Initial Stresses induced in Permanent Maxillary First Molar in Mixed Dentition under Normal Masticatory Forces: A Finite Element Study

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Objective: *The cross-arch space maintainers are used to prevent mesio-distal movement of teeth under physiologic forces, contrary to adult orthodontics where these are used as anchorage against orthodontic forces. Stresses in periodontal ligaments (PDL) are supposed to be different in pediatric dentistry and need to be studied. This study aimed to create mathematical model and calculated the initial stresses generated in the PDL and the behavior of movement in developing permanent maxillary first molar under masticatory forces using 3D finite element analyses (FEA).* ***Study design***: *Data acquisition, image processing, geometric modeling followed by FE analyses was done under vertical load of 70N. The generated stress and tooth displacement were observed with or without primary second molar, mesial to permanent maxillary first molar.* ***Results***: *Masticatory forces resulted in insignificant initial PDL stresses and mesial displacement of permanent maxillary first molar in the intact arch. In the case of missing primary second molar, maximum stresses were on the palatal root and the tooth showed greater mesial displacement with mesio-palatal rotation.* ***Conclusions***: *Any space maintainer preventing mesio-palatal rotation of permanent maxillary first molar, under physiologic masticatory loadings, may be inserted in case of multiple tooth loss.*

Key words: *Initial stresses, Finite element analyses, Space maintainer*

INTRODUCTION

Various designs of space maintainers in pediatric dentistry preserve the arch dimensions, commonly by passively restricting mesio-distal movement (tipping) of the teeth adjacent to edentulous space. During mastication, a portion of occlusal forces is projected towards the front of the mouth as an anterior component of force (ACF).[1] The ACF was found to progress anteriorly through interproximal contacts but not in open contacts, thus likely to tip the molars under otherwise normal masticatory forces. Space maintainers for short edentulous space can effectively manage these forces. However, multiple premature loss of primary teeth in developing dentition may complicate the situation, where the prime focus is to preserve arch length, width and perimeter as well, by preventing the mesial and bucco-lingual tipping of erupting young permanent first molar.

The direction of movement of tooth is mainly dependent on stress distribution in periodontal ligament (PDL) generated during force loading. Functional, parafunctional, orthodontic or other forces differ in magnitude and direction generating vivid reactions in PDL. Zone of compression and tension are created in orchestrated PDL leading to bone resorption or deposition, which in turn moves the tooth in a particular direction. Previously, these biologic reactions and tendency of tooth movement have been investigated histologically.[2] These studies found that tooth tend to tilt in the direction of applied forces.[2]

Some periodontal[2] and orthodontic studies[3-14] emphasized the importance of developing a mathematical model to simulate biologic behavior of tooth, PDL and alveolar bone assembly to study the tooth movement as accurately as possible. These studies investigated PDL stress and movements in mature teeth and found computed finite element analysis (FEA) very useful. Contrast to these studies, developing dentition has completely different conditions e.g. incompletely formed roots, partially erupted position and different magnitude of various functional forces acting on them.

Stresses considered normal for permanent tooth with fully developed roots may be deleterious for an immature permanent tooth with developing open apex roots. If this developing tooth is acting as an abutment for space maintainer, added stresses are compounded on

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it. Under physiologic functional forces, movement of a developing tooth cannot be expected to be same as of a fully developed permanent tooth. The center for tooth movement may not lie at same point as that in permanent tooth, for the length between cusp tips to apex is longer in a mature permanent compared to a developing tooth. Moreover, results of FEA studies with active unidirectional orthodontic forces probably cannot be applied while choosing the design of space maintainer, where physiologic occlusal masticatory forces mostly prevails on permanent maxillary first molar.

Most dilemmas, in pediatric dentistry exist between transpalatal arch (TPA) and Nance palatal arch (NPA) which is mainly based on orthodontic studies, where these space maintainers are used as anchorage to first molars against mesially directed orthodontic forces. Contrast to this, pediatric dentistry uses these space maintainers passively against functional masticatory forces only. Therefore, applying results of orthodontic studies in pediatric cases may be questionable. Studying behavior of tooth movement of an immature tooth with the help of FEA may help, not only in choosing a space maintainer but also modifying the design.

Therefore, the objective of this preliminary study was to create mathematical model using FEA with simulated model of an immature permanent maxillary first molar for evaluation of 1/- stresses in PDL of roots and crown and 2/- behavior of movement of permanent maxillary first molar in presence or absence of primary second molar (mesial constrain).

MATERIALS AND METHOD

Prior approval for the study was obtained from institutional ethical committee. A computerized tomography (CT) scan of the maxillary dental arch of a 6-year old child (mixed dentition stage) was obtained from a radiologic diagnostic centre in Indore (MP, India). Image acquisition parameters were: tube voltage of 120 kV, tube current of 200 mA and slice thickness of 0.6 mm. These DICOM images were processed with the help of commercial MIMICS 9.0 (Materialize Inc. Belgium) software. Using the thresholding function, separate masks were drawn for teeth and alveolar bone. After using above segmentation tools, masks for all regions of interest were finalized and 3D models for high quality were computed. This gave us the 3-D surface models of all the teeth. Maxillary permanent maxillary first molar was selected for solid modeling for being the tooth of interest.

For making solid model Pro-E WF 4.0 (Parametric Technology Corporation, USA) was used after preprocessing data through Geomagic Studio software 11.0 (Geomagic Studio Product, Morrisville, North Carolina) whose input was point cloud data (Figure-1). The 3-D realistic geometry of the teeth (solid model) developed by using medical imaging scans data was used for analysis. The model in Pro-E WF 4.0 was taken into Pro-Mechanica WF 4.0. The Periodontal fibers on root surface was constructed as a surface model in Pro-E via copy command and this was given the thickness 0.2 mm followed by assigning material properties in Pro-Mechanica Integrated mode via use of shell modeling.

The model was then discretized in nodes resulting from 10 noded tetrahydron solid element having 3 degree of freedom (DOF) at each node (Translational DOF in X, Y & Z) and quadrilateral shell element with 8 nodes having 6 DOF at each node (Translational DOF in X,Y&Z and Rotational DOF in X,Y & Z). Since there is no moment loads thus the loads can be directly applied at the shell surface.

The sharing of nodes for shell model and 3D solid model of the base teeth geometry was done via rigid connection between the shell nodes and solid element nodes. The process was followed for constructing the shell-solid connection around each root of molar.

There are many advantages of 10 node tetrahedron element as has been described by Gautam *et al* [13]. The discretinization gave total number of elements 9364; nodes 3108; edges 15145; faces 21400; degrees of freedom/node-9324.

The alveolar bone was created with solid model made in shape of cube assembled to the assembly with tooth geometry assembled on default as a parent component. The cube was also assembled with the base position co-ordinate system. The exact cutout shape of the tooth was made via use of merge-cutout command of Pro-E. The cutout of the parent teeth feature was generated in the child cube component, and the assembly of the 3 i.e. the base cube, the teeth and the surface of 0.2 mm was then taken into the FEA mode of Pro-E software.

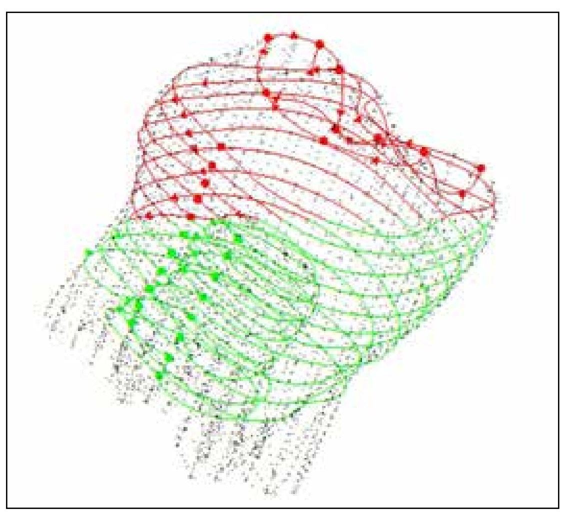
The various elements were assigned the properties of the tissues according to previous literature[9] using elements properties toolbox of the software. The modulus of elasticity and Poisson's ratio for bone, tooth and PDL were considered as 14.7 GPa; 20.7 GPa; 6.89 x 10^{-5} GPa and 0.30; 0.30, 0.45 respectively, for these basic elemental properties remain constant under different mechanical loadings.[2]

In Loads / boundary conditions toolbox, the outer border of the bone was fixed. Hence, this part of the tooth-bone assembly did not have any translations or rotations, so all x, y, z translations were zero for this outer border of the bone. After assigning material properties to the three dimensional finite element model of tooth, an occlusal load of 70 N was applied on the mesio-palatal cusp (functioning cusp which occludes with central fossa of mandibular molar) of maxillary permanent maxillary first molar in vertical direction.

The finite element analysis for stress and displacement of tooth model was run using analysis toolbox of software. Quantitatively the tooth model after FEA shows areas of different stresses in PDL. The magnitudes of stresses are denoted between dark blue to red color, the greater i.e. compressive with blue and lower i.e. tension with red.

RESULTS

Figure 1 – Curve model of maxillary first permanent molar.



The observations of FEA for initial stresses were done in two parts i.e. with or without mesial constrain.

Part I – Pattern of stress distribution and displacement in the maxillary permanent maxillary first molar with mesial constrain (Figures 2-4, table-1)

When an occlusal load of 70 N was applied on the mesio-palatal cusp (Figure-2), maximum amount of stress, 62 MPa, was generated on the mesial aspect of the crown in the region of applied constrains, indicated as red (Figure-3a). A stress of 5-7 MPa was seen on the mesio-palatal cusp indicated as green. A stress of 2.5 MPa was seen distributed on the rest of mesio-palatal cusp whereas the remaining occlusal surface was free of any stresses indicated with dark blue (Figure-3b).

The stresses in PDL of roots and crown are given in table-1. There were insignificant stresses in PDL of the disto-buccal root (Figure 3a and c).

The maximum value of displacement of crown recorded was 2.2 µm in the mesio-palatal direction (Figure-4a). No displacement was seen in any of the roots (Figure-4b).

Figure 2 – Area of load application on mesio-palatal cusp of maxillary first permanent molar and constrain on mesial surface.

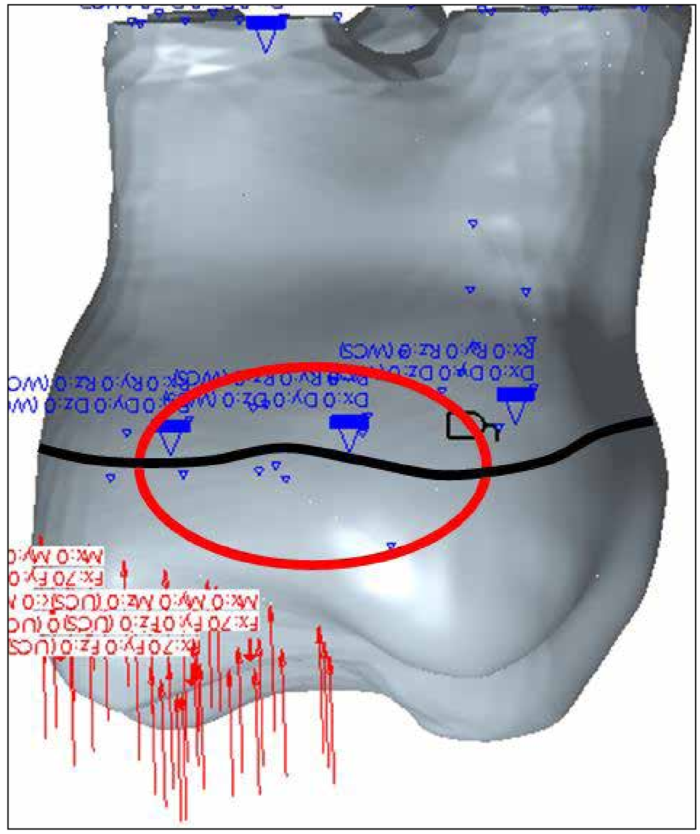


Figure 3 - Pattern of stress distribution in maxillary first permanent molar with mesial constrains (a) Mesial aspect (b) Occlusal aspect (c) Top view

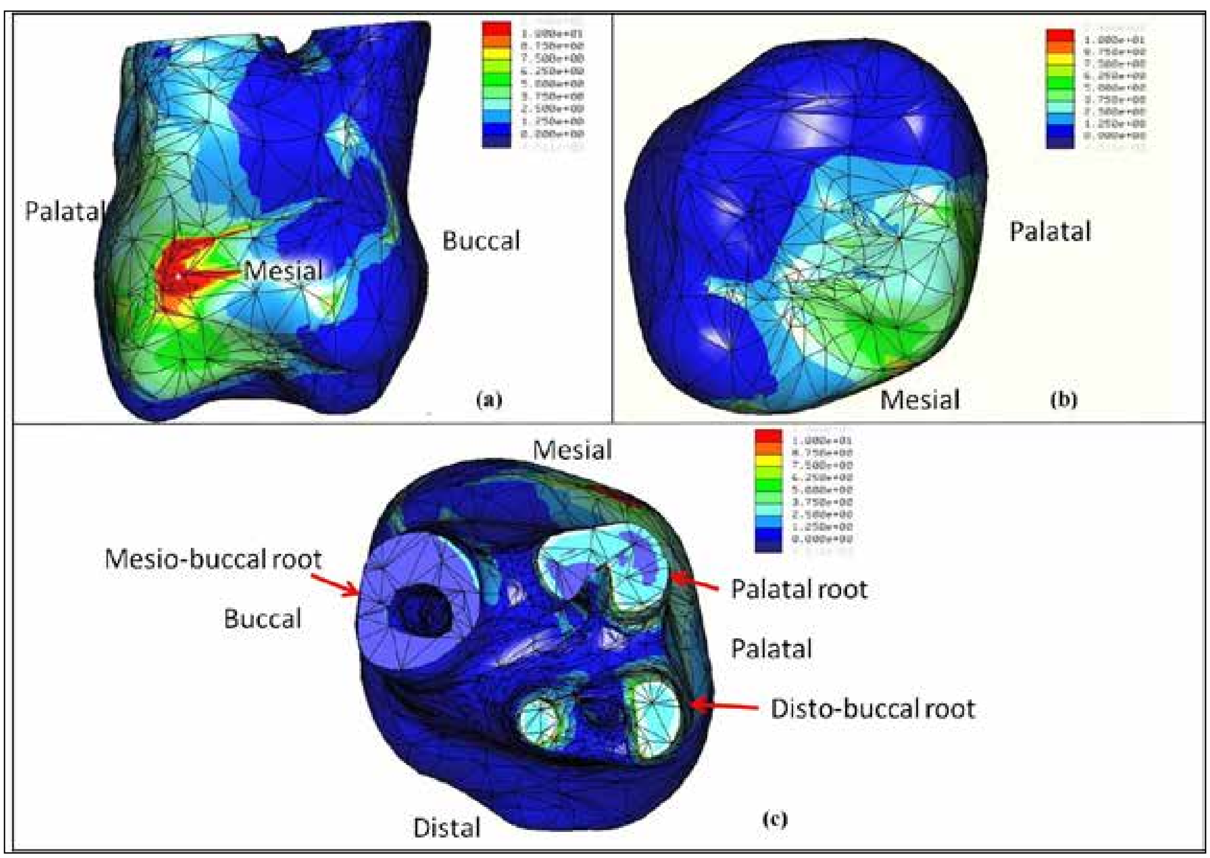


Figure 4 - Displacement pattern in maxillary first permanent molar with mesial constrain.

Occlusal view (b) Mesio-palatal view

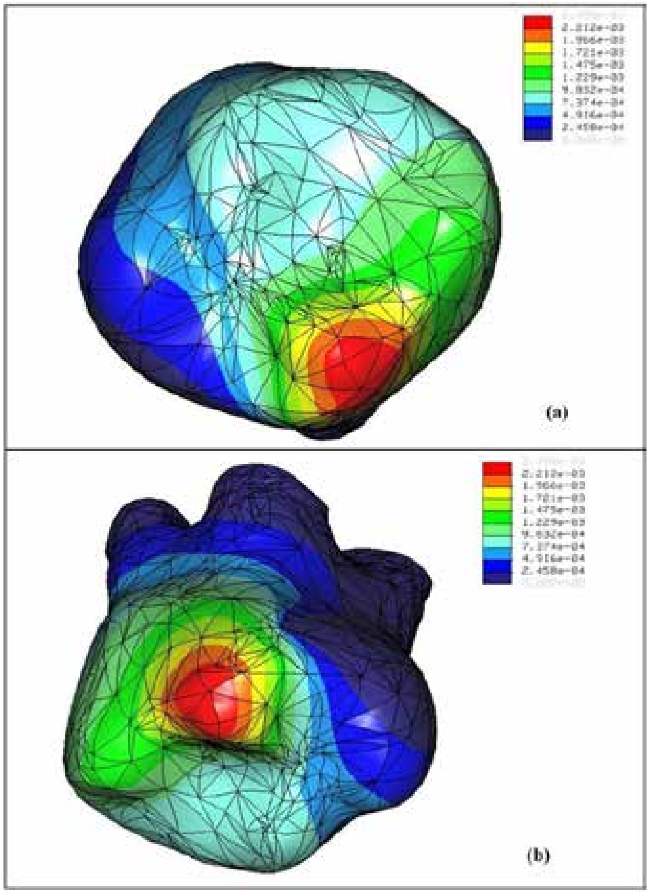


Figure 5 - Maxillary first permanent molar showing load application without any constrains on mesial surface

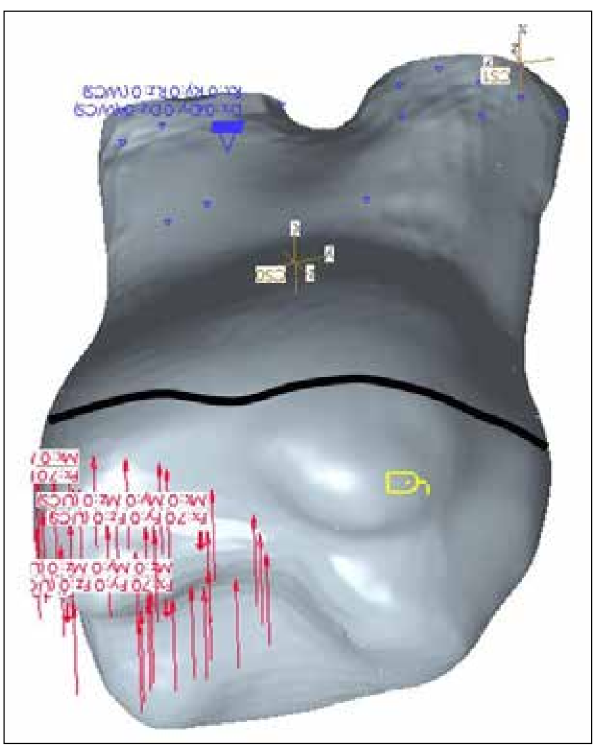


TABLE-1 – Mean Stresses in roots and crown of the permanent maxillary first molar with and without mesial constrain.

Particulars	With mesial Constrain MPa	Without mesial Constrain MPa
Maximum mean stress in the mesio-buccal root	2.56 distributed in broad area	1.87 distributed in broad area
Maximum mean stress in the disto-buccal root	0.012 distributed in broad area	1.87 distributed in broad area
Maximum mean stress in the palatal root	2.56 distributed in broad area	14.40 In apical and cervical area
Maximum mean stress in the crown	62 on the mesial contact area	1.87 on mesio-palatal cusp

Part II – Pattern of stress distribution and displacement in the maxillary permanent maxillary first molar without mesial constrain (Figures 5-7, table-1)

An occlusal load of 70 N was applied (Figure-5) on the mesio-palatal cusp. The stress generated on the mesio-palatal cusp was 1.87 MPa whereas the rest of the occlusal surface was free of any stresses indicated as dark blue (Figure- 6a).

The PDL of palatal root experienced greatest stresses in the range of 7.5-15MPa, indicated as yellow, green and red. Maximum stresses in the range of 13-15MPa were concentrated in apical and cervical area, indicated as red. Much less stress was seen in the PDL of other 2 roots i.e. mesio-buccal and disto-buccal roots which were in the range of 0 to 1.87 MPa indicated with dark blue and light blue respectively (Figure 6b and 6c, table-1).

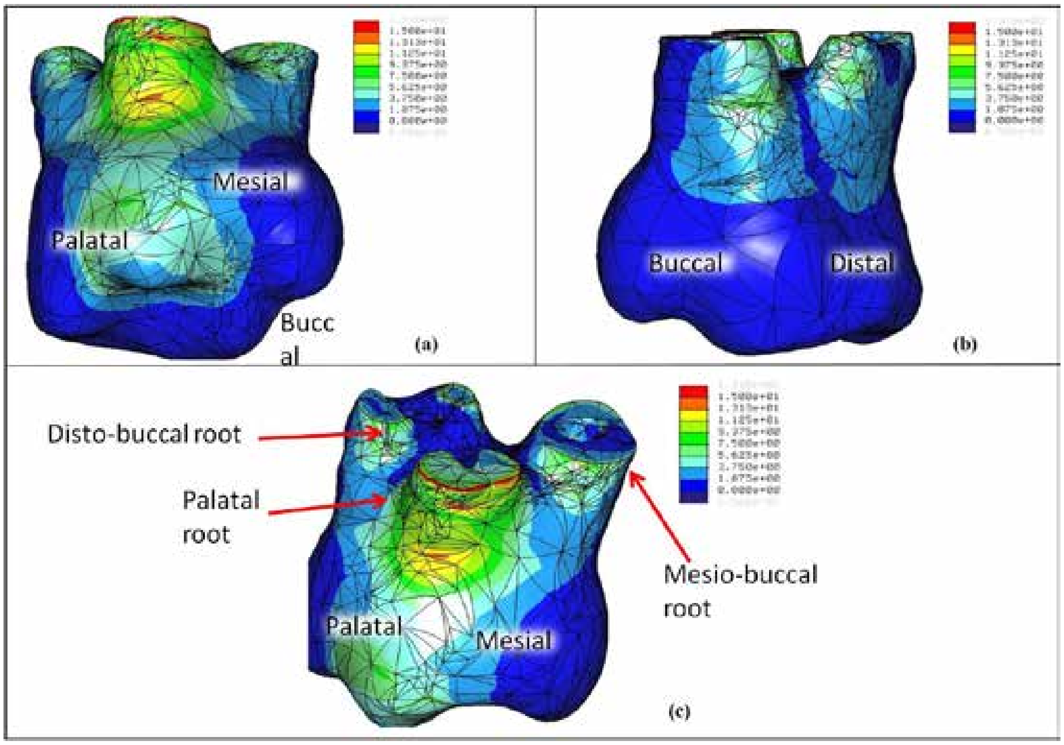
The maximum value of displacement was 8.1 µm, recorded in the mesio-palatal direction. Insignificant displacement (0.81 µm) was seen in the roots (Figures-7 a and b).

DISCUSSION

During the period of mixed dentition, the maxillary permanent maxillary first molar is still in a process of development. Its roots are not completely formed and this differentiates it largely from the mature permanent molar. When the tooth is acted upon by physiologic masticatory loads, the stress is transferred via the periodontal ligaments to the underlying bone. In the case of mature tooth, long slender roots are present which provide a large surface area for the transmission of these stresses, so the stresses are distributed along the entire root surface. Whereas, in the case of a developing tooth, only a small surface area is available for the same load to be transferred to the underlying bone. Therefore greater amount of stress was expected to be concentrated in the PDL along the root surface.

During the process of tooth eruption, the amount of tooth structure covered by bone constantly varies. In a fully mature tooth that has attained occlusion, the CEJ lies at the level of alveolar crest allowing occlusal load to transmit to the underlying bone via only the root structure embedded in the bone. Whereas in an immature permanent tooth, during eruption, the CEJ is at a level below the alveolar bone embedded inside the bone. This

Figure 6 - Pattern of stress distribution in maxillary first permanent molar without any mesial constrain (a) Mesio-palatal view (b) Disto-buccal view (c) Top view

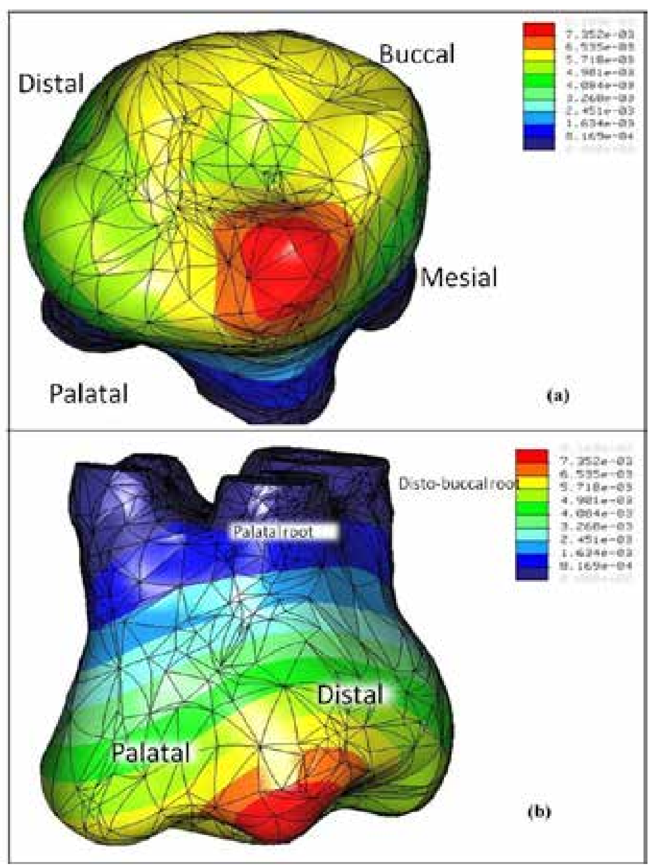


further supports the tooth structure by decreasing the area of tooth to move freely thus transmitting the major occlusal stresses to the bone. Therefore in FEA model, we considered the bone to be present a few mm above CEJ.

The functional forces generated during mastication have been measured using transducers incorporated within fixed and removable prostheses. The occlusal forces during mastication are considerably lower than maximum bite forces. The maximum bite force is the maximum efficiency with which a person can bite and it cannot be considered as normal masticatory load. Occlusal forces and maximum bite force falls in the range of 50 N to 100 N and 140 N to 393 N respectively during simulated chewing for normal children of the age group 6-12 years.[15-19] Maximum axial loads range between 70 to 150 N during chewing and swallowing of a variety of foods.[20] A mean bite force is 78 N at age 6-8 years.[21] Thus 70 N was thought to be fairly representative of the normal physiological load occurring during mastication and was chosen as the load for the study (Figure 2 & 5).

The ACF (maximum stress) was generated, at the place of applied constrains on mesial surface of permanent maxillary first molar during occlusal loading in intact arch which was in accordance with Southard T E (1989)[1] (figure-3a). This ACF get dissipated anteriorly through contact areas of anterior teeth without transferring to the roots (figure-3a). Conversely in absence of mesial constrain, the generated ACF got transferred to the PDL of roots which resulted in tooth movement that the tooth tipped mesially in the gap anterior to it. Although the mode was expected different under physiologic masticatory force (vertically directed) contrary to unidirectional orthodontic force (mesially directed) but it moved mesially with mesio-palatal rotation as was found by Kozima *et al* [8] under unidirectional orthodontic force.

Figure 7 - Displacement pattern in maxillary first permanent molar without mesial constrain (a) Occlusal view (b) Mesio-palatal view



The distal root experienced practically no stresses. The stresses in this case were seen only in the palatal and mesio-buccal roots. The results mimic the *in vivo* condition that the permanent maxillary first molar is angulated slightly buccally with mesio-palatal cusp occluding the central fossa of mandibular first molar, that the occlusal forces acting on this cusp might get transferred in this direction- to the palatal root primarily.

Immediately after force application in presence of mesial constrain, no displacement of roots was observed. The displacement for crown was 2.2 μm that was practically insignificant and can be considered physiologic. This was in accordance with the vivo conditions in which no movement is observed in the case of an intact arch under normal masticatory loads.

In the second case, with no mesial constrain, vertically directed force of 70 N generated maximum mean stress concentration on the palatal root in the range of 13-15 MPa in the cervical and apical area of root whereas rest of the palatal root experienced a stress in the range of 7.5 to 11.25 MPa (Figure-6a and 6c). Much less stress was observed with the other two roots. No stresses were found on crown portion. Kojima and Fukui[8] also reported the maximum stresses to be concentrated at the most apical portion of the root and near the CEJ when a mesial horizontal force of 1 N was applied on the buccal surface of maxillary permanent maxillary first molar. Some minor differences might be due to the incompletely formed roots of the molar and vertically directed forces in the present study that is likely to affect the stress distribution. Maximum stresses were concentrated around the palatal root. The anterior component of occlusal force generated on vertical load application did not progress beyond open contacts and was found to be transferred entirely to the roots. Under normal functional force, the tooth was displaced in the mesio-palatal direction which was in accordance with the in-vivo conditions. For this movement, the bone at the cervical portion acted as a fulcrum and the whole movement occurred around the palatal root.

In the case without mesial constrain the displacement was recorded to be 8.1μm in mesio-palatal direction. This was nearly the same as that reported by Kojima and Fukui (2008)[8] who reported a mesial movement of 7.6μm under a mesial force of 1 N. They did not consider physiologic forces acting on the teeth and only applied a 1 N mesial force on the tooth. This suggests that under masticatory loads, the tooth has a tendency to move in mesio-palatal direction when an extraction space is presented mesial to it. Also there was insignificant displacement seen in the roots of the tooth. This suggests that there is a tendency of the tooth to tip in mesial direction rather than entire bodily movement. This displacement was almost 4 times the value recorded with intact arch. Same were the findings of Kojima and Fukui[8] , where in spite of mesially directed force, the mesial tipping movement of permanent maxillary first molar was associated with mesio-palatal rotation. They assumed that tipping was because of mesial force while transverse movement was due to rotation. Both mesio-palatal rotation and mesial tipping was observed in our study in spite of the absence of any mesially directed forces which was around the palatal root, showing maximum stress distribution. Also they concluded that maximum stresses in the PDL of permanent maxillary first molar were smaller in intact arch as compared to those without the premolar (mesial constrain). Similar results were observed in our study too. Our study also validates the rationale, given by Kupietzky and Tal[22], in their article where they discussed about transpalatal arch and Nance palatal arch that when permanent maxillary first molar moves anteriorly (tipping), they rotate mesio-lingually around the large lingual root. As transpalatal arch was found to prevent the rotation of permanent maxillary first molar[8] and as no mesially directed forces but only the masticatory loads are acting on space maintainers, it can successfully be given in mixed dentition even in cases of bilateral teeth loss in same arch. Future studies with space maintainer components included in this FEA model shall validate the statement.

One additional dilemma that permanent maxillary first molar moves bodily in case of missing tooth anterior to it, has been clarified by our results that the tooth only tips forwards. The roots of the permanent maxillary first molar lies in a mesial position whereas that of the mandibular permanent maxillary first molar lies in a distal position in relation to the crown. Each permanent molar tend to move mesially in case of missing primary second molar. If this is not prevented, the lower molar will erupt in a straight line path, giving the appearance that it has tipped to the mesial. By contrast, the upper permanent molar swings to the mesial and, because the roots are more mesial-ward to begin with, gives the impression that there has been more bodily displacement of this tooth.[23]

According to the parameters set by Kojima and Fukui[8] the validity of the assumption in present article seems correct as the FEA results were very much similar to the clinical conditions. This was the additional purpose of our study. The calculation of tooth movement in clinical conditions is difficult, thus mathematical simulation may provide a base for future studies for understanding the behavior of tooth movement in various clinical situations.

Two limitations of the present study were that the study was not time dependent and the periodontal ligament was considered as a continuous and linear structure, whereas the periodontal ligament is a non-linear and fibrous structure. Further studies needs to be carried out considering time as a factor to study the long term effects of the normal masticatory loads.

The present study expands the results of orthodontic studies by providing three dimensional finite element analysis of immature first permanent maxillary molar under simulated physiologic vertical masticatory loading in mixed dentition.

CONCLUSION

Within the limitations of this study following conclusion could be concluded that

1. In intact arch, anterior component of occlusal force was detected and most of the stresses were transferred to the primary second molar through the contact area without transferring it to root area.
2. There was practically no mesial displacement of permanent maxillary first molar in the intact arch.
3. In the case with missing primary maxillary second molar, maximum stresses were concentrated on the cervical and apical area of the palatal root of the permanent maxillary first molar.
4. Maxillary permanent maxillary first molars showed a tendency of mesial tipping with mesio-palatal rotation.

Based on the results, therefore, any space maintainer capable of preventing mesio-palatal rotation of permanent first molar, can be given in mixed dentition. The model can be utilized for future time dependent FEA studies, designed to quantify stresses and tooth movement with or without space maintainer.

ACKNOWLEDGEMENT

We are thankful to Mr. Rishi Kumar, Deputy Manager, JCB India Ltd., Talegaon India Design Centre, Pune (Maharashtra), India for continuous and untiring technical help.

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