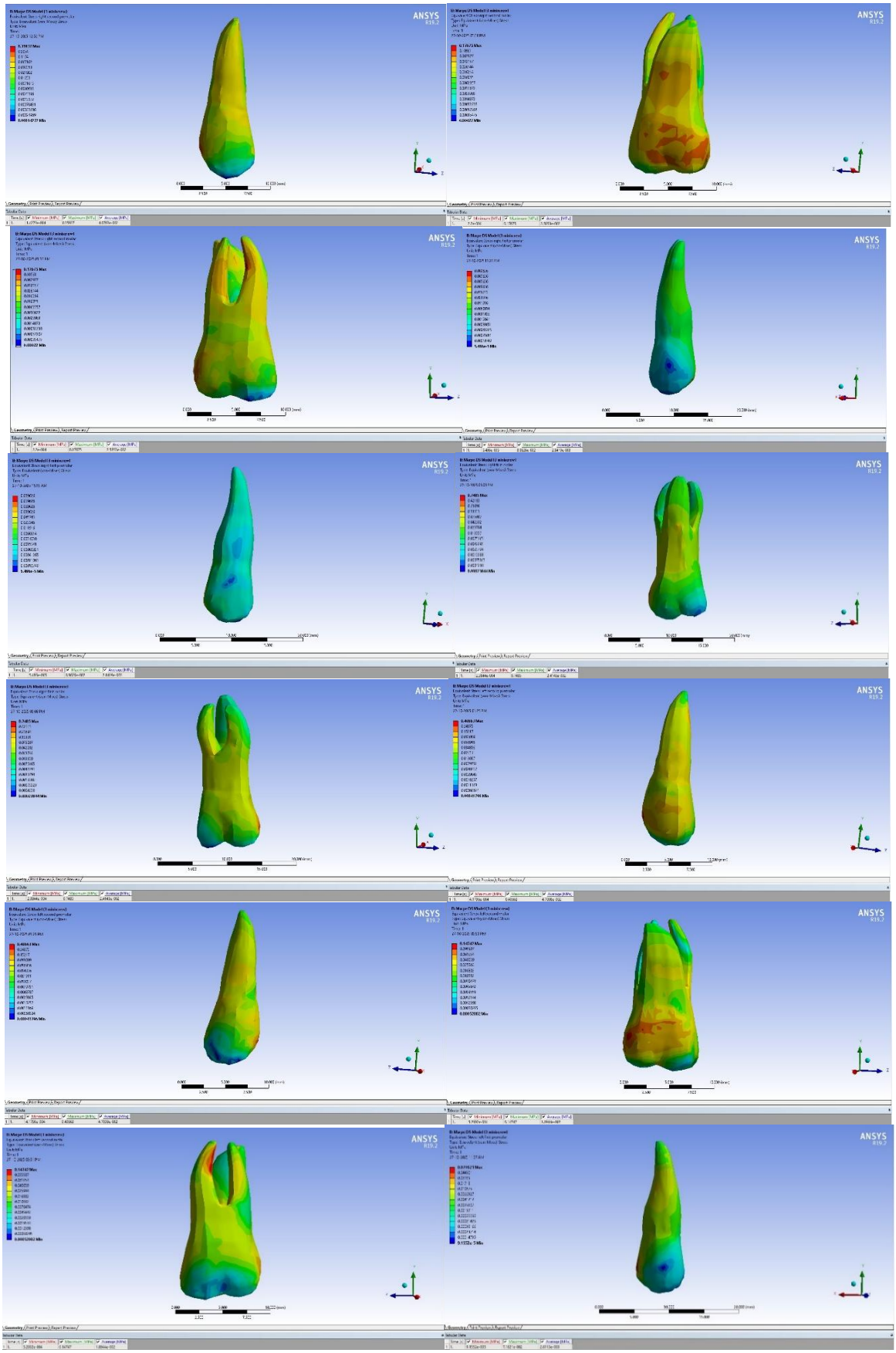


Fig 6. Von Mises stress distribution in the MARPE No-DS model demonstrating minimal stress concentration and predominantly skeletal stress transmission.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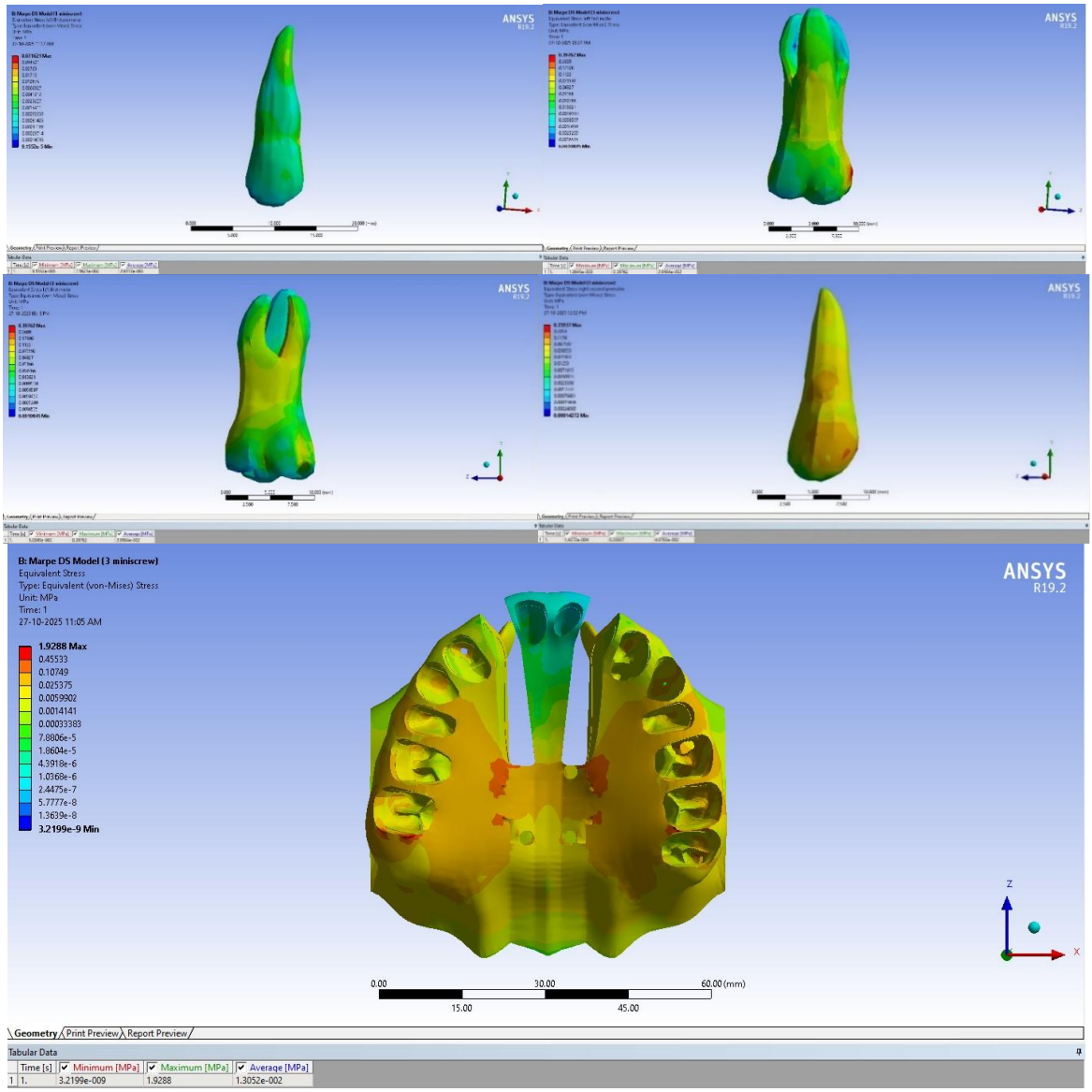
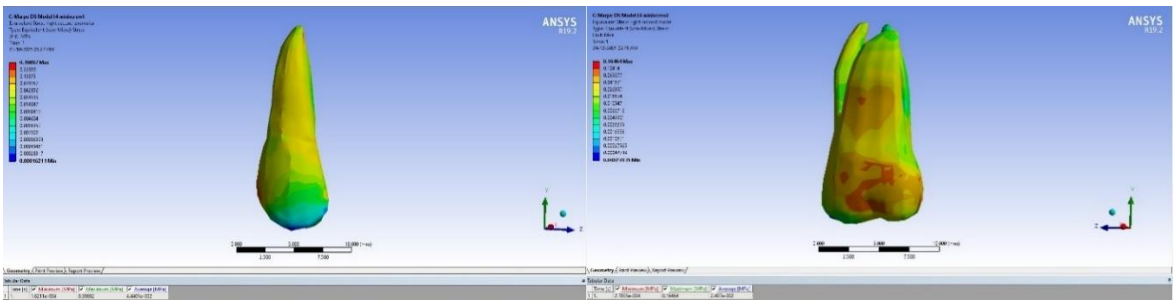
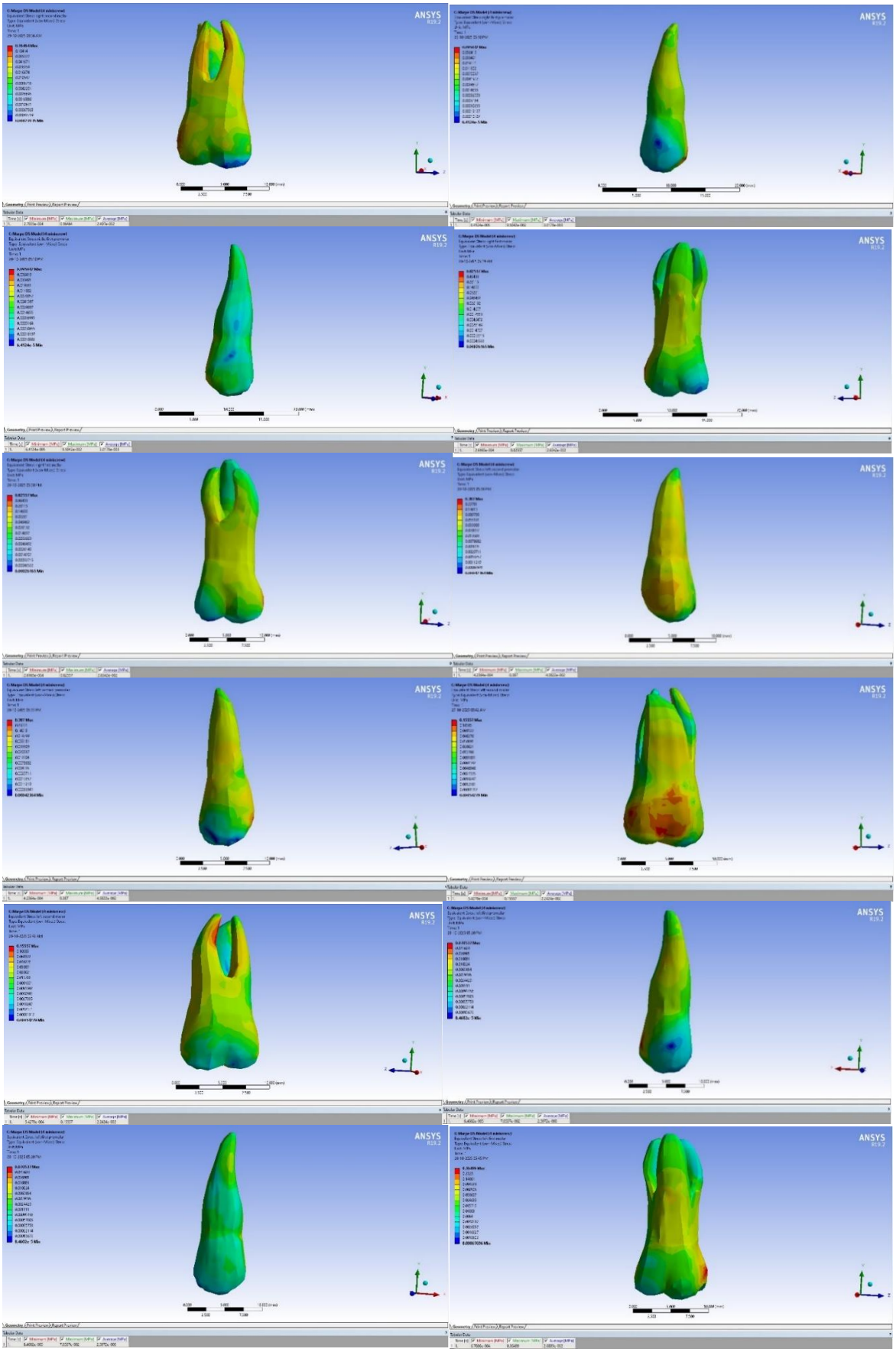


Fig 7. Von Mises stress distribution in the MARPE DS appliance supported by three miniscrews, demonstrating combined skeletal and dentoalveolar stress distribution.

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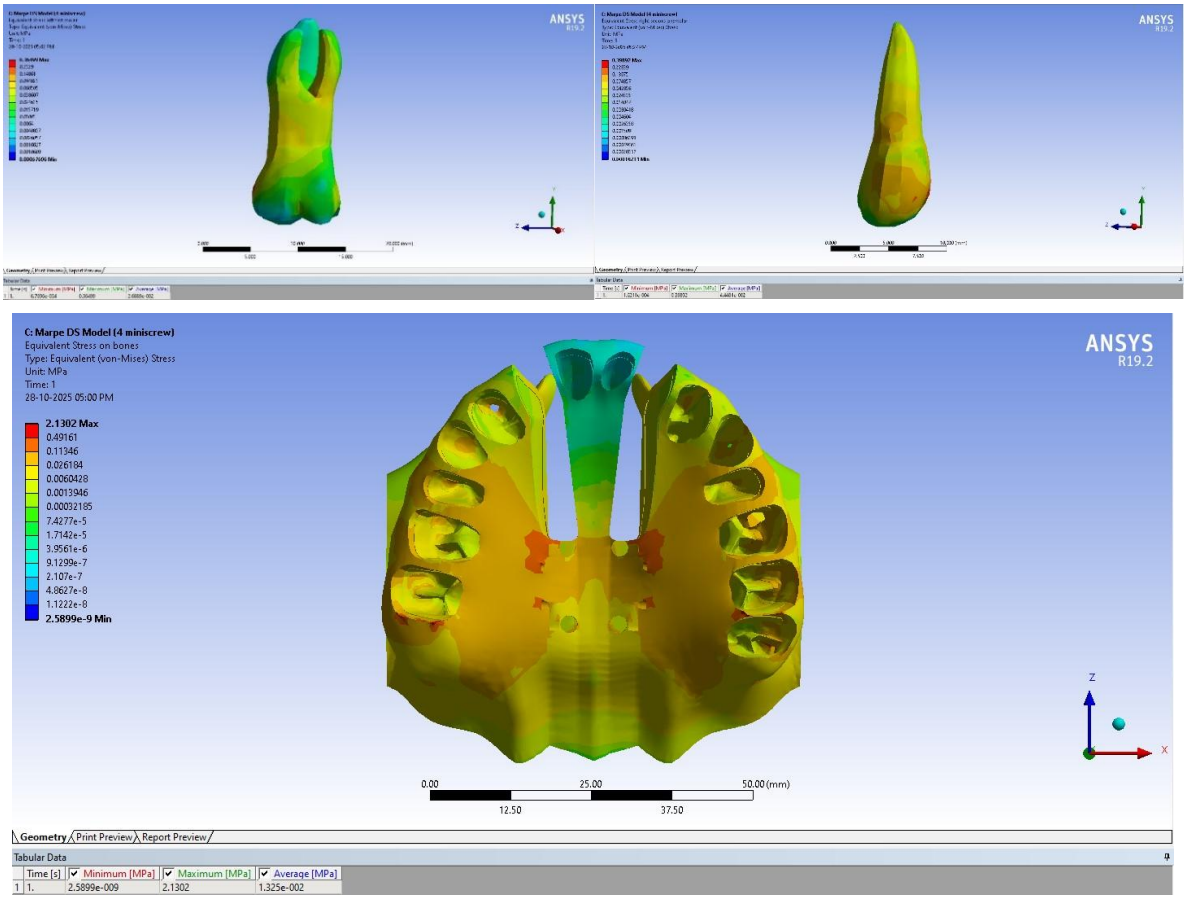

Figure 8. Von Mises stress distribution in the MARPE DS appliance supported by four miniscrews, demonstrating symmetrical stress distribution and improved biomechanical stability.

3.2 DISPLACEMENT PATTERN AMONG THE MODELS

Distinct differences in displacement patterns were observed among the four appliances. The Hybrid Hyrax appliance demonstrated the greatest displacement, whereas MARPE No-DS exhibited the least displacement, indicating predominantly skeletal expansion. Both MARPE DS models produced intermediate displacement values, with the four-miniscrew design showing a more uniform and symmetrical displacement pattern than the three-miniscrew configuration **(Table 4).**

Overall, displacement increased in the following order:

MARPE No-DS < MARPE DS (3 Miniscrews) ≈ MARPE DS (4 Miniscrews) < Hybrid Hyrax

Table 4. Average Displacement (mm) in Premolar and Molar Regions among Different Expansion Models.

Tooth No.	MARPE No-DS	MARPE DS (3 Miniscrews)	MARPE DS (4 Miniscrews)	Hybrid Hyrax
Right 1st Premolar	6.3847E-06	0.00011429	0.00012389	0.00013243
Left 1st Premolar	0.000012015	0.00015703	0.00015053	0.00016264
Right 2nd Premolar	6.6624E-06	0.00024031	0.00025908	0.00025549

Left 2nd Premolar	7.0719E-06	0.00026474	0.00025701	0.00026657
Right 1st Molar	7.5089E-06	0.00014947	0.00015638	0.00021852
Left 1st Molar	6.2277E-06	0.00016432	0.00016673	0.00025756
Right 2nd Molar	7.5953E-06	0.0001419	0.00013532	0.00015198
Left 2nd Molar	6.9002E-06	0.00012171	0.00012913	0.00015109

Hybrid Hyrax produced the greatest displacement, while MARPE No-DS exhibited minimal displacement. The four-miniscrew MARPE provided better control of displacement than the three-miniscrew configuration.

3.3 Buccolingual Angulation Among the Models

Differences in buccolingual tooth angulation were observed among the four appliances. The Hybrid Hyrax appliance demonstrated the greatest tooth angulation, whereas no measurable angulation was observed with MARPE No-DS. Both MARPE DS models exhibited moderate angulation, with the four-miniscrew design producing a more symmetrical pattern than the three-miniscrew configuration **(Table 5).**

Overall, tooth angulation increased in the order:

MARPE No-DS < MARPE DS (3 Miniscrews) ≈ MARPE DS (4 Miniscrews) < Hybrid Hyrax

Table 5. Tooth Angulation (°) among Different Expansion Models

Tooth No.	MARPE No-DS	MARPE DS (3 Miniscrews)	MARPE DS (4 Miniscrews)	Hybrid Hyrax
Right 1st Premolar	**0**	**0.63**	**0.69**	**0.74**
Right 2nd Premolar	**0**	**1.76**	**1.89**	**1.87**
Right 1st Molar	**0**	**0.82**	**0.86**	**1.21**
Right 2nd Molar	**0**	**1.04**	**1.00**	**1.11**
Left 1st Premolar	**0**	**0.87**	**0.84**	**0.90**
Left 2nd Premolar	**0**	**1.93**	**1.88**	**1.96**
Left 1st Molar	**0**	**0.95**	**0.96**	**1.50**
Left 2nd Molar	**0**	**0.56**	**0.96**	**1.09**
Left 3rd Molar	**0**	**0.61**	**0.65**	**0.51**

Hybrid Hyrax showed the greatest buccolingual angulation, whereas MARPE No-DS demonstrated no measurable tooth angulation. The MARPE DS models exhibited intermediate angulation with improved symmetry in the four-miniscrew design.

4.DISCUSSION

Bilateral cleft lip and palate patients frequently present with maxillary transverse deficiency due to intrinsic developmental disturbances and scar tissue formed after primary lip and palate repair, making rapid maxillary expansion an important component of orthodontic treatment.[1–3]

The introduction of bone-borne and miniscrew-assisted rapid palatal expanders has reduced many of the dentoalveolar side effects associated with conventional tooth-borne appliances by directing expansion forces to the palatal bone.[4–8]

4.1 Stress pattern

The **Hybrid Hyrax** appliance produced the highest von Mises stress values, particularly in the first molar region, indicating

greater transmission of expansion forces to the dentition.

[Fig 9]

These findings agree with previous studies reporting that tooth-borne expanders generate greater periodontal stress, dental tipping, and alveolar loading than bone-borne appliances.[3,6,9–15]

The **MARPE No-DS** model demonstrated the lowest stress values, indicating predominantly skeletal force transmission with minimal dentoalveolar involvement. This finding is consistent with studies showing that skeletal anchorage minimizes dental loading while improving orthopedic expansion.[4,5,16–21]

The **MARPE DS** models showed intermediate stress values because expansion forces were distributed through both skeletal and dental anchorage. Among these, the four-miniscrew configuration demonstrated a more symmetrical stress distribution than the three-miniscrew design, suggesting greater biomechanical stability. Similar observations have been reported in finite element and clinical studies evaluating miniscrew-assisted rapid palatal expansion.[22–24]

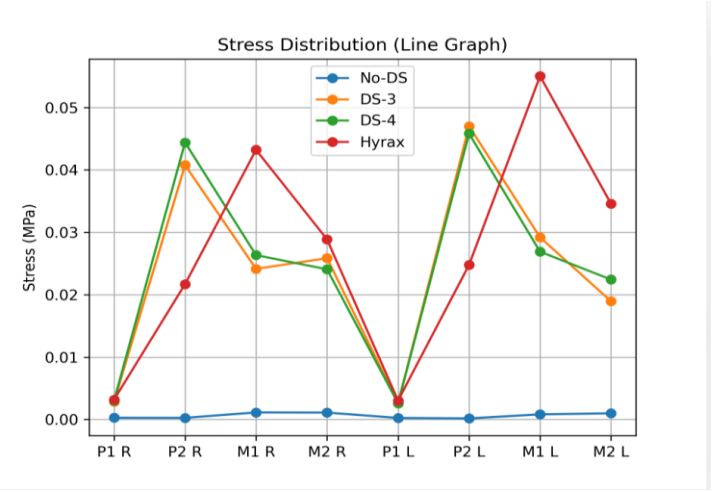

Fig. 9 Comparison of Average Equivalent von Mises Stress in the Premolar and molar Region among Different Expansion Models.

4.2 Displacement pattern

The **Hybrid Hyrax** appliance exhibited the greatest displacement of the posterior teeth, whereas the **MARPE No-DS** model showed negligible displacement, indicating predominantly skeletal expansion [Fig 10].

The MARPE DS models demonstrated controlled displacement, with the four-miniscrew design producing a more uniform pattern than the three-miniscrew model. These findings agree with previous CBCT and finite element studies comparing tooth-borne and bone-borne expanders.[18,19,20,22,23]

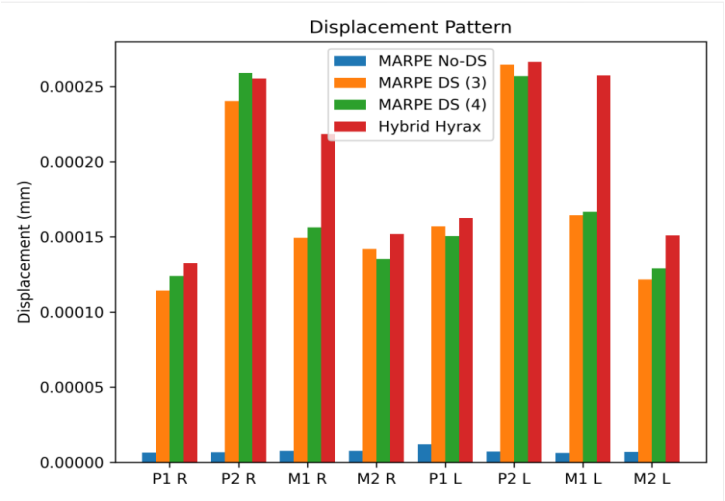

Fig. 10 Average Displacement in Premolar and Molar region.

4.3 Buccolingual angulation

Buccolingual angulation was highest in the Hybrid Hyrax model, confirming greater buccal tipping associated with tooth-borne expansion. In contrast, no measurable angulation was observed in the MARPE No-DS model, while both MARPE DS models demonstrated moderate and controlled tooth inclination [Fig.11].

These observations support previous reports that increasing skeletal anchorage reduces unwanted dental tipping and improves force control during expansion. [16,17,24–28]

Overall, the findings of the present study demonstrate that increasing skeletal anchorage significantly improves the biomechanical response during rapid palatal expansion.

Among the four appliances evaluated, the MARPE DS with four miniscrews exhibited the most favourable balance between skeletal expansion and controlled dentoalveolar effects, while the Hybrid Hyrax appliance produced the greatest dental stress, displacement, and buccolingual Angulation.

Clinically, these findings suggest that increasing skeletal anchorage improves force distribution while minimizing undesirable dentoalveolar effects. The four-miniscrew MARPE configuration may therefore be considered a favorable option for maxillary expansion in bilateral cleft lip and palate patients requiring greater skeletal expansion with controlled dental movement.

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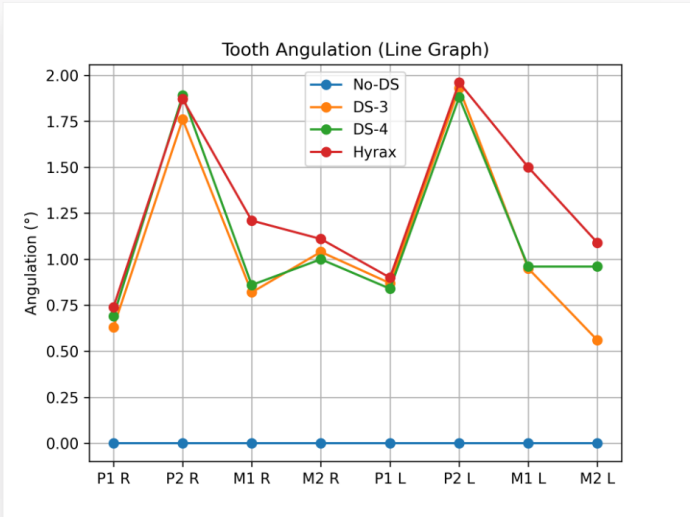

Fig 11. Comparison of Buccolingual Tooth Angulation among Different Expansion Models

5.CONCLUSION

Within the limitations of this finite element study, it can be concluded that the biomechanical response of maxillary expansion varies significantly depending on the type of appliance and anchorage system used.

The MARPE No-DS model demonstrated negligible stress, displacement, and tooth angulation, indicating a predominantly skeletal mode of expansion with minimal dentoalveolar involvement. This suggests that bone-borne expansion without dental support is highly effective in minimizing unwanted dental side effects.

The MARPE DS models exhibited a combination of skeletal and dentoalveolar effects. Both three- and four-miniscrew configurations showed increased stress, displacement, and angulation compared to MARPE No-DS, particularly in the second premolar region. However, the four-miniscrew model demonstrated more uniform and symmetrical distribution of stress, displacement, and strain, indicating improved stability, better force distribution, and greater biomechanical control.

The Hybrid Hyrax appliance produced the highest stress concentration, displacement, and tooth angulation, especially in the molar region, reflecting a predominantly dentoalveolar mode of expansion. This was associated with increased buccal tipping and greater load transfer to posterior teeth.

Across all models, the second premolars exhibited the highest displacement and angulation, while the first molars showed maximum stress concentration in tooth-borne expansion. Strain distribution patterns further confirmed that skeletal anchorage enhances force transmission to the palatal bone, whereas tooth-borne appliances result in greater dental loading.

Overall, the study indicates that increasing skeletal anchorage reduces dentoalveolar effects and improves the efficiency of maxillary expansion. Among the models evaluated, MARPE with four miniscrews provides the most favorable balance between skeletal expansion and controlled dental effects, making it the appliance that demonstrated the most favorable biomechanical behavior under the conditions of this finite element study.

Credit authorship contribution statement

Rajesh kumar Balani, Amitabh Kallury, Chandrika Dubey: Writing - review & editing, Supervision, Project Methodology, administration, Conceptualization...

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