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REVOLUTIONIZING ORTHODONTICS WITH FINITE ELEMENT METHOD

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ABSTRACT

The Finite Element Method was introduced in orthodontics as a powerful computational tool for analyzing the biomechanical effects of various treatment modalities and is an approximation method to represent both the deformation and the 3D stress distribution in bodies that are exposed to stress. By constructing detailed models of teeth, periodontal ligaments, and surrounding bone, FEM enables the simulation of stress and strain distributions resulting from various orthodontic forces. This methodology enhances the understanding of tooth movement mechanics, aiding in the optimization of treatment strategies and appliance designs. The article explores the principles of FEM, its applications in orthodontics, and its potential to revolutionize patient care through evidence-based decision-making.

Keywords: *Finite Element Method (FEM), orthodontics, biomechanical analysis, stress distribution, strain distribution, tooth movement, periodontal ligament, bone modeling, orthodontic forces, treatment optimization, appliance design, computational simulation, evidence-based decision-making.*

INTRODUCTION

Orthodontics is the specialty of dentistry which in brief deals with correcting the malaligned teeth with the application of force delivery system, which includes wires, brackets, elastics etc. The study of craniofacial orthodontics requires the precise understanding of the stress and strain induced by orthodontic forces in the periodontium. The applied force brings about resorption in the alveolar bone on the tension areas and deposition of new bone on the pressure areas. This is how the teeth are moved to their ideal positions in the dental arch by means of orthodontic forces. But there are also mechanical considerations that need to be made since there is a stress-strain relation as well as force vectors involved. This is the reason why there needs to be a better understanding of the forces involved and the effects they bring about for which finite element analysis is becoming a very popular method.[1]

The Finite Element Method was introduced in orthodontics as a powerful tool for analysing the biomechanical effects of various treatment modalities and is an approximation method to represent both the deformation and the 3Dstress distribution in bodies that are exposed to stress.FEM study analyses the biomechanical effects of various treatment modalities and calculates the deformation and stress distribution in the bodies exposed to the external forces. The principal of FEM is based on the division of a complex structure into smaller sub sections called as elements, in which the physical properties such as modulus of elasticity are applied to indicate the object response against an external stimulus which could be even an orthodontic force.[2]

The article is designed to extremely simplify the concept of FEM and to integrate it with orthodontics from the very basic levels.[3]It is well supported with scientific literature evidence for the assertion it implies.

THE FEM

Finite element method is a computational system for continuum mechanics that estimates the deformation (fully detailed changes of position of all component particles) that are expected to result from a specified pattern of stresses (forces) upon a mechanical system.[4] According to Cook et al[5], individual finite elements can be visualized as small pieces of a structure.[5]The FEM can definitely analyse the stress and its patterns and can analyse the biomechanics and can determine the final position of the teeth from its initial position.

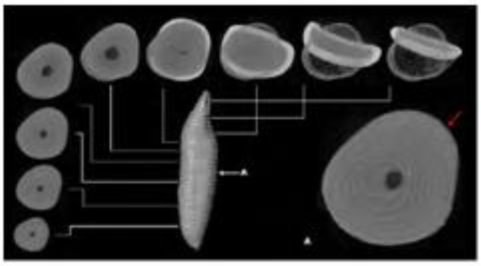

Figure 1- Multiple sketches were created in various slices of the micro-CT data. The sketch defined the contour of the root[12]

HISTORY

Turner et al[6] in 1956 introduced Finite element analysis (FEA). The finite element (FE) method is used in orthopaedic biomechanics since the early 1970's to evaluate and analyse and study the patterns of stress in the calcified tissues (bones). From then, this analytical tool of the modern era is being used in the field of Orthodontics as well.[6]

BIOMECHANICS OF BONE REMODELING IN ORTHODONTICS MODELS

Within the field of dentistry and to its related field, mathematical models are used for research and treatment planning.[7]
(A) **The gingiva**- The gingiva has a viscous nature due to its composition of collagen therefore not considered the mechanical activity of the gingiva during tooth movement in Finite element studies. [8]

(B) **The dental components**-

1. **Enamel**- It is the hard as well as a brittle substance probably seen in the human body, which is composed of mainly inorganic materials. Enamel could be categorized as an elastic material which is linear in nature. [9]
2. **Cementum**- Very few studies focus on characterizing the cementum, either mechanically or histologically. The group of Darendelier provides a comprehensive body of work on the physical characteristics of cementum.[10]
3. **Dentin**- The Dentin is reinforced by radial microscopic tubules. These tubules are filled with fluid and this gives the dentin a viscoelastic character. Since the mid-1970's, studies show its viscoelastic property and this is supporting evidence.[11]
4. **Pulp**- When their literature is reviewed, barely any studies are done to characterize the properties of the neither dental pulp nor acknowledges its existence.

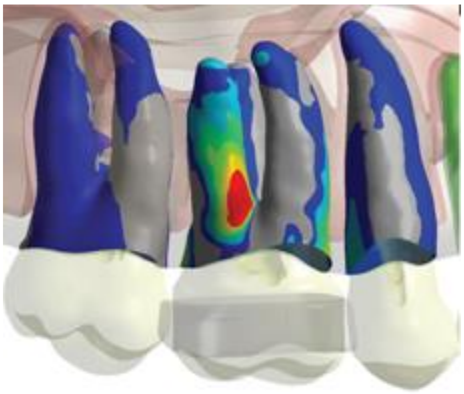

Figure 2- Areas of stress concentration on the periodontal ligamentafter submission to orthodontic force. Near the furcation area, we observe (red) higher stress concentration that gradually decreases towards the apex[12]

5. **Periodontal ligament (PDL)-** PDL works well as an attached cushion between tooth and the alveolar bone, as well as act as a shock absorber. The load applied to the teeth during the functions like chewing and clenching is transmitted to the respective jaw bones through the PDL fibers.[12]

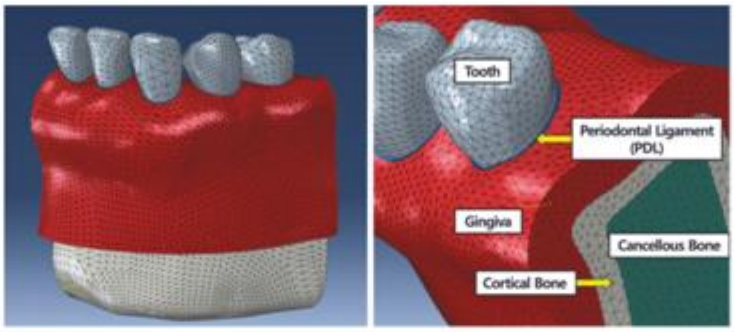

Figure 3- Dental Component &FEM[12]

ORTHODONTIC TOOTH MOVEMENT (OTM) MODELS

Orthodontic Tooth Movement (OTM) models in Finite Element Analysis (FEA) are used to simulate and study the biomechanics of tooth movement in response to orthodontic forces. These models help in understanding the stress distribution, tooth displacement, and bone remodelling that occur during orthodontic treatment.[15]

Here are the key aspects and components of OTM models in FEA:

1. Geometry and Meshing:
    - The geometry is discretized into finite elements, which can be hexahedral, tetrahedral, or other types depending on the complexity and desired accuracy.

2. Material Properties:
    - The materials involved, particularly biological tissues like bone and PDL, exhibit anisotropic and nonlinear mechanical properties.
    - The PDL exhibits viscoelastic behaviour, meaning its response to loading is time-dependent. This needs to be incorporated into the model.

3. Boundary Conditions:
    - Appropriate boundary conditions must be applied to simulate the clinical scenario. This includes fixed constraints where movement is restricted and forces where orthodontic appliances apply pressure.

4. Interaction Between Components:
    - The interactions between teeth, PDL, bone and appliances (braces, aligner)are critical to understand the force transmission. Contact mechanics can be complex due to the nonlinear nature of the interfaces.

5. Bone Remodeling Algorithms:
   - Bone remodeling is a biological process involving resorption and deposition. This can be 46rabecul using algorithms that update bone properties and geometry based on stress or strain criteria.

6. Validation and Calibration:
   - Models need to be validated against experimental data from clinical studies or laboratory experiments to ensure their accuracy.[15]

STEPS IN DEVELOPING OTM MODELS IN FEA

1. Data Acquisition:
   - Obtain detailed anatomical data using imaging techniques (e.g., CT scans, MRI)
   - Collect material property data from literature or experiments

2. Geometry Creation and Meshing:
   - Create 3D geometrical models of the teeth, PDL, and bone using CAD software.
   - Discretize the geometry into finite elements with appropriate meshing techniques.

3. Defining Material Properties:
   - Assign material properties to each component, considering anisotropic and nonlinear behaviours.
   - Include viscoelastic properties for the PDL.

4. Applying Boundary Conditions:
   - Set boundary conditions based on clinical scenarios, including constraints and orthodontic forces.
   - Apply physiological loads if necessary.

5. Simulating Tooth Movement:
   - Run the FEA simulation to compute stress, strain, and displacement fields.
   - Use bone remodelling algorithms to update the bone structure over time.

6. Validation:
   - Compare simulation results with experimental or clinical data to validate the model.
   - Adjust the model parameters as needed to improve accuracy.[15]

ORTHODONTIC TOOTH MOVEMENTS

I. Initial tooth movement-

Early models in the field of orthodontics were mainly directed to study the initial movement of the tooth in its socket (no bone remodeling). Within the initial tooth movement models, mainly fully linear elastic homogeneous isotropic models were used.[16]

Figure 4- Elements of a Molar- The bonds connect the elements to each other and are located in their extremities[18]

II. Long-term tooth movement-

After an initial tooth movement under the applied pressure the tooth tries to stay in that position and tries to attain stability in the newly moved position. FEA models at times usually involve an update of displacement (in addition to that due to external forces) or of forces based on an empirical bone remodelling law.[17]

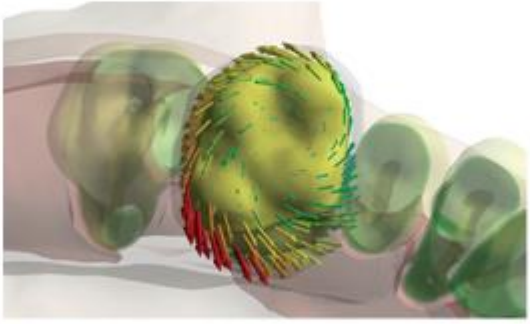

Figure 5- Direction of Tooth Displacement- Arrows indicate the direction of tooth displacement and its intensity (red for higher displacement; green for lower displacement)[18]

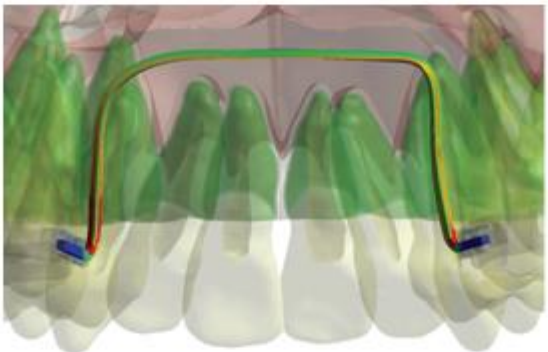

Figure 6- Areas of Stress Concentration - Areas of stress concentration on the orthodontic wire. Stress is more intense near the area with the wire bends (red)[18]

IMPORTANT RESULTS OBTAINED USING FINITE ELEMENT ANALYSIS

(A) **Tipping Movement -**

When tipping forces were applied to the crown of a canine tooth model, Mc Guiness et al, when found stresses at the cervical margin to be 0.132 N/mm^2 for a 1 N tipping force, applied mesiodistally at the center of the crown(Fig. 7). A buccopalatal tipping force produced a stress of 0.086 N/mm2 at the level of cervical margin of the periodontal ligament.[19]

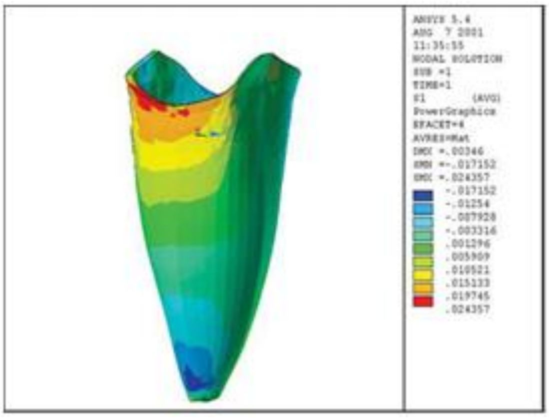

Figure 7 -Stress distribution in periodontal ligament during tipping[18]

(B) **Bodily Movement** –

If two forces are applied simultaneously to the crown of a tooth, the tooth can be moved bodily. Therefore, for the same stress response, more force is required for bodily tooth movement as compared to tipping movement.When a net force of 18.4 gm (50 gm labially and 31.6 gm lingually) was applied to obtain bodily movement, the stress observed at the middle of the periodontal ligament was well below the optimal stress levels observed by iteration at a net force of

209.6 gm measured at the middle of the periodontal ligament (Fig. 8). So, to obtain the same optimal stress levels during bodily tooth movement as compared to tipping movement, approximately 4.19 times more force is required.[19]

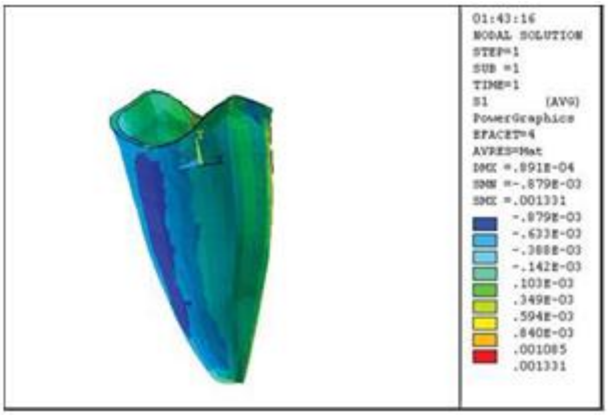

Figure 8 -Stress distribution in periodontal ligament during bodily movement with a net force of 18.4 gm[18]

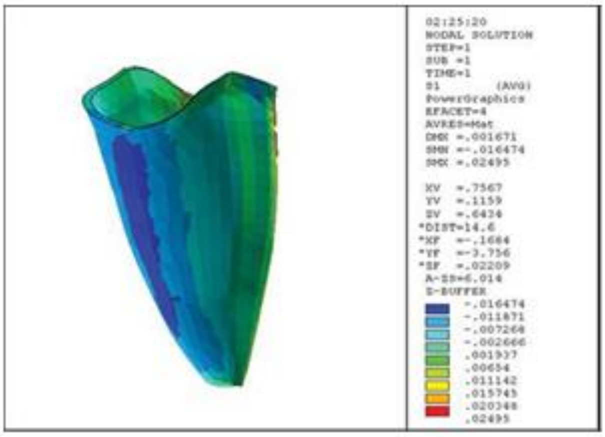

Figure 9 -Stress distribution in periodontal ligament during bodily movement with a net force of 209.6 gm[18]

APPLICATIONS OF FEM IN ORTHODONTICS

1. **CRANIOFACIAL GROWTH-**

According to Moss et al., FEM permits analysis of the skull at a scale significantly finer than previously possible, by considering cranial structure as consisting of a relatively large number of contiguous finite elements.

Montegi et al in their study used FEM model by 3D surface measurement of rapid laser device from human dried skull and to analyze the changes of facial growth based on FEM by the volume and the direction of strain. The results indicate especially the growth change of mandible were predominantly showed in the early stages, and the direction of growth strain changed backward and above from mental area to condylar area. [20]

2. **PERIODONTAL STRESS & TOOTH MOVEMENT-**

Tanne K et al., investigated the stress levels induced in the periodontal tissue by orthodontic forces using the three-dimensional finite element method. They found out that the pattern and magnitude of stresses in the periodontium from a given magnitude of force were markedly different, depending on the center of rotation of the tooth.

Mestrovic et al used three-dimensional finite element model to analyze the tooth movement in response to orthodontic forces. They also concluded that the tipping tooth movement is 60. greater if the force is applied more gingivally. [21]

3. **ORTHOPAEDIC FORCES** –

Tanne K et al, through three-dimensional FEA models of the mandible including the temporomandibular joint studied the biomechanical changes of the mandible from orthopaedic chin cup forces. This study indicated an association of stresses with remodelling of the mandible from chin cup therapy applied to adolescent patients with mandibular prognathism.[22]

4. **TEMPOROMANDIBULAR JOINT DYNAMICS-**

Gupta et al, in a study evaluated the patterns of stress generation in the temporomandibular joint after mandibular protraction, by using a 3D FEM. This study indicates that the mandibular condyle experiences tensile stresses in the posterosuperior aspect that might help explain condylar growth in this direction. Similarly, on the glenoid fossa, tensile stresses are created in the region of posterior connective tissues which might be correlated with the increased cellular activity in this region.[23]

5. **ORTHOGNATHIC SURGERIES**-

With the advent of facial 3D simulation models and virtual orthognathic surgery gives the patient and the surgeon new way to interact with each other. Obaidellah et al, in his paper describes a surgical planning, simulation and prediction of facial soft tissue appearance with regard to mandibular advancement through the osteotomy planning system using FEM on 3D facial models.[23]

6. **ORTHODONTIC IMPLANTS**-

Jiang et al, carried out a finite element analysis to evaluate continuous and simultaneous variations of orthodontic mini-implant diameter and length and to identify their optimal ranges in the maxillary posterior region. They found out that diameter exceeding 1.5mm in combination with the longest length in safety range was the optimal biomechanical choice.[23]

7. **BRACKETS & WIRE DESIGNS**-

Ghosh et al, compared six commercially available ceramic brackets with different designs and FEM was used in stress analysis of them subjected to various forces. They found out that stresses were concentrated at corners, edges and other areas of abrupt change in the shape of the bracket.[24]

8. **ALIGNERS-**

FEM can simulate the fit and force distribution, helping in designing aligners that efficiently move teeth while maintaining patient comfort. FEM can also assist in predicting how the aligners will perform over time, leading to better treatment outcomes.[25]

9. **CRANIOFACIAL ANOMALIES-**

FEM provides a powerful tool for simulating and analyzing the biomechanical behavior of craniofacial structures under various conditions, offering insights that can improve clinical interventions.[26]

10. **ASSESSMENT OF FUNCTIONAL OUTCOMES**-

(a) Masticatory Function:

- **Bite Force Analysis:** FEM can simulate the distribution of bite forces in patients with craniofacial anomalies, helping in assessing the impact on masticatory function and in planning treatments to improve it.

(b) Respiratory Function:

- **Airway Analysis:** FEM can model the airway structures to evaluate the impact of craniofacial anomalies on respiratory function. This is particularly important in conditions such as cleft palate, where airway management is a critical concern.[27]

11. **PERSONALIZED TREATMENT PLANNING**-

Creating individualized FEM models based on patient-specific anatomical data allows for personalized treatment plans. This can predict how each tooth will move in response to applied forces, leading to more accurate and efficient treatments.

12. **EDUCATIONAL AND TRAINING TOOLS**-

FEM models can be used in educational settings to train orthodontic students and professionals, providing a visual and interactive way to understand the biomechanics of orthodontic treatments.

13. **MORPHOMETRICS-**

Finite element analysis has been applied to the description of form changes in biological structures (morphometrics), particularly in the area of growth and development.

ADVANTAGES OF FEM

1. **Detailed Stress and Strain Analysis:** FEM allows for precise calculation of stresses and strains in teeth, periodontal ligaments, and surrounding bone structures under different orthodontic forces.
2. **Customization and Personalization:**FEM can be tailored to individual patient anatomy, allowing for personalized treatment planning.
3. **Predictive Modeling**:FEM can simulate the effects of various orthodontic appliances and forces before actual treatment, predicting tooth movement and bone remodeling.
4. **Optimization of Orthodontic Appliances:**FEM helps in the design and optimization of orthodontic appliances, such as braces, aligners, and wires, by analyzing their mechanical performance.
5. **Improved Treatment Efficiency**:By accurately predicting the effects of orthodontic forces, FEM helps in reducing treatment time and improving the efficiency of tooth movement. [28]

DISADVANTAGES OF FEM

1. **Complexity and Technical Expertise**: Developing and interpreting FEM models requires a deep understanding of biomechanics, computational modelling, and material science. This means that orthodontists need additional training or need to collaborate with engineers, which can be challenging.
2. **Model Development:** Creating accurate finite element models involves detailed geometric modelling, meshing, and setting up appropriate boundary conditions. This process can be very time-intensive.
3. **High cost &Expensive Tools:**FEM software can be expensive to purchase and maintain. Additionally, the computational hardware required to run detailed simulations can be costly.
4. **High-Quality Imaging-**The process of converting imaging data into usable models involves complex image processing and segmentation steps.
5. **Clinical Implementation**: Incorporating FEM into routine clinical practice can be challenging due to the need for specialized equipment, software, and expertise.[29]

FUTURE OF FEM

Although FEA techniques have greatly improved over the past few decades, further developments remain. The ability to fix minor problematic geometry and easily create models with minor variations would greatly reduce the time required to model different biomechanical situations. Additionally, adding frictional boundaries conditions between teeth and active ligations for orthodontic appliances will continue to increase the accuracy of these models.[30]

CONCLUSION

The Finite Element Method (FEM) proves to be an important instrument in orthodontic research, highlighting several points, such as: stress distribution areas in the periodontal ligament and alveolar bone during tooth movements; direction of the tooth displacement; the ideal position of orthodontic appliances during a specific mechanics; areas most likely to present root resorption; In addition, the stress distribution on the arch wires.

As a tool to describe the mechanics of orthodontic tooth movement due to remodelling, the Finite Element Method (FEM) can be definitely utilized. The FEM is an advanced engineering tool that has shown fruitful benefits in the field of dentistry, dental and biomedical research and as well as orthodontics. It is a highly precise technique which can expose various key research points in the research field. The FEM can be implemented in different cases to predict the results. It is a highly precise technique which can expose various key research points in the research field.

FEM is accurate, non-invasive, controls the study variables and provides quantitative data about internal structures of nasomaxillary complex, as the periodontal ligament. The method, however, requires knowledge in Computer Engineering, as it is run on very specific software.

There are still researches going on. Clinically proved studies are rechecked with the software and after a series of studies, the FEM can be implemented in different cases to predict the results. Every person is unique, hence the bone density, the model etc. So definitely just one FEM study cannot predict all the results from that single result obtained from the unique model of a person. Running a FEM study for independently from person to person is also unique.

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