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Review Article

Finite element analysis-A biomechanical tool in orthodontics

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ABSTRACT

In orthodontic research, the finite element method (FEM) has been widely used as an engineering resource for calculating the stress and deformation of complex structures. Applying the FEM can predict the graphic representation of these tissue responses through the observation of areas of stress created by applied orthodontic mechanics. This method has the advantage of being non-invasive, accurate, and providing quantitative and detailed data on the physiological reactions possible to occur in tissues. The purpose of this article is to review and discuss the steps involved in applying the concept of finite elements and how they can be used in orthodontics. The stress distribution at the interface between the alveolar bone and the periodontal ligament, as well as the shifting trend in different tooth movement types while employing different kinds of orthodontic devices, may both be assessed using FEM. For this reason, expertise with certain software is required. Despite the drawbacks of other experimental techniques, FEM is a crucial technique for addressing inquiries regarding tooth movement.

1. Introduction

One of the fundamental principles of orthodontics is the systematic imposition of bone remodelling, which entails applying particular force systems on the teeth in order to cause progressive and permanent bone deformations. The process of bone remodelling causes the teeth to move into new positions, and the alveolar bone and the periodontal ligament play a significant role in this process. The mechanical, biochemical, and physiological responses to the orthodontic forces are inextricably linked.[1,2]

Orthodontic treatment can be carried out with an evidence-based approach, clinical experience, knowledge and experience gained from a postgraduate curriculum, or even through specialised training and workshops. In dentistry, orthodontics is a fascinating and challenging field, an orthodontist's work can be compared to solving a puzzle as they work on each patient. This is linked to rational thinking, a fundamental understanding of biomechanics, as well as common sense.[3]

Finite element analysis (FEA) was initially introduced by Turner et al. in 1956. Since then, it has been applied to a variety of projects, including the construction of bridges, dams, airplanes as well as in biomedical field. For a particular load, the distribution of stress inside the body is determined by using computer software designed for complex calculations. In addition, it illustrates the body's displacement both before and after the load is applied.[4,5]

This review is intended to greatly simplify the idea of FEM and link it with orthodontics in order to provide readers with an original take on the subject and to reinforce existing knowledge for those who are already familiar with it.

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Table 1: List of the materials with their physical properties

Materials	Youngs modulus (MPa)	Poisson's ratio
Tooth	20000	0.30
Periodontal ligament	0.059	0.49
Alveolar bone	20000	0.30
Bracket	200000	0.33
Arch wire (Stainless steel)	200000	0.33
Cancellous bone	1500	0.30
Cortical bone	15000	0.30
NiTi coil spring	83000	0.33
Buccal mucosa	8.33	0.30
Gingiva	37.63	0.30

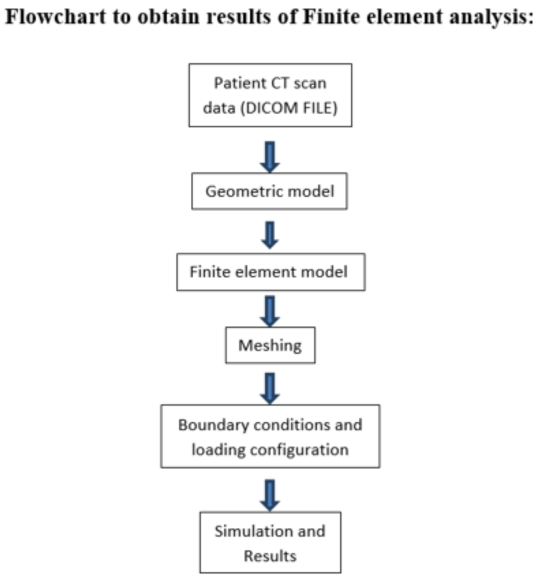

Figure 1: Workflow to obtain results of finite element analysis

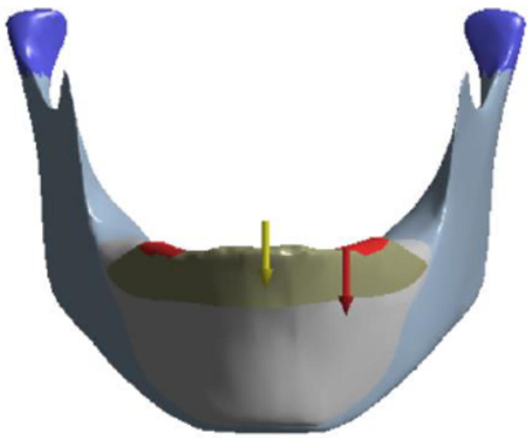

Figure 2: Geometric model of mandible

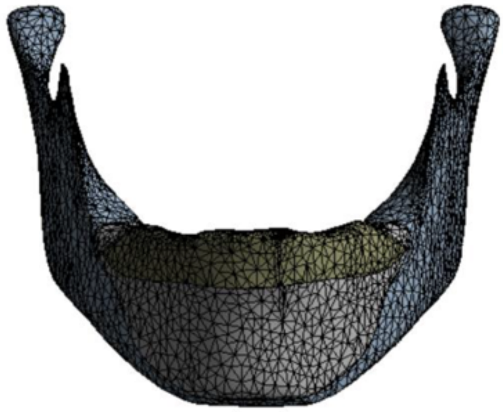

Figure 3: Meshing of mandibular model showing nodes and elements

1.1. Role of FEM in Orthodontics

In orthodontics, there are various analytical instruments readily available. When contemplating a diagnosis and treatment strategy, analysis is essential. Every approach has advantages and disadvantages, which explains why more advanced techniques for analysis are being devised. The need for an enhanced analytical tool has gotten to the point where traditional tools are no longer adequate.[6]

A three-dimensional subject is depicted in two dimensions in radiography. The overlapping of structures makes it difficult for the clinician to understand. Although there are other techniques, such as digital radiography, Positron Emission Tomography, and Computer tomography scanning, issues associated with radiation risk and three-dimensional imaging remain to be addressed. Coned Beam Computed Tomography provides a three-dimensional image, but it also has disadvantages such as motion artifacts and radiation danger.[7] In contrast to these, FEM is unique in that it is radiation-free, non-invasive, supports three-dimensional analysis, and can be used for both static and dynamic biomechanical research. The first reconstruction model on the computer can be created using any of the traditional techniques; this model is then analysed and simulated by FE using computer software.[8]

2. Armamentarium for FEM analysis[9]

A) CT (Computed Tomography) SCAN of required area and its DICOM Files

B) Software available in market

- MIMICS, 3D Slicer, Invivo5, OsiriX MD etc.
- FUSION 360, Free CAD, Blender, Solve Space etc.
- Hyper Mesh CAE, Abaqus, MATLAB, Solid Edge and ANSYS etc.

C) Workstation

- i5 quad core or higher version processor
- 16GB RAM 2.5 GHz or higher configuration
- 4GB or more Graphics
- 2TB or more HDD or SDD
- 15" or higher dimension screen monitor

3. Steps involved in the Finite Element Model Preparation

Following the acquisition of the necessary DICOM (Digital Imaging and Communications in Medicine) files, the following procedures must be taken in order to receive the appropriate results (Flowchart Figure 1)

4. Construction of the Geometric Model

In order to create geometrically superior and correct models, it is fascinating to employ a resource with anatomical records and adjustments in CAD software to carry out this experimental approach. In order to achieve that, a virtual model must be created using image processing and digital reconstruction tools like 3D Slicer and Mimics etc. For better resolution, computed tomography should be produced using cross-sections that are at least 0.25 mm apart. The segments will be captured in DICOM format and then transferred into software for digital reconstruction and image processing.

5. Conversion of the Geometric Models to a Finite Element Model

We also discretized the model, or converted it from a solid state into a mesh of nodes and elements, using the previously stated software to facilitate analysis using FEM. The elements are space coordinates represented by tetrahedrons and hexahedrons, which are the most common formats in which they can appear. Each element's extremities have points, or nodes, connecting them to construct an ordered mesh between the elements. Information is transmitted between elements through their bonds. The virtual model is exported from Solidworks software to Ansys Workbench V11 or other similar programme for finite elements simulation after it has been completely rebuilt and converted into this mesh of finite elements. (Figures 2 and 3)

6. Boundary Conditions and Sumptions

Suppose an element is constructed on the computer and a force is applied to it, it will act like a free-floating rigid body and will undergo a translatory or rotatory motion or a combination of the two without experiencing deformation. To study its deformation, some degrees of freedom (movement of the node in each direction x, y, and z) for some of the nodes must be restricted. Such constraints are termed boundary conditions.

6.1. Assigning of Material Properties

Poisson's coefficient and the young modulus of elasticity are set for the model. Young's modulus depicts the inclination of the linear section of the stress-deformation diagram, whereas Poisson's coefficient relates to the absolute value of the relationship between transverse and longitudinal deformations in an axial traction axis. These physical properties have to be introduced for teeth, gingiva, cortical bone, cancellous bone, and periodontal ligament etc. according to the literature.[10] (Table 1)

7. Simulations and Result Interpretation

Finding the areas of stress and, consequently, the places where tooth movement takes place is made possible by the FEM's results, which allow for examination of the stress distribution caused by forces between the bone and the periodontal ligament. It also makes it possible for us to draw conclusions regarding regions where root resorption is more likely. In order to show the direction of tooth displacement following force application, colours and arrows are used to reveal these results.

8. Review of Literature and Discussion

To truly grasp the essence of this review, the reader must initially realise that the FEM is a theoretical concept and that it cannot withstand arguments based solely on scientific evidence without the highest possible standard of clinical trials. In addition to dealing with material qualities and properties, FEM also takes geometrical considerations into account. The entire system, including the body's dimensions, produced stress, and initial force, differs substantially from its final state. The conclusion that one cannot compute or forecast the tooth's final position from its beginning one without the use of mathematical formulas and precise numerical values seems reasonable.

With experimental animal models, numerous investigations on orthodontic force-induced tooth movement were carried out. These investigations offer insights into the effects of using orthodontic stresses on human tissues. Animal research ethics committees frequently object to this kind of investigation since it uses live animals in a lab setting. It is possible to predict the tissue reactions to applied orthodontic mechanics using FEM. Photoelastic models are an alternative set of experimental models that are used to study the biomechanics of tooth movement; however, they have the drawback of just studying the model's outside, leaving internal structures like the periodontal ligament unexplored.[11–16]

In their research, Jafari et al. employed transverse orthopaedic forces to analyse the stress distribution patterns within the craniofacial complex during rapid maxillary expansion using a 3D FE model of a dry human skull. This study indicates that the expansion stresses are dispersed to the sphenoid and zygomatic bones as well as other related structures, not just the intermaxillary suture.[16]

Using a FEM model, Chaturvedi et al. assessed the impact of orthodontic retraction force on thick and thin gingival biotypes of anterior teeth with grade I and II gingival recession. They discovered that orthodontic treatment significantly altered the gingival tissue and helped to correct periodontal defects; however, bone density was found to be a significant factor in improving gingival recession.[17,18]

Because PDL is crucial for tooth movement, there is a clear correlation between PDL stress and orthodontic tooth movement. Using the three-dimensional finite element method, Tanne K et al. examined the stress levels caused by orthodontic forces in the periodontal tissue. They discovered that, depending on the tooth's centre of rotation, the pattern and amount of stresses in the periodontium caused by a given force magnitude varied significantly.[19]

Aesthetics is a primary consideration in orthognathic surgery because individuals are extremely concerned about their post-operative facial morphology. Virtual orthognathic surgery and the development of facial 3D simulation models have opened up new avenues of communication between the surgeon and the patient. In their work, Obaidellah et al. use FEM on three-dimensional face models to present a surgical planning, simulation, and prediction of facial soft tissue appearance with relation to mandibular advancement using the osteotomy planning system. Using a 3D FE model of the soft tissues of the face, Chabanas et al. predicted the soft tissue deformations in the face that arise from repositioning bones during maxillofacial surgery.[20,21]

In order to assess continuous and simultaneous alterations in orthodontic mini-implant diameter and length and to determine their ideal ranges in the maxillary posterior region, Jiang et al. performed a finite element analysis. They discovered that the best biomechanical option was a diameter larger than 1.5 mm combined with the longest length within the safety limit.[22]

sing a three-dimensional finite element computer model, Shyagali et al. evaluated the variations in stresses produced in the bracket-cement-tooth system by means of a peel load in single and double-mesh bracket bases. The findings indicate that altering the bracket's shape can enhance bonding capabilities and lessen enamel damage as it debonds. These details could help develop new, creative bracket designs intended for therapeutic application.[23]

In order to assess the torque-induced bracket slot deformation in the widely used 0.018-inch (") and 0.022" conventional Stainless Steel (SS) brackets with clinically relevant archwires during various angles of twist, Harikrishnan et al. conducted an in-silico study. They found that the slot deformation in both the 0.018" and 0.022" brackets increased with the angle of twist. Therefore, it can be said that bracket slots only bend elastically up to a 30-degree twist angle, and clinicians should stay within these torque limitations to prevent plastic deformation that could result in incorrect tooth positioning.[24]

A Finite Element (FE) model for clear thermoplastic teeth aligners was successfully designed and validated by Ye et al. As a result, we can accurately capitalise on the model to anticipate the stresses and moments that the aligners will apply to teeth, enhancing our knowledge of the biomechanics of these devices and the movement of teeth they cause.[25]

9. Limitations of Finite Element Analysis

1. Like every theoretical model of a biological system, this one has certain limitations such as mistakes made in the modelling, material property assignment, boundary condition application, or even the application of inaccurate forces to an incorrect formulation may lead to improper results.
2. This is a complex analysis that depends on computers and programmes, much care must be given both during the modelling phase and in the steps that precede the final run of the results to ensure that the right input data is sent in for the desired results.
3. It is also difficult, if not impossible, to recreate biological tissue exactly like it exists in mechanical models.
4. The expense of the FEM study is another main constraint. The fact that the FEM is mostly utilised for research and does not now have an appropriate cost in several countries should be emphasised.

10. Conclusion

The Finite Element Method (FEM) is a valuable tool in orthodontic research because it highlights a number of important points, including the following: the direction of tooth displacement; the optimal location of orthodontic appliances during a particular mechanics; the areas most likely to exhibit root resorption; and the distribution of stresses on the archwires. Because FEM is precise, noninvasive, controls the research variables, and yields quantitative data about the internal structures of the nasomaxillary and mandibular complex, including the periodontal ligament, it can overcome the shortcomings of other experimental methods. The method, however, uses extremely specific software, therefore it demands understanding of computer engineering.

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None.

12. Conflict of Interest

None.

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