REVIEW ARTICLE

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The role of radiographic imaging and finite element analysis in evaluating occlusal loads and stress distribution in the periodontal ligament

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ABSTRACT

Objectives: Biomechanical behavior analysis of the periodontal ligament (PDL) under various loading conditions is essential for understanding the impact of occlusal force distribution. A comprehensive understanding of this aspect is fundamental, and radiographic examination is a crucial modality for evaluating periodontal health. This review aims to illustrate the role of radiographic examination in influencing dental prognosis through the use of Finite Element Analysis (FEA) to assess occlusal load and stress distribution in PDLs.

Review: Radiographic imaging techniques are critical for assessing the extent of occlusal trauma and its impact on the periodontal ligament and surrounding structures. Modalities such as conventional radiography, cone-beam computed tomography (CBCT), and micro-computed tomography (micro-CT) are commonly used to evaluate occlusal load. Studies have demonstrated that a balanced occlusal scheme results in a more uniform stress distribution, while an unbalanced scheme leads to localized stress concentrations, increasing the risk of periodontal damage. FEA has emerged as a powerful tool for simulated and visualizing stress patterns in the PDL and quantitatively calculating stresses and deformations in the periodontium. Technological advances in imaging, when applied in conjunction with finite element computational techniques, have shown that oblique loading results in higher stress concentrations compared to vertical loading, particularly in the PDL of mandibular first molars. These higher stresses, often observed in the cervical and apical regions, highlight the potential for more significant PDL damage, making it useful for evaluating bone loss and PDL integrity. for eligibility and completeness of journals.

Conclusion: Integration of advance radiographic imaging with FEA has significantly enhanced the understanding of occlusal load and stress distribution in the periodontal ligament. This advancement has propelled the field of periodontal biomechanics, offering very valuable insights into PDL's biomechanical behavior as it responds to varying occlusal loads, to optimize outcomes in periodontal and orthodontic care.

Keywords: *Finite element analysis, periodontal ligament, stress distribution, occlusal trauma*
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INTRODUCTION

Periodontium has its own ability to respond to the stress produced by occlusal forces within the tooth and supporting structures. Regarding the occlusal force loads, the adaptive capacity of the periodontal structures varies from individual to individual.[1] Periodontal ligament (PDL) is a specialized connective tissue of the periodontium that plays a critical role in maintaining the health and functionality of teeth, as well as the maintenance and health of the periodontium by connecting the tooth to the alveolar bone. It is not only a supportive structure but also a sensory apparatus that provides proprioceptive feedback to the central nervous system. It works as a shock absorber, distributing occlusal loads and stress to prevent damage to the tooth structure and surrounding bone, anchoring teeth within the alveolar bone, and absorbing occlusal loads to prevent damage to dental and periodontal structures.[2,3]

The PDL contains a network of collagen fibers, blood vessels, and nerves, providing structural support and sensory feedback.[2,3] The PDL's ability to adapt to mechanical forces is vital for maintaining periodontal health. Abnormal occlusal loads can lead to alterations in the PDL, resulting in inflammation, resorption of alveolar bone, and eventually, tooth mobility or loss.[4,5] Analysing the biomechanical behavior of the PDL under various loading conditions is very important, especially for optimizing dental treatments, such as prosthodontics and orthodontics. Understanding how the occlusal forces are distributed is crusial for the diagnosis and treatment of periodontal and dental circumtances. The stress distribution within the PDL under occlusal loads is vital for assessing

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the biomechanical environment of the periodontium, particularly in response to varying occlusal forces and their potential pathological consequences. These occlusal forces may vary based on the somatic and physical changes in the individual toward the PDL reaction even in the same individual, from time to time.[1,6]

Radiographic imaging has become an indispensable tool in evaluating the PDL, as it provides detailed visualizations of the structures involved and allows for assessing occlusal loads and stress distribution.[7,8] Finite Element Analysis (FEA) become a powerful tool for simulating stress distribution within the PDL, providing detailed insights into the effects of occlusal forces, using geometry data obtained from radiographic imges to create a three dimensional model, for example, the PDL space widening on the radiography, that may indicate local stress concetration, can be further analysed using FEA to predict the area of stress distribution or PDL's potensial damage area. Shetty at. al study using CBCT data and 3D Finite Element Model (FEM) to evaluate stress distribution of maxilla molar PDL under different occlusal loading conditions, showed that oblique loading resulted in higher stress concentrations in cervical and apical regions of the PDL compared to vertical loading. These tensile stresses, can obstruct blood flow, resulting in PDL damage that can lead to other supporting structures damage or further more become traumatic occlusion. This review aims to summarize recent advancements in the role of radiographic appearance in understanding the impact of occlusal forces and understanding mechanical behaviour of the PDL and how this knowledge can influence the prognosis of teeth as well as the FEA applications for studying occlusal loads and stress distribution in the PDL.[9–11]

REVIEW

Radiographic examinations are indispensable tools in the evaluation of periodontal health and the assessment of occlusal forces. They provide a visual representation of the bone and PDL, allowing for the detection of pathological changes. Radiographic techniques, including periapical, bite-wing radiographs and panoramic, are commonly used to assess the bone level and the condition of the PDL space. Image of excellent quality is necessary because the fine details are required for interpretation of the periodontal tissues, in the example it can clearly show a radiolucent line along the mesial-distal aspects of the teeth between the roots and lamina dura is the appearance of normal PDL space.[8] Normally the PDL has a width of around 0.15 mm to 0.21 mm, widening or changes in the PDL can be a sign of abnormalities in the condition of the teeth and their supporting structures.[12]

The reaction of occlusal forces is absorbed by PDL plays a role in reffering it to the surrounding bone, so the PDL destruction can result in various disorders including matrix connective loss, pathological tooth movement, bone resorption, malocclusion and TMJ disorders.[13] Accurate radiographic assessment is essential for diagnosing conditions like occlusal trauma, which may manifest as an alteration of PDL space, and for planning therapeutic interventions.

Recent advancements in imaging technologies, such as CBCT and digital radiography, have enhanced the accuracy and detail of radiographic evaluations. These technologies provide high-resolution images that can better delineate the fine structures of the periodontium, allowing for more precise measurements and assessments of the PDL under various occlusal conditions. This detailed imaging capability is crucial for both diagnosis and treatment planning, particularly in complex cases involving occlusal discrepancies and periodontal disease.[7,14–16] Radiographic imaging techniques are critical in assessing occlusal trauma and its impact on the PDL and surrounding structures. Conventional radiographs, CBCT, CT and micro-CT are commonly used modalities to visualize occlusal loads effect. Traditional periapical and panoramic radiographs provide a broad overview of the dental

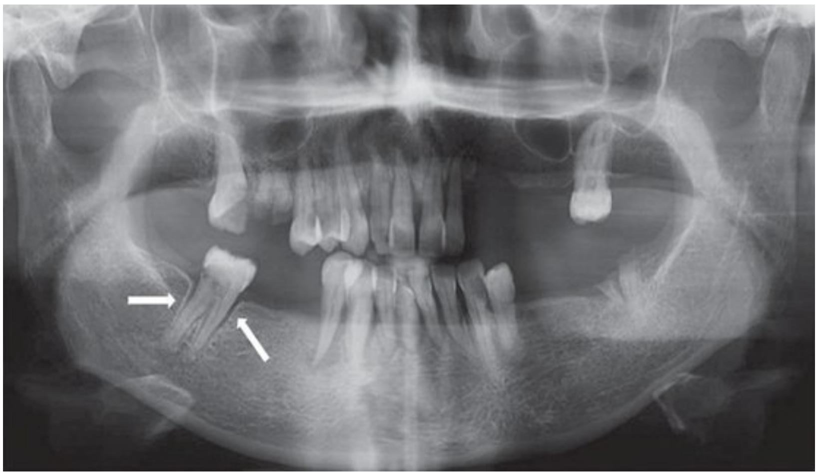

Figure 1. Panoramic radiograph shows periodontal ligament widening around the second molar mandibular right is evident with loss of neighboring teeth, subjecting it to heavy occlusal trauma[12]

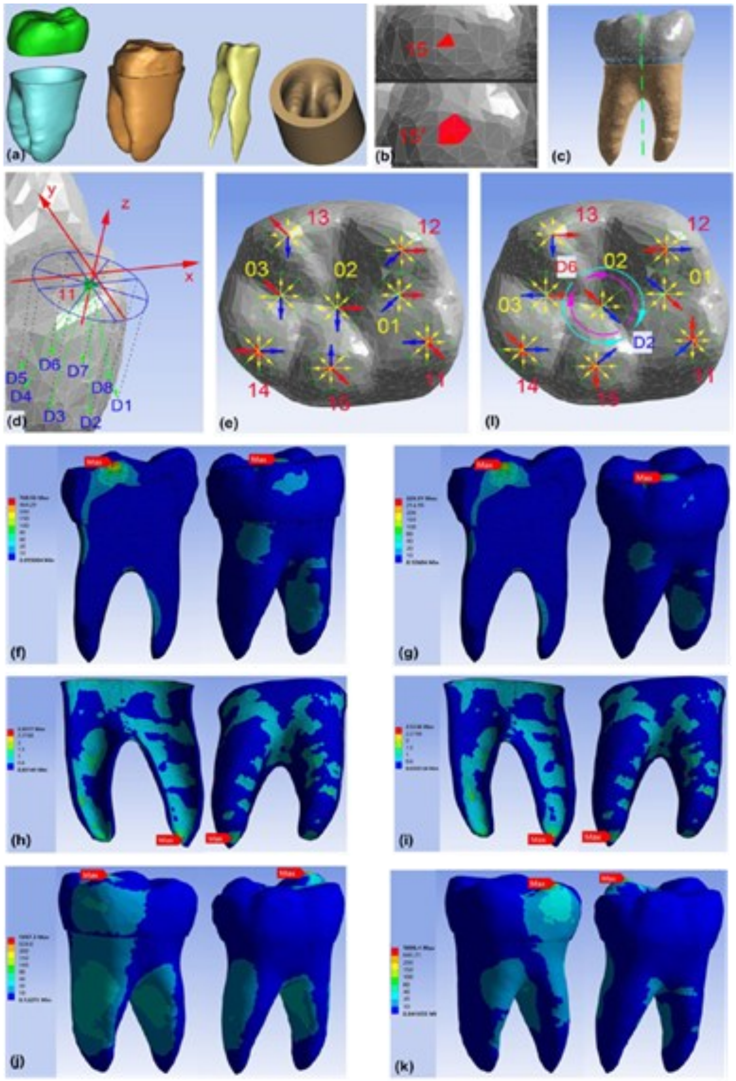

Figure 2. Finite element modeling of first molar mandibular right, with effects of area, location, and direction of loading. (a) Model of enamel (green), periodontal membrane (blue), dentin-cementum complex (brown), pulp (dark yellow), and alveolar bone (dark gray). (b) Loading using single and double triangular planes at site 15. (c) tooth long axis (d) eight loading directions map at site 11. (e) Eight loading map locations on occlusal surface, indicating directions of maximum (red arrows) and minimum (blue arrows) Maximum Periodontal Stress. Stress concentration from vertical loading at location 15 for single triangle planes (f) and (h), at five single triangle planes (g) and (i), Mesial-distal map at site 12 (j) and 13 (k). (l) Maximum Tooth Stress with direction of stress change[22]

and periodontal structures, they are helpful for identifying gross changes in the PDL space, alveolar bone resorption, and tooth mobility. However, the resolution is often insufficient for a detailed analysis of stress distribution.[7,17,18] CBCT offers three-dimensional imaging, providing detailed views of the dental and periodontal structures. It is particularly useful for evaluating the extent of bone loss and the integrity of the PDL. Studies have shown that CBCT can effectively detect changes in the PDL space due to occlusal trauma, offering a more precise assessment compared to conventional radiographs.[19,20]

Finite element analysis is a methode that can be used to analyze structural stresses, using a computer to solve large equations to calculate stresses based on the physical properties of the structure being analyzed. In-vivo studies are difficult in assessing biomechanical effects such as stress and strain, finite element analysis, is a valuable option for evaluating biomechanical factors. The stresses, strains, and deformations of structures with complicated geometry can be evaluated under deifferent loading and boundary sate using numerical methods, based on dividing a complex structure into elements, icluding tooth material heterogeneity and tooth contour irregularity in the model design and apply loads and magnitudes in different directions to complete analysis.[21] FEA using anatomical data obtained from various imaging modalities such as CBCT and CT with computational approach can help in visualizing the stress patterns and identifying areas of high stress concentration, and showing how the PDL responds to various occlusal forces, and understanding the biomechanical behavior of PDL under various loading scenarios.[13]

Research by Zhang et. al studying pattern of stress distribution using a FEM of the mandibular first molar based on a volunteer's CT image, by reconstructing the geometry of various components, as a digital representation of the teeth and their supporting structures, including the periodontal ligament using software (Mimics 10.1), by inserting a periodontal membrane between the root and the alveolar bone with 0.2 mm uniform thickness with the task of conducting simulations to determine the influence of the location, pattern, and mechanical loads direction on the teeth and periodontal Von Mises pressure. In this study, the

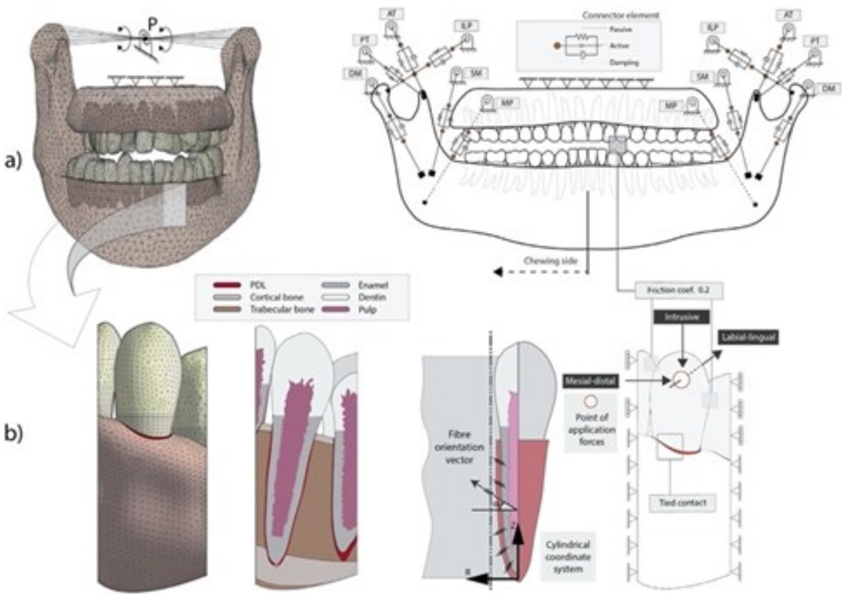

Figure 3. (a) Left: full dentition model mesh obtained by CBCT scan with mandible, maxilla, teeth, and PDLs. Right: schematic of boundary conditions applied to the model and the muscle system modelled. SM, superficial masseter; DM, deep masseter; ILP, inferior lateral pterygoid; AT, anterior temporalis; PT, posterior temporalis; MP, medial pterygoid. (b) Left to right: mesh of the portion of a human mandible obtained by µCT; section of the model with color-coded components; schematic showing of the cylindrical coordinate system used to describe the orientation of the fibres bundles, and boundary conditions applied to the model[13]

distribution and concentration of stress on the teeth and periodontal tissues under various occlusal load conditions were analyzed, it was seen that the pressure value on the periodontal ligament was generally much lower than that on the teeth under the same loading conditions, and it was seen that the size of the loading area affected the maximum periodontal pressure (MPS) value, where a larger loading area resulted in a smaller MPS value, indicating that the distribution of force in a larger area can reduce the pressure experienced by the periodontal ligament. The analysis also revealed that loading direction significantly affected the stress distribution in PDL.[22]

Micro-computed tomography (Micro-CT) has a relevant role in multi-disciplinary approaches, provides high-resolution, also three-dimensional images of of the internal structure of materials and biological tissues, suc as periodontal ligament. Micro-CT is an advanced imaging technique that generates X-rays that rotate around the sample, penetrate the sample, which is placed in the scanner, capturing multiple 2D images from different angles. As the X-rays penetrate the sample, they are attenuated to varying degrees depending on the density and composition of the material. A detector captures the transmitted X-rays, creating a series of 2D projection images that are processed using sophisticated algorithms to reconstruct a 3D representation of the internal structure of the sample. This reconstruction provides detailed information about the morphology, density, and microstructure of the sample. Micro-CT has high resolution, reaching resolutions of up to several micrometers, which can produce images of fine detail in biological tissues, such as the fibrous structure of the periodontal ligament (PDL).[13,23]

Micro-CT provides detailed anatomical and material property data, such as the microstructure of the PDL including its thickness, fiber orientation, and composition. These detailed structural data are essential for creating an accurate FEA model to analyze the damage mechanisms of the PDL under occlusal forces. The 3D reconstructions obtained from micro-CT scans serve as the basis for developing finite element models. This information is essential for determining material properties in FEA, to obtain a more realistic simulation, by integrating micro-CT data into FEA, effect of various occlusal forces and ditribussion on PDL can be performed. The FE model was scanned ex vivo using a micro-CT scanner, resulting in tomographic images that were rebuilt using computer software. It can display simulations that show stress distributions, potential failure points, and damage mechanisms, such as excessive fiber stretching or fluid pressure changes.[13,17] It can provide biomechanical insight, allowing for precise stress analysis that can lead to the determination of PDL mechanisms damage, which might be generated by mechanical loading and a hint of PDL in parafunctional and traumatic loading patterns. Micro-CT imaging can be one of modality for creating accurate FEA models to study the biomechanical behavior of the PDL under various occlusal loads.[13,17]

Study by Ortún-Terrazas et al. analyzed the PDL mechanical response and the destruction it endure when exposed to normal, parafunctional and traumatic occlusal forces considering the 3D loading, biological composition and PDL micromorphology. A 3D model of the human mandible containing canine teeth based on CBCT and micro CT images was created separately using finite element analysis (Figure 3). The first model

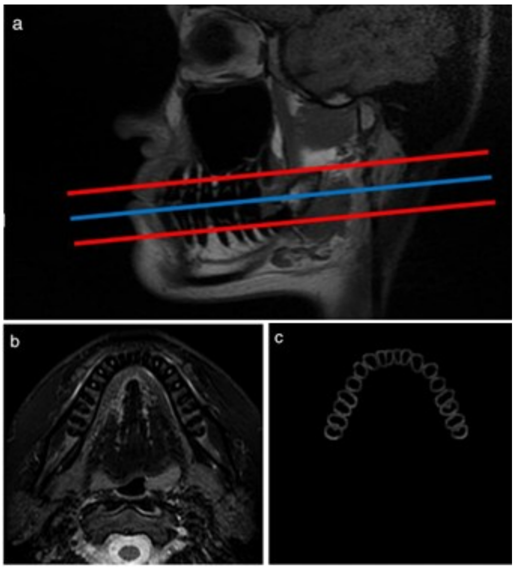

Figure 4 MRI image. (a) Positioning of imaging range by T1 weighted images. (b) Image of the mandible obtained by the IDEAL method. (c) Image obtained by extracting only the periodontal ligament equiv- alent based on the image in b[25]

was experimentally validated with occlusion analysis and exposed to muscle loading, where the calculated occlusal forces were then applied to a single tooth model to evaluate the collagen tissue damage and the extracellular matrix of the PDL. FE simulations produced similar occlusal patterns, with an initial contact on the left canine, driving the rotation of the tooth around its center of rotation due to the laterally applied occlusal forces. The collagen network damage and PDL extracellular matrix can occur under traumatic and frictional circumstances, mostly due to excessive fiber stretching and interstitial fluid pressure. The absorption of lateral occlusal forces is often caused by the initial contact of the canine tooth, the response of the PDL to occlusal forces is time-dependent and can be distinctively by cycles of occlusal forces and residual displacements of continuous state of tension. This study shows understanding biomechanical behaviour is important to determine the damage mechanisms caused by loading mechanism and PDL role in parafunctional and traumatic loading.[13]

Magnetic resonance imaging (MRI), although less commonly used in dental practice, offers excellent soft tissue contrast, making it a potential tool for assessing the PDL. Advances in MRI technology have improved its spatial resolution and 3D image capability, allowing for detailed visualization of the PDL and surrounding tissues without ionizing radiation.[24–26] In prognostic implications, understanding the radiographic appearance of occlusal loads and stress in the PDL is crucial for predicting the future prognosis of teeth. During clinical practice occlusal trauma evaluation is limited to clinical manifestations due to examination of articulating paper or fremitus. The presence of radiographic signs such as widened PDL spaces, angular bone loss, and hypercementosis can indicate a compromised periodontal environment, necessitating timely intervention.[14] Edema occurs in PDL of teeth that endure traumatic occlusion, the presence of the edema can responsively detect by MRI.[11,25]

Study of Dewake et. al evaluate association between clinical occlusal trauma score and the maximum signal intensity of the PDL observed on MRI. Higher clinical scores of occlusal trauma were associated with increased maximum signal intensity on MRI, indicating that MRI can effectively reflect the severity of occlusal trauma. MRI shows early occlusal trauma can be found even in obvious clinical manifestations absence. Early detection of these signs allows for implementing preventive measures, such as occlusal adjustments or splinting, to redistribute occlusal forces more evenly and reduce stress on the PDL. This suggests that MRI may be a valuable tool for early detection and treatment of occlusal trauma, potentially before significant clinical symptoms develop.[25] Radiographic evaluation is very important if clinical examination may not be enough to diagnose the suspected abnormal entity, furthermore radiographic monitoring can track the progression or resolution of periodontal conditions, providing valuable feedback on the effectiveness of therapeutic interventions.[27]

DISCUSSION

Occlusal loads, whether physiological or pathological, influence the stress distribution significantly within the periodontal ligament. Finite Element Analysis (FEA) has become an essential method for simulating and visualizing stress patterns in the PDL. It quantitatively calculates the stress and deformation within the periodontium using detailed anatomical models derived from micro-CT imaging, allowing for assessing the PDL's mechanical response under varying loading conditions.[6,13] The PDL plays a crucial role in transferring occlusal forces to the surrounding bone. Once occlusal loads are absorbed, they can lead to disorders ranging from mild to severe. Damage to the PDL can cause oral diseases, occlusal dysfunction, and even bone and tooth loss.[13]

Studies have demonstrated that occlusal loads can create stress concentrations in specific regions of the PDL, particularly in the apical areas of the root, during orthodontic tooth movement and other dental procedures. Under different loading conditions, stress distribution in the PDL can vary significantly, with higher stresses often observed in the cervical and apical regions.[4,28,29] Understanding this stress distribution is crucial for dental treatment planning, including orthodontic and restorative procedures. The PDL's ability to remodel and adapt to mechanical stimuli emphasizes the importance of controlling occlusal forces to prevent pathological conditions like occlusal trauma and periodontal damage.[4,28,30]

Clinical evaluation of occlusal trauma and PDL strength studied by Dewake et al. suggesting a potential new method for analyze occlusal trauma with MRI examination.[25] The magnitude and direction of occlusal loads greatly influence the stress distribution within the PDL. Vandana and Muneer investigated different occlusal forces on the PDL of a maxillary central incisor using FEA, showing that balanced occlusal schemes resulted in uniform stress distribution, and in contrast, unbalanced schemes caused localized stress concentrations, increasing the risk of periodontal damage.[1,18,31] Similarly, Chen et al. examined the effects of parafunctional occlusal loads, such as bruxism, on the PDL. Their FEA models revealed that excessive forces due to parafunctional activities significantly increased stress levels in the apical third of the PDL, potentially contributing to root resorption and other periodontal issues.[32] Pini et al. analyzed the impact of different loading conditions on stress distribution in the PDL of maxillary incisors, finding that lateral and oblique forces generated higher stress levels compared to axial forces, thus highlighting the PDL's vulnerability to non-axial loading.[33]

FEA models are often simplified by presume that occlusal forces act along the tooth's axis, with simplified PDL geometry and homogeneous behavior.[13] However, these models accuracy depends on the quality of the data input and assumptions about material properties and boundary conditions. Recent advancements in imaging technologies, such as micro-CT and MRI, have improved the accuracy of PDL models used in FEA.[11] Wang et al. used high-resolution micro-CT scans to create detailed FEA models of the PDL, enhancing the reliability of stress analyses. The integration of patient-specific data into FEA models represents a significant advancement, providing personalized insights into PDL biomechanical behavior.[31]

FEA has also been applied to evaluate the effects of periodontal treatments on stress distribution within the PDL. Murakami et al. studied the effect of splinting mobile teeth on PDL stress distribution, with their FEA model showing that splinting significantly reduced stress concentrations, demonstrating its potential benefit in periodontal therapy.[34] FEA has also been used to analyze the biomechanical implications of dental implants on adjacent teeth and periodontal structures. For example, Chen et al. assessed PDL stress distribution of teeth adjacent to implants, finding that implant placement can alter the stress distribution in neighboring teeth, which is crucial for implant planning.[32]

Recent studies have also utilized FEA to model the PDL and investigate stress distribution patterns under different occlusal loads. Patient-specific FEA models are now used to predict orthodontic treatment outcomes, offering a tailored approach to managing occlusal loads and minimizing periodontal risks.[35] Vukovic et al. applied FEA to analyze stress distribution in the PDL of a mandibular first molar under various loading scenarios, with their findings showing that oblique loads produced higher stress concentrations compared to vertical loads, suggesting tremendous potential for PDL damage under non-axial forces.[36] Lee and Kim incorporated the anisotropic and viscoelastic properties of the PDL into their FEA model and found that the highest stress concentrations occurred at the cervical margin, underscoring the importance of this area for periodontal health.[37] Research by Natali et al. further investigated the mechanical behavior of the PDL using an FEA model that accounted for its nonlinear, time-dependent properties. Their findings highlighted the role of the PDL's viscoelastic properties in dissipating stress under dynamic loading conditions.[38]

Nowadays evaluating methods to exam clinical occlusal trauma are mostly qualitative due to the complex pathophysiology and diverse clinical manifestations of occlusal trauma, making it challenging to integrate and evaluate them. Terrazas et al. used T-Scan III and FE simulations to visualize occlusal contact, showing similar results, which confirmed early contact on the left cuspid and lead the mandible slightly to the right.[13] These studies demonstrate that combining radiographic examinations with FEA can identify the PDL distribution patterns of occlusal loads. A recent case study involving a patient with severe bruxism demonstrated the utility of integrating radiographic imaging and Finite Element Analysis (FEA) in treatment planning.[39] The FEA model revealed significant stress concentrations in the apical third of the periodontal ligament (PDL), leading to early detection of potential root resorption. Based on these findings, the clinician was able to modify the occlusal load distribution through selective grinding and a custom occlusal splint, which successfully alleviated the excessive forces and prevented further periodontal damage. This case highlights the potential for FEA to enhance clinical decision-making, especially in cases where visual examination alone may be insufficient.[39]

FEA is a highly effective, non-invasive, and qualitative method for identifying regions of high stress contributing to soft tissue and bone degeneration in complex structures. The findings by Dewake et al. suggest that early occlusal trauma may be present even without visible clinical symptoms. Traumatic occlusion cannot be reliably detected through clinical examination alone; radiographic evidence is necessary to identify changes in the periodontal ligament. Integrating radiographic imaging with FEA makes early awareness and treatment of traumatic occlusal become possible. This method shows promise for the rapid assessment of both the morphological and physiological characteristics of the PDL space.[25]

Incorporating of 3D loading conditions from occlusal contact in future studies will aid in developing dental treatments and further promote the use of computational methods in medical practice.[19] The nature and magnitude of occlusal loads significantly influence stress distribution within the PDL. Moreover, radiographic monitoring provides valuable insight into periodontal health, allowing for the evaluation of treatment effectiveness and disease progression. Given the effectiveness of FEA in identifying high-stress areas within the PDL, it is recommended that clinicians incorporate FEA in the routine diagnostic workflow for patients exhibiting signs of occlusal trauma. This helps in early detection and prevention of occlusal trauma while providing precise data for treatment decisions. This approach can enable more precise treatment strategies, such as customized occlusal adjustments or splinting, to alleviate excessive stresses and prevent further periodontal damage. Additionally, integrating FEA with advanced imaging modalities like CBCT may enhance accuracy in identifying occlusal loads and stress distribution in the periodontal ligament, finding regions that risk for bone resorption, improving patient outcomes in both restorative and orthodontic treatments. Clinicians can identify high-stress areas and adjust treatment plans to optimize outcomes in periodontal and orthodontic care. Incorporating FEA into routine assessments may improve patient outcomes by enabling personalized treatment strategies.

Future research should focus on further validating FEA models through longitudinal clinical studies to assess their predictive accuracy in various occlusal load scenarios. Investigating the role of different occlusal forces, such as parafunctional habits like bruxism, in diverse patient populations could also provide deeper insights into the relationship between stress distribution and long-term periodontal health.

CONCLUSION

Advanced radiographic imaging modalities integrated with finite element analysis (FEA) can evaluate the distribution of occlusal force loading and show how stress processes are transmitted within the periodontal ligament (PDL). This shows that radiography play significan role in improving the understanding of periodontal biomechanical behavior, providing important insights into the mechanical response of the PDL to varying occlusal loads, and can be very useful in periodontal and orthodontic treatment.

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FOOTNOTES

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