Effect of hyperfunctional occlusal loads on periodontium: A three-dimensional finite element analysis

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INTRODUCTION

The role of occlusion on periodontal health is challenging, and the results of research studies are contradictory and inconclusive. Several studies have tried to assess the stress produced by the occlusal forces within the tooth and supporting structures. Finite element analysis is a numerical form of computer analysis using mechanical engineering that allows the stress to be identified and quantified within the structures constructed using elements and nodes.

The periodontal structure shows varied adaptive capacity from individual to individual and time to time in the same individual with regard to occlusal forces. The somatic and psychic changes also play a role in varied occlusal forces. The clinical and histological changes produced in the periodontal tissue to various occlusal forces have been described in the literature. Unfortunately, these stresses are not quantified.

Few studies on FEM analysis of stress have focused on primary and secondary trauma from occlusion (TFO) include: A two-dimensional model of post reinforced maxillary central incisor evaluated the principal stresses in periodontal ligament (PDL) at various base levels;[10] Geramy and Faghini utilized a three-dimensional (3D) FEM model (ANSYS 5.4, ANSYS Inc., USA) of natural central incisor to calculate maximum and minimum principal stresses in the PDL of maxillary central incisor with different bone heights.[11] In both the studies, only the PDL stresses were calculated; however, in alveolar bone and root stresses are important in alveolar bone destruction due to occlusal trauma either alone or during periodontitis. A study done by Reddy and Vandana was the first report of distribution of stresses on tooth and abfraction.[12] A study done by Vandana et al. studied the role of stresses on tooth and abfraction.[13]
In the present study, first attempt has been made to apply normofunctional (150N) and hyperfunctional (290N) occlusal loads on maxillary central incisors with normal alveolar height and with compromised alveolar height with 25%, 50%, and 75% bone loss to quantify various stress levels in tooth root, PDL, and alveolar bone.

**MATERIALS AND METHODS**

The finite element analysis was performed on a personal computer (Pentium III, Intel) using in ANSYS software, marketed by ANSYS Inc., USA. In this study, a 3D FEM of the anatomical size and shape of an average Indian maxillary central incisor was constructed. Variable PDL widths were developed at different occlusogingival levels derived from the data of Coolidge. The use of these varying thicknesses makes the model more precise and realistic.

In this study, the analytical model was built by scanning the pictures of the maxillary central incisor in the Wheeler’s textbook. The geometric model was converted into the FEM. The type of element used for modeling was a 3D quadratic tetrahedral element with three degrees of freedom (dof) for each node. The FEM was the representation of geometry in terms of a finite number of elements and nodes, the complete model consisted of 47,229 elements and 68,337 nodes, and Table 1 represents the number of elements and nodes for varying bone levels. The different structures such as tooth [Figures 1a and 2], PDL [Figure 1b and 3] and alveolar bone [Figures 1c and 4] were assigned the material characteristics conforming to the data available in the literature. In this study, all the tissues were assumed to be isotropic, homogeneous, and linear [Table 2].

**RESULTS**

The criteria used to evaluate a structure from the stress perspective are the minimal principle stress criteria. The results are summarized in Tables 3 and 4.

The results are as follows:

**Normal bone height [Table 3]**

At a load of 150N (normofunction), the minimum stresses were seen at a point D (−1.18 Mpa) which is located at the cementoenamel junction (CEJ) on the mesial side, and maximum stresses are seen at point D (−10.93 Mpa) on the labial site. As the load increased to 290N, stresses also increased by 90%.

**Compromised bone height [Table 4]**

At a load of 150N (normofunction), the minimum stresses were seen at a point D (−0.02 Mpa) which is located at the cervical third of root on the palatal side and maximum stresses are seen at point F (−140.45 Mpa) a point at the junction of middle and apical third on the tooth on the labial site with 75% bone loss. As the load increased to 290N, stresses also increased by 90%.

**Table 1: Number of elements and nodes used in different models of the tooth**

| Percentage bone level reduced | Number of elements | Number of nodes |
|------------------------------|--------------------|-----------------|
| 0                            | 47,229             | 68,337          |
| 25                           | 42,998             | 62,766          |
| 50                           | 35,639             | 52,740          |
| 75                           | 28,147             | 42,429          |

**Table 2: Material parameters used in finite elements model**

| Material          | Young’s modulus (kg/mm²) | Poisson’s ratio |
|-------------------|--------------------------|-----------------|
| Tooth             | 2.0×10⁶                  | 0.30            |
| PDL               | 6.8×10⁵                  | 0.49            |
| Alveolar bone     | 1.4×10⁵                  | 0.30            |
| Pulp              | 0.2                      | 0.45            |

**Table 3: Stress values in tooth, periodontal ligament and alveolar bone height at normal bone height at different occlusal loads**

| Site  | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum |
|-------|---------|---------|---------|---------|---------|---------|
| Site  | Point Value (MPa) | Point Value (MPa) | Point Value (MPa) | Point Value (MPa) | Point Value (MPa) | Point Value (MPa) |
| 150N  | Mesial D*  | −1.18   | Labial D*  | −10.93  | Mesial D*  | −0.005 | Distal H*  | −4.06  | Distal D*  | −0.04  | Labial D*  | −4.3   |
| 290N  | Mesial D*  | −2.28   | Labial D*  | −21.33  | Mesial D*  | −0.01  | Distal H*  | −7.8   | Distal D*  | −0.08  | Labial D*  | −8.4   |

D* denotes the minimum amount of stress; Significant values are not drawn as it is an observation of maximum and minimum stresses; *Minimum value at given point and site mentioned; **Maximum value at given point and site mentioned. PDL – Periodontal ligament; MPa – Megapascals; N – Newtons
Stresses on periodontal ligament

**Normal bone height [Table 3]**
At a load of 150N (normofunction), the minimum stresses were seen at a point $D_p$ (−0.005 Mpa) which is located at the CEJ on the mesial side, and maximum stresses are seen at point $H_p$ (−4.06 Mpa) on the palatal side. As the load increased to 290N, stresses also increased by 90%.

**Compromised bone height [Table 4]**
At a load of 150N (normofunction), the minimum stresses were seen at a point $F_p$ (−0.02 Mpa) which is located at midpoint of PDL on distal side with 50% bone loss and maximum stresses are seen at point $G_p$ (−73.46 Mpa) which is located at the junction of middle apical third of PDL site with 75% bone loss on palatal side. As the load increased to 290N, stresses also increased by 90%.

Stresses on alveolar bone

**With normal bone height [Table 3]**
At a load of 150N (normofunction), the minimum stresses were seen at a point $D_b$ (−0.04 Mpa) which is located at the crest on the mesial side, and maximum stresses are seen at point $D_b$ (−4.3 Mpa) on the labial side. As the load increased to 290N, stresses also increased by 90%.

**Compromised bone height [Table 4]**
At a load of 150N (normofunction), the minimum stresses were seen at a point $F_b$ (−0.06 Mpa) which is located at the midpoint of the alveolar bone on the distal side with 50% bone loss, and maximum stresses are seen at point $G_b$ (−44.01 Mpa), a point at the junction of middle and apical third of the bone on the palatal side with 75% bone loss. As the load increased to 290N, stresses also increased by 90%.

DISCUSSION

It has been said that the balance in the stomatognathic system will contribute to periodontal health. Conversely, when the interrelationship is disturbed, periodontal disease may follow.³⁴

There always existed a dilemma, about the precise role of occlusion in periodontal disease. There are many contradictory theories regarding the same. For a proper treatment plan, one...
In this study, maxillary central incisor was modeled and analyzed using finite element analysis. The average force of 15 kg (150N) was applied at the middle third of the crown on the palatal surface at an angle of 50° in a palatolabial direction. This represented the normal occlusion. This normal occlusion was compared with one other loading at the same direction, 29 kg (290N) representing hyperfunction as this load is excessive. The average force on the bicuspid, cuspids, and incisors is about 300N (30 kg), 200N (20 kg), and 150N (15 kg), respectively. These occlusal forces produce a constant stress on the tooth and its supporting structures, so the measurement of the stress produced is mandatory.[9]

The results of the following study are discussed as follows:

The compressive stresses induced in the root, PDL, and alveolar bone, by the occlusal load representing the hyperfunction (290N) increased by 93% or 1.9 times, the stress values produced by normal occlusal load (150N) representing primary TFO.

Reduction of alveolar bone height represents the weakened periodontal support or more appropriately secondary TFO, it had little effect on the tooth and the supporting tissue when 25% of the bone support was lost, however, the stresses increased dramatically when 50 and 75% of bone support was lost and also shifted apically on the tooth coinciding with the alveolar crest for the amount of bone loss.

Thus, the increase in stresses by 93% at hyperfunctional load with normal bone heights explain the reason for primary TFO and with compromised bone levels explain the reason for secondary TFO. In compromised bone height levels, the stresses increased as we reached the apex of the tooth, this can be explained as the amount of force distributed in relation to surface area is increased as the loss of the tissues lead to decrease in surface area.

Reinhardt et al. 1984 studied only the principal PDL stresses in primary and secondary occlusal trauma. The results showed maximum compressive stresses near the alveolar crest (~0.415Mpa) which increased dramatically as the bone levels diminished and to a lesser extent in the apical one half (~0.163) of the root for all the loads applied in the study at different bone levels.[11]

Reddy and Vandana 2005 studied the Von Mises stresses in a natural model of the maxillary central incisor tooth, PDL, and alveolar bone using a higher load of 24 kg. They used Von Mises stresses which are used for ductile materials in which the stresses are normalized in all areas and compression...
and tension cannot be interpreted adequately. Since tooth is brittle material, Von Mises stresses are not ideal to study compression and tension on a tooth. Therefore, the present study used minimum principle stresses to measure the stresses as it best represents the compression state of the stress.

Geramy and Faghihi studied the compression stresses in the labial site of the PDL in 3D FEM model of maxillary central incisor with normal to reducing alveolar bone heights. Based on the FEM analysis, 2.5 mm of alveolar bone loss can be considered as limit beyond which stress alterations were accelerated, and the alveolar bone loss increases stress produced in PDL.[2]

Other studies which were done with the similar interest are

Poiate et al. 2009 studied hyperfunctional/parafunctional loads in three different conditions, but the results are expressed in tooth as a whole.[10] Our comparative study considered normo- and hyper-functional loads at the different bone levels influence of stresses on individual periodontal tissues.

Chen et al. 2011 studies distribution of forces and mobility of tooth analyzed using a 10N force.[11] which is far below the normofunctional load. In our study, normo- and hyper-functional loads and the behavior of tissues are discussed, respectively.

Zhang et al. 2017 in this study, a mandibular first molar FEM was built from computed tomography images.[12] The effects of area-size, location, and direction of occlusal loading on both tooth and periodontal stresses were analyzed using a load of 150N. We studied and compared normofunction load, i.e., 150N and effect of hyperfunctional load on central incisor.

None of the above recent literature is comparable due to variations in methodology and their objectives.

Although all the studies conclude the same that with increased stresses the damage to the periodontal tissues is increased the presentation of this study varies as it compared the stresses at health and compromised state and also expressed the percentage of increased of stresses in compromised states in periodontal tissues. And also, many of the previous studies overlooked or omitted the simulation of PDL in their 3D models to simplify the study which lead to inaccurate stress-strain relations.[13] That is avoided to the best of our knowledge.

The possible clinical transfers from the current FEM study are as follows:

The improvements in this study are a 3D modeling of natural tooth, and the PDL width modeled with different widths instead of the average thickness around the root. The types of elements were quadratic tetrahedral which have three dof than triangular elements.

At all bone heights, the stress values were found to be higher in relation to apex. This may explain the de novo occurrence of periapical abscess represented as periapical radiolucency in those teeth with primary TFO without periodontitis.

In compromised bone height levels, the stresses increased as we reached the apex of the tooth, this can be explained as the amount of force distributed in relation to surface area is increased as the loss of the tissues lead to decrease in surface area.

The results of the excessive load applied in this study (290N) would cause development of the typical histologic lesion of primary occlusal trauma. Alterations of the periodontium that have been associated with occlusal trauma will vary with the magnitude and direction of the applied force and location (pressure vs. tension). These changes may include widening/compression of PDL, bone remodeling (resorption/repair), hyalinization, necrosis, increased cellularity, vascular dilatation/permeability, thrombosis, root resorption, and cemental tears.[14-22] Collectively, these changes have been interpreted as an attempt by the periodontium to adapt and undergo repair in response to traumatogenic occlusion. The compressive stress curves for the excessive loads used in this study showed the highest ligament stress at the crest of the alveolar bone. This pattern is consistent with the widening of the PDL space that occurs with the lesion of occlusal trauma. Values decreased when measured in an apical direction but again increased at apex, suggesting a relation of excessive stress at the apex to periodontal destruction in the periapex in primary TFO.

Observations from this study showed that as the bone levels are compromised the stresses increased as the crest moved apically, this can explain the occurrence of angular bone defects as one of the classic features of TFO.

Clinical implications

The compressive values were subject of the clinical interest in this study since these values appear to play the greatest role in the initiation of bone resorption and lesion of occlusal trauma.

During occlusal discrepancy correction, the results of this study will be useful to measure mechanical values of the stress before and after treatment, provided a chairside stress measurement device is made available. The need of the hour is to manufacture a chairside measuring device to help academicians and practitioners.

So far, there is no report of numerical stress values being presented for the changes brought about in supporting periodontal tissues

It was written subjectively as more of stresses being produced as the alveolar bone levels reduced.

The advantage of FEM study is that we are able to show the changes in numerical stress values at normo-, hyper-, and hypo-occlusal loads. The normal occlusal load is applied as per the literature information. However, hypo- and hyper-functional loads are hypothetical situations to determine the possible numerical stress values at that point of static application of occlusal load. In a given mouth, there is a great variation in occlusal load on every tooth depending on the type of food consumed, physiologic activity, muscular action, and other parafunctional habits.
The determination of stress values in a functional mouth is the need of the hour to decipher the role of occlusion on periodontal tissues. The future direction on this raw topic requires the comprehension of biologic adaptation by the mechanical engineers to design a method to evaluate most complex issue of structural and functional interplay.

Further, the histologic evaluation of periodontal tissue changes should be correlated with stress values using FEM.

Further research
A stress analysis inside the PDL would be possible by means of processing the results obtained with our model when a micromechanical model of PDL is made available.

Further, no quantitative guidelines exist to assist clinicians in making proper adjustment of traumatic occlusion, orthodontic force, for controlled tooth movements and placement of implants so that the stress in the supporting structures get evenly distributed. The FEM has been tried in this aspect but with certain approximations and assumptions. Therefore, further studies should be done to correlate the effects of frictional increases in loads of the dynamic occlusion to the changes in the periodontal tissues.

CONCLUSION

Based on the findings of the present study, there is reasonably good attempt to express numerical data of stress to be given normal occlusal and hyperfunctional loads to simulate clinical occlusal situations which are known to be responsible for healthy and diseased periodontium. The study of excessive loads in terms of primary TFO and with grades of bone loss for secondary TFO has clearly demonstrated variations in stress reactions of various periodontal tissues. At this juncture, the requirement is to assess the various occlusal forces to its histologic effects in an in vivo study. Considering the dynamicity of occlusion the possibility of studying the histologic changes to representative excessive loads, is highly questionable.

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Conflicts of interest
There are no conflicts of interest.

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