Chapter

Finite Element Analysis in Orthodontics

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Abstract

One of the governing ideologies in orthodontics is gradually imposing remodeling, which involves progressive and irreversible bone deformations using specific force systems on the teeth. Bone remodeling results in the movement of the teeth into new positions, with two tissues having a major influence along with it: the periodontal ligament and the alveolar bone. There is a definite connection between the mechanical, biological and physiological reactions to the orthodontic forces. The development of the Finite Element Analysis and administration of this new age computer-aided method in orthodontics applies to this chapter. Finite Element Analysis is a computational procedure to calculate the stress in an element, which can show a model solution. The FEM analyses the biomechanical effects of various treatment modalities and calculates the deformation and the stress distribution in the bodies exposed to the external forces. The ideology behind this particular chapter is to introduce this scientific approach to the orthodontist and to reinforce the effects and advantages to the ones who are already aware of the same. In this chapter there is a detail discussion and explanation systematically on Finite element analysis method and its application strictly in and around orthodontics without much deviation from the subject.

Keywords: FEM, Nodes, Voxels, PDL, Orthodontic tooth movement (OTM)

1. 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. It is just one branch of dentistry which is deeply interlinked with the engineering branch of mechanics. Application of force and its resultant effects are the key stones in orthodontics, hence the fundamentals of physics also applies to the physics such as the Newtonian physics. The intention of the Orthodontist is to make betterment in function and esthetics. The treatment is just not limited it and has intentions to correct things like a tooth implanted to the alveolar bone can lead to caries or other paraodontal infections or affect the oral hygeine), esthetics (of the dentition or the face), or prosthetic (orthodontic treatment preceding a prosthetic replacement/missing tooth or teeth) [1].

An Orthodontic treatment might be carried out with evidence based system or by a clinical experience or by a acquiring knowledge and experience from a postgraduate curriculum or even via specific trainings and hands on programmes. Orthodontics is a spectacular as well as brain buzzer branch in dentistry where the work undertaken by an orthodontist could be considered as solving a puzzle, when he or she treats each case. It is associated with logical reasoning and through knowledge about the basics of biomechanics and even common sense. Turner et al. in 1956 introduced Finite element analysis (FEA). From then it has been used in different sectors such as in building aircrafts to dams to bridges etc. The usage of computer software's for the stressful calculations are used in order to find the stress and its distribution within a body for a given load. It also sketches the displacement of the body before and after the application of the load as well [2]. It could be a different dimensional opening for the chapter readers who are not familiar as well as to reinforce the knowledge for the readers who are already aware of this topic, so the chapter is designed to extremely simplify the concept of FEM and to integrate it with orthodontics from the very basic levels [2].

The Finite Element Method was introduced in orthodontics as a powerful tool for analyzing 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. The Finite Element Method is used to study the stresses and strains in engineering, it can be used to evaluate the biomechanical component such as displacement, strains and stresses induced in living structures from various external forces, the biomechanical response of the bone to external forces are quite complex. The FEM analyses the biomechanical effects of various treatment modalities and calculates the deformation and the stress distribution in the bodies exposed to the external forces. It should also be understood that the stress and strain in living tissues are thought to be key factors in biologic change, it is important to understand that stress and strain to understand its relationship to bone remodeling, the belief is such that the pattern of the stress will affect the localized proliferation of cells and growth activities [3]. The chapter is discussed from the fundamentals of FEM and further notes its usage in dentistry and particularly in orthodontics, followed by stepwise procedure explanations in detail.

The chapter further takes a road from its aspects such as construction of the models, which is the soul step in the FEM, with the help of scans such as the CT scans and FEM's credibility is in question due to the complexity and accuracy of the model seems to represent from truth and reality in the oral cavity [4].

Many new concepts and terminologies are being introduced and explained to its best in this chapter. Keeping in mind that many of readers, being from a medical academic background, including Orthodontists and clinicians hesitate to understand and relate the formulas and equations which are quite natural, a few vital equations are presented with ease. Further the chapter goes in detail to bone remodeling concepts and the brief explanations of individual components of the dental organ and its reaction to force and the chapter sinks with the concepts of FEM and orthodontics in the body. Towards the end the advantages as well as the limitations of FEM is discussed with some insight. This chapter is well supported with scientific literature evidence for the assertion it implies and it credits each and every scientist for their contributions and valuable time in life they have devoted for the good of the mankind.

2. Utility of finite element analysis

Orthodontics is periodically changing from an opinion-based practice to an evidence-based practice. Currently, it is necessary to have a scientific approach for any treatment modality and the evidence of tissue response to it [5]. Finite element analysis (FEA) has the ability of being applicable to solids of irregular geometry that contain heterogeneous material properties. It is therefore suited to evaluate the structural behavior of teeth. The use of FEM is wide seen in dentistry and in the field of orthodontics in the field of research in topics such as the geometry of the tooth, materials used, prosthetics etc. In the field of orthodontics, it's used to find the stress values or its distributions in appliances used in orthodontics etc. FEA could be wisely used to estimate the stress and strain patterns within the tooth structure, Periodontal Ligament (PDL) and the bone which is subjected to tooth movement by the means of orthodontics [6].

The forces to single-tooth system can also be modeled with the FEA with ease. The centre of resistance (C_R) of the tooth lowers and creates an altered stress pattern which is seen in the root as there is an experience of alveolar bone loss. The same effect could be experienced when there is an alteration of root length. The biomechanical properties of PDL are not the same for adult and adolescents respectively [7].

3. Road to finite element analysis

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. It is said to be finite element analysis since, the elements are finite in count and the nodal points are the blocks which builds the model, which in turn connects to attribute to the formation of element [8]. A meshwork is considered to be a degenerated material which is subjected to modeling. There is an absolute control in the degree of simplification with this method which is an advantage to the FEM [9]. FEA techniques are potential to replace the stereo lithographic models for the presurgical planning. Every finite element is based on an assumed-shape function which expresses an internal displacement as a function of nodal displacement. Which means a certain element may give accurate answer for a particular type and location of support and loading but can give inaccurate answers for another type and location [10].

4. Steps in finite element analysis

1. The geometric model construction

2. The geometric model to a Finite element analysis model conversion

3. Data representation of the material properties

4. The boundary condition defining

5. Application of the load

6. Solution to the linear algebraic equation system.

7. Analyzing the results [10].

Basic Steps in Finite Element Method for any solution corresponds to the steps involved in finite element to analyze a structure.

4.1 The geometrical model construction

It is the first requirement for the analysis of the geometrical model. These can be created either in analysis software or the model can be created also in any CAD software and can be imported to the analysis software. The model has to be saved with extension *.iges or *.igs or *.sat to achieve this. The usage of a computed tomography image (fig ct img) can be done to serve as a geometrical model.

4.2 Discretization process

Discretization is a process of dividing the domain or component into number of elements & nodes. For this purpose, an assumption is made that the elements are interconnected by nodes. The idea behind the process is to improve the accuracy of the results. The entire component is divided into number of elements, then the stress distribution in each element will be almost the actual results and the operator gets accurate plot of the stress distribution in a component.

4.3 Applying material properties

The mechanical properties such as young's modulus, Poisson's ratio etc., are defined to the component in this particular step. This is done to feed the values for calculation of the solution. These values mark the natural properties to the built up model so that it can behave and react in the same manner as that of a natural biologic body would, when subjected to external stimuli (stress). For the particular element, the property is to be defined. First of all the operator has to define the type of element. There are several types of elements available, which can be implemented to the domain component.

4.4 Defining boundary conditions and nature of problem

The boundary condition is chosen depending upon the mode of analysis such as structural, dynamic, thermal, fluid etc.

4.5 Application of load

After the application of boundary conditions, the discretized domain is applied to the known loads. The application of loads will depend upon the geometry of the component used. The nodes are applied with loads. Different types of loads will include Forces or Moments, pressure, gravity. - For structural problems- Gravity, radiation, convection and temperature for thermal problems.

4.6 Solution or results

The results can be obtained instantly as well as in the most accurate manner. It will consist of model images which represent levels of stress by various colors signifying different stress for different colors respectively, which can be directly read from a color chart (provided below the image). The results can be further tabulated and subjected to analysis.

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5. Computed tomography (CT) and extraction of morphological parameters from CT scans

Computed Tomography or C.T is cross-sectional image of an object from either transmission or reflection data collected by illuminating (by any kind of penetrating radiation) the object from many different directions or angles. Frankly speaking, tomographic imaging deals with the reconstruction of an image from its projections. The technique constitutes of irradiating a section of a sample from a number of positional angles and then the intensity of the transmitted or reflected radiation is measured. For example, the projections symbolize the X-rays attenuation within a body, the bodies' radioactive nucleoids decay as in the case of emission tomography, or the variation seen in refractive index in an ultrasonic tomography (USG).

When the X-ray is considered, the projections consist of line integrals of the attenuation coefficient. This attenuation of photons (tiny particles that constitute an electromagnetic radiation) are due to either being absorbed by the atoms of the material, or being scattered away from their original paths of travel. Photoelectric absorption involves an X-ray photon imparting all its energy to a tightly bound inner electron in an atom. The images are 2D maps of the distribution of the attenuation coefficient of the X-rays. By stacking the obtained 2D images, we can reconstruct 3D images. The attenuation coefficient is measured in Hounsfield Units (HU) [11].

This macroscopic response of the trabecular bone is closely related to the underlying microstructure. It is beyond scope of this book to describe in details the geometry and spatial arrangement of the trabeculae and its advised to refer standard textbooks for the same, The volume fraction which is considered one among the major parameter in characterization of microstructure of cellular materials geometrically, gives no much clue about the orientation as well as the organization of the above said microstructures. The material microstructure is modeled using tensors of higher rank which mimics the architecture of the microstructure and is the most common method adapted for the same. Fabric tensors are needed as a quantitative measure of the microstructural architecture, to serve as positive definite. The principal axes of a tensor whose principal axes coincide with the principal microstructural direction and its eigenvalues are proportional to the microstructure distribution with respect to its principal direction. It is a must thing to include the parameters which can define those orientations. Hence it

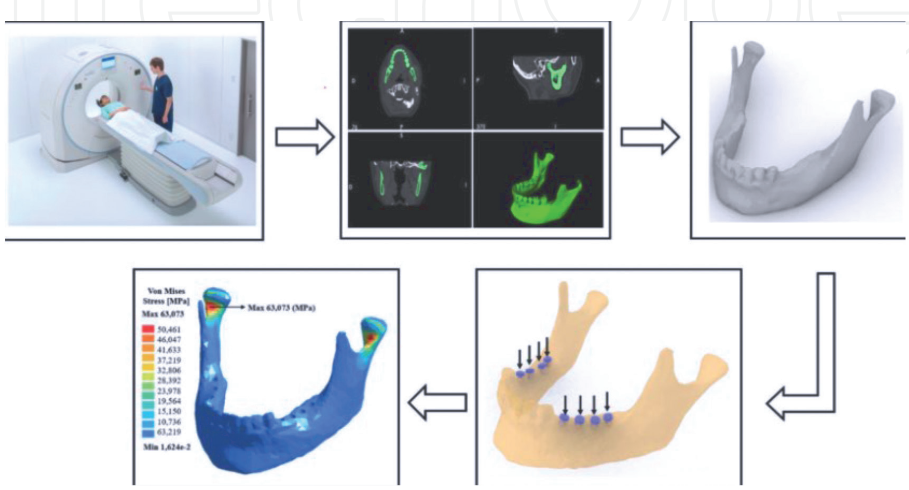

Figure 1.
Conversion of CT scan into a finite element model.

requires acquiring a 3D representation of the bone first using tomography. It is then a morphological analysis used to describe the microstructure (**Figure 1**) [12].

6. Generation of finite element model

Three primary considerations in the development of the three-dimensional finite element tooth model are to be considered; which includes the tooth and other periodontal geometry, properties of different materials and as well as the configuration of the load applied. In a given tooth geometry and structures of the periodontium and its associated geometry, one can say nodes simply as points that occupies the corners of the elements which meet each other; further the boundary conditions are well defined at all peripheral occupying nodes. A specific material property is assigned to individual elements. Location of the centre of resistance and centre of rotation of the modeled tooth will be deeply affected by the modeling of the root as a symmetric parabolic structure or as a real tooth, as well as root conicity, buccopalatal vs. mesiodistal bone levels and bone insertion [11].

The problem with three-dimensional models is that the geometrical input needs to be generated. The bone structure replicated with a CT scan is preferred as the geometrical input data which should be generated for the 3-D model, which is considered as one among the problems. It is suggested to convert the CT image voxel to eight node hexahedral; but the possibility of numerous element creations in model and the unwanted change in the model's external shape is the pay for this. In order to exempt the outer rough surfaces, it's better to model the external geometrical contours. After these steps, automatically a mesh is produced out as the result of the software. Material properties are assigned to each element of the model, once the generation of the mesh is done (**Figure 2**).

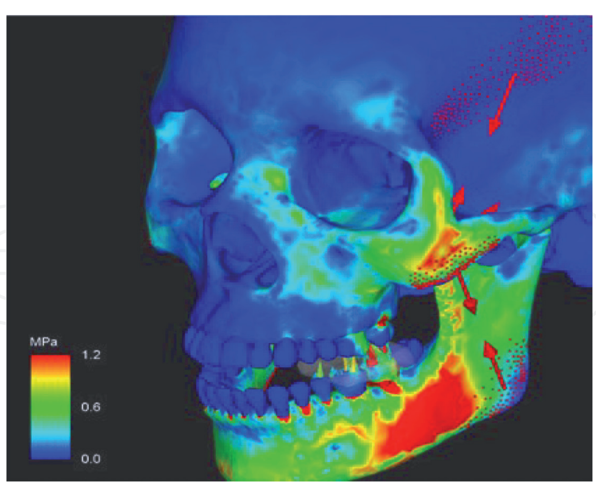

Figure 2.
FEA carried out on a modeled human skull. Source: Mechanical Finder [13]. Used with permission. Available from: https://mechanical-finder.com/.

7. Morphological analysis

Morphological analysis provides the tools to extract morphological parameters of an object. The actual values of the parameters extracted depend on the object as well as the quality of the object representation. Better way to say is voxel size affects the 3D images and pixel size would affect the 2D images. Higher the resolution better is the analysis quality. TV, BV, Tb.Th, and MIL are the four respective parameters of morphology which are taken into account.

7.1 Tissue (or total) volume TV

TV does quantification of the volume in total at the region of interest (ROI). If bone is to be considered, the entire trabecular bone and the total volume of its pores along could be considered as the term 'tissue'. It is a simple task to calculate TV, just by taking the product of the total number of voxels at the region of interest and the volume of a single voxel. The usage of 2-D images could be an option to obtain the volume. The volume is computed by assuming the cut thickness to be same as the pixel's side length measurement.

7.2 Bone volume BV

By multiplying the number of voxels in the solid objects, one can find out this parameter and it's the representation of the 3-D object's volume in total. Bone volume (BV) will therefore be interpreted as the solid phase volume.

7.3 Trabecular thickness (Tb. Th)

It is the thickness of the rods of the cellular solid [14].

7.4 BV/TV

The important parameter is the ratio of the two previous parameters.

8. Distribution of trabecular thickness (Tb.Th)

It is the thickness of trabeculae and its associated distribution.

Locally when it comes to thickness specifically at a point within a state of body is said to be the biggest sphere which consoles the spot, the spot is not needed to be the centre of the body but within the surface of the object which is considered as a solid [15]. To calculate (Tb.Th), the idea of structuring the body of the object is carried out, where the trabecular midline is used [16].

9. Fundementals in non linear computation method

The mechanics which is an engineering branch is the soul element in the field of (**Figure 2**) biomechanics; one can never understand biomechanics without understanding the fundamentals of mechanics. Mechanics deals with forces and the response of the object or body, whereas bio means study of living organisms, so the application of the forces and its response to the forces in living bodies are dealt in biomechanics. The hierarchical arrangement in organisms starts from sub atoms ending in organized living body. With the help of quantum mechanics, we can study at the cell or atomic levels and Continuum mechanics could be used in the higher levels such as the organ levels [17].

9.1 Finite strains associated with a body in its kinetics

The Continuum Mechanics is the ideology where volume $_{V(t)}$ is the amount of matter contained by a body in the respective space at a given time T and the surface area of the body could be symbolized as $S_{(t)}$. Further when we look the reader must understand that the body undergoes change in dimension from its initial orientation for the respective boundary definition after a stress is being applied to the body. The fact is such that, the irrelevance of working with the same body with and without stress because of the obvious above said reason of reasonable transition in shape of the body from initial and final state of the body before and after applying stress. It is mandatory for the above said reasons a thorough understanding of the basis of kinematics is required [18].

10. The FEM

Coming to the FEM we must strictly adhere to the principles of kinematics. The chapter is never complete without discussing few important equations in FEM, where shape functions (N) and the displacement of the nodes (q), which we are not certain about could attribute the displacement fields shape and could be equated as follows;

$$\mathrm{U}(\mathrm{x}) = \mathrm{N}(\mathrm{x})\mathrm{q} \tag{1}$$

In Eq. (1) the nodal values (q) are determined by the method of calculating the equation which is already in a state of equilibrium via formulation which is made incrementally [19].

$$\delta\mathbf{q}\underbrace{\left[\mathbf{M}\ddot{\mathbf{q}} + \mathrm{Fint} - \mathbf{Fext}\right]}_{\mathbf{F}^{oe}} = 0 \quad \forall\delta\mathbf{q} \tag{2}$$

In Eq. (2) q represents the nodal accelerations, M the mass matrix and Fint and Fext the (nodal consistent) internal and external forces respectively

$$\begin{aligned} M &= \int_{V(t)} \rho N^{\top} N dV \\ F_{\text{int}} &= \int_{V(t)} B^{\top} \alpha d\,\mathrm{V} \\ \mathbf{F}ert &= \int_{V(t)} \rho \mathbf{N}^{\top} \mathbf{b} dV + \int_{S(t)} \mathbf{N}^{\top} \mathrm{t} dS \end{aligned} \tag{3}$$

In Eq. (3) B = ∇NT and t represents the traction on the surface.

$$\frac{\left\|\mathbf{F}^{oe}\right\|}{\mathbf{F}_{\mathrm{aXt}}} < \mathrm{prec} \tag{4}$$

In Eq. (4) Foe denotes the residual or remaining forces and it's not equal to zero. Prec is a user defined precision. The equilibrium equations are iteratively solved using Newton–Raphson method. Starting from a trial nodal displacement is given as, q0 (several possibilities to evaluate such a trial [20].

Field exist but will not be treated in this work), the displacement field is iteratively updated in such a way that:

$$\Delta q = -KT - 1\text{Foe}$$

$$\text{qi}+1 = \text{qi}+\Delta \text{q} \tag{5}$$

Eq. (5) denotes KT = d Foe/dq, which is considered to be called as the tangent stiffness matrix.

The tangent stiffness matrix will be resolved into its parts as well as the shape. The shape aspect of this depends on the shape functions used in FEM [21].

By use of linearization of the small stress values with its corresponding strain values this can be obtained. Intergration tool is used to discrete the matrix of material stiffness [22].

11. Biomechanics of bone remodeling in orthodontics models in orthodontics

Within the field of dentistry and to its related field, mathematical models are used for research and treatment planning. The tendencies in mathematical models (either numerical FE models or analytical models) for tooth movement and in particular the constitutive models used for dental tissues. Many contributions exist focusing on implant related problems, which are not our interest. The forces alone are only considered and it's not about the means of force delivery system which may also include the brackets are to be considered in here [23].

11.1 The gingiva

The mechanism which is responsible for the asymmetrical behavior of the tooth when rotated around its main axis is at times assumed to be in the gingival tissue which is a complex fibrous structure that envelops the entire dental arch and it provides an additional anchorage to the teeth, tends to contract. This creates force acting on the different proximal teeth, which in turn produce an internal momentum and asymmetries. The gingiva has a viscous nature due to its composition of collagen. We do not consider or value much the mechanical activity of the gingiva during tooth movement in Finite element studies [24].

11.2 The dental components

11.2.1 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 [25].

11.2.2 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.

11.2.3 The 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 shows its viscoelastic property and this is a supporting evidence.

Dentin is also looked as a non-homogeneous and anisotropic material in various recent experimental model studies.

11.2.4 Pulp

When there literature is reviewed, barely any studies are done to characterize the properties of the neither dental pulp nor acknowledges its existence [26].

The crown of the tooth is modeled as one material with 19 GPA modulus of elasticity, without even considering the 2 components of the crown (enamel, dentin) independently shows young's modulus of 80 and 18 GPA respectively. The Poisson's ratio is, regardless of the proposed study, taken as 0.3 [27].

11.2.5 The periodontal ligament (PDL)

The periodontium is a structure which constitutes the cementum, the PDL fibers and the alveolar complex. The PDL constitutes the tissues which are loose connective type. It is innervated as well as vascularized. It holds the teeth to the bone and compensates the wearing of the crown structure of the tooth at points in contact or the incisal/occlusal portion of the tooth. The functions of the PDL include the regulation of mastication as well because of the associated sensory nerve fiber innervations. It 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 [28].

Many studies on PDL take bilinear elastic nature of it; one can also find many studies which speak or valuate the anisotropy of the fibers of the PDL. There are advantages when it's done so, as it provides more accurate and validity of the stress calculation for a better eccentricity of the movements of the teeth [29]. But studies talk about the PDL and its non- linear nature which is stated by the properties like Poisson's ratio and the modulus of elasticity (Young's) (**Figure 3**).

A Young's modulus around 0.1 MPa is most likely to represent best of the linear part of the PDL's mechanical behavior. Bilinear elastic models are also found and are defined with three values which are tangential modulus, Young's modulus and a limit value of about 7% strains in tension tests. Last but never the least, Cattaneo et al., Verna et al. introduced a multi-linear model, different in tension and in compression [30].

Many researchers consider the PDL as a hyper elastic material (Mooney-Rivlin material with, for Natali et al., reinforced fibers, expressed in an Ogden-type formulation) and estimated strain which corresponds well with the in vivo experimental data by Parfitt.

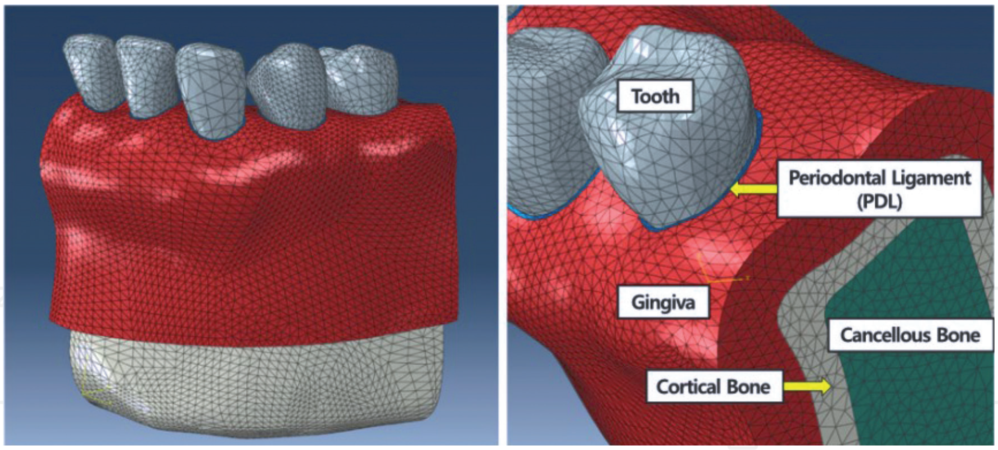

Figure 3.
Mesh model after assigning the charecteristic material properties of each constituent of dento-alveolar complex independently.

Models proposed by various other researchers, accounts for a time dependency through the use of viscoelastic models using up to four time-constants. These models are either generalized as Maxwell models [31].

There are instances where the periodontal ligament is believed to be composed of fibers which are arranged in linear nature [32]. The poroelastic model allows considering a time-dependent behavior through the fluid flow inside a porous matrix.

12. Orthodontic tooth movement (OTM) models

12.1 Initial tooth movement

The finite element (FE) method is used in orthopedic biomechanics since the early 1970's to evaluate and analyze 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. It very evident to find the use of FEM in the field of prosthodontics, implantology etc. as well to analyze the stress, the stress pattern and to optimize or go with the design of the appliances, to study the materialistic properties of the appliance as well as the reactions of the bone to it. We currently use for biomechanics in the field of orthodontics as well [33].

It is a wise decision to use the non-linear behavior of the periodontal ligament to study the wider aspects of tooth movements [34]. The initial design of models in Finite element methods FE models were 2 Dor axi symmetric models and now it's no more used since it's a 3-D era. The FEM can definitely analyze the stress and its patterns and can analyze the biomechanics and can determine the final position of the teeth from its initial positions [35]. Early models in the field of orthodontics were mainly directed to study the initial movement of the tooth in its socket (no bone remodeling included) following the implementation of a system of forces and moments by means of braces or fixed orthodontic appliances. Most current studies still follow the same principle, using geometry and a system of forces which is more complex. Within the initial tooth movement models, mainly fully linear elastic homogeneous isotropic models were used. How so ever, models with non uneven bone density is also used where modulus of elasticity is taken into account. Orthotropic behavior of the bone and the anisotropic nature of PDL also exist [36]. Studies consider the periodontal ligament to be elastic. All these could be applied to the posterior teeth, multi rooted and of different forms of roots as well [37].

12.2 Long-term tooth movement

The tooth movement due to bone resorption and apposition which obeys the pressure tension theory is not obeyed by the teeth initially and the early tooth movement is just the effect of the PDL fibers which instigate the tooth movement initially. 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 [38]. 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 remodeling law: The stimulus for remodeling is either the strain energy density, strain dependent or stress dependent remodeling algorithms obey the laws of mathematical tools such as the integration under the limit of time. The FEM analyses the forces and the associated tooth movement with it in the model and it all obeys the laws of equilibrium from its initial to final position under the stipulated time.

13. Dento-facial orthopedics modeling

Since the early 1980's, finite element models of maxillary and mandible were used. The model is built with elements which is comparable or represents the bone structure and symbolizing its properties. The magnitude of the force levels applied by appliance like brackets or others like head gears or the expansion appliance etc. is taken into consideration. As a part of modeling the movement of the jaw, a great effort is made to characterize the temporomandibular joint (TMJ). In most cases, the type of materials used for the bone is linear elastic in nature. It is considered that cortical bone is distinguishable from trabecular bone. However, the presence/absence of teeth in the cranio-facial models is variable in nature. As for the models of the TMJ, the cartilage and the disks are modeled either as linear elastic materials or as hyper elastic ones. It can be also found out that the models include muscle activation of the jaw, either performing an inverse dynamic analysis to compute the activity of the large amount of muscles in the face, or modeling a given number of muscles, often by applying a spring model to describe the muscular forces. Finally, one can also find models of the facial bones and skull by analyzing the response to external orthopedic systems [39].

14. Bone remodeling models

In addition to growth of the skeleton and resorption of fractures, which are of temporary in nature, the structure of bone is, stabilized by the action of osteoclast and osteoblast and its metabolism is a total different interest of subject which is to be discussed, which in turn is beyond the scope of this chapter. Through understanding of the remodeling process of the bone should be understood by an orthodontist to get an idea of how the teeth move in the maxilla or mandible during tooth movement. The Roux hypothesis claims the whole remodeling procedure is a self-organized procedure where the stiffness of the bone is achieved after a force is applied and stress is developed within the bone, the bone trabaculae obeys the Wolff's law and last but not the least the bone reacts upon itself for load application. It is equally important to understand the Frost model of the bone which is stated as the mechanostat theory where is notes that if the stress range exceeds the limit, there is a chance of formation of a new bone, but if the same stress is lesser to the optimal value there is a bone loss associated to it as well. Both these goes hand in hand which creates a balance. The theory sounds simple for the readers but it's simply an effective one and a tricky one when equations are derived from it mathematically and used for computing. Earlier the bone in a bone model was technically considered to be a poroelastic media which is pooled by a liquid. Later models have proposed the universal mechanical nature of a living substances, here the depth of biological activity is considered, where as there is also another model which does not propose the depth of remodeling within the bone (Phenomenological model) [40].

15. FEM in orthodontic tooth movement

Now coming to the soul of this reading, the reader must understand the real fact initially that the FEM is a theoretical study concept and does not stand alone debates of scientific evidence based ideology without the gold standard of clinical trials. FEM deals with material properties and parameters, further the geometrical aspects are even being considered. The complete system with its constituent initial force, dimension of the body, stress developed is drastically different with respect to its final state. It is logical to think that it's inevitable without mathematical formulations and definite numerical values one cannot calculate or predict the final position of the tooth from its initial one [41].

Before the application of the FEM, there were several other methods which were implemented to carry out the stress strain relations and its calculations over the PDL, but due to the complex nature of it the end results achieved or obtained stayed insignificant. When the sequence of reactive force developed after an implementation of load is checked, the root suffers the most, followed by the PDL and the alveolar bone the least (due to its higher density). These findings are due to the different mechanical properties of each structure: such as the tooth, periodontal ligament and alveolar bone. The stress applied on the bone is the active factor in the new configuration arrangement of the bone. There is a significant association of the PDL in the remodeling procedure of the bone due to its viscous nature and the storage of energy within it due to the same nature.

The stresses are of different types such as the longitudinal stress, compressive stress, or the shear stress depending on the type of the force and its line of action over the body, so it's mandatory to specify it. There is always a chance for a tooth or teeth to undergo a combination of the above said stresses in various directions as well. When comparison is done among the types of tooth movements against each other, the tipping, extrusion and intrusion result in the greatest stress at the root apex. For extrusion and intrusion, the stress concentration is mainly at the apex of the root. Stresses at the root apex after intrusive tooth movement is seen but the distribution is different when compared to other types of tooth movement. When a vertical force is applied on the buccal surface of the tooth, some torque may be expected due to the relationship between the point of application of force and the centre of resistance of the tooth. In such cases, labial and lingual portion of the apical region of the root experiences way higher reactive forces to the applied tension.

After analyzing different FEM studies in orthodontics, studies show the stress distribution patterns are more in the crest of the alveolar bone, when compared to the periodontal ligament nor the crown or the root of the tooth. When the tipping forces where studied, it showed more or less the same feature of the stress distribution over the crest of alveolar bone. The tooth and the bone suffer greatest stress at the cervical level and the PDL at the apex.

The forces in rotation create the only difference of all the situations, where the apical stress is comparatively lesser. The FEM depends on the model and the property of the material assigned and boundary conditions, any change or errors creeping in these aspects will affect the foreseeing of the results. The type of the force delivered by each system is never the same, so there is change in the results. To get these right results the proper implementation of the force system and its understanding is inevitable. After all this there are other instances to point out like, up to 50% or more of the applied force can dissipate as friction in an edgewise bracket system; which can significantly affect the stress produced at the PDL of the tooth [42].

16. Limitations of finite element analysis

As with any theoretical model of a biological system, there are some limitations which need to be considered. A thorough reading and interpretation of this chapter would give the insight of the limitation of the FEM and it's not much to emphasis on the same. But then as said before any errors in modeling or material property assignment or the boundary conditions application, even wrong forces applied to wrong formulation, will earn the wrong results. It's a sophisticated and computer dependent or programme dependent analysis, so at most care should be taken during the modeling stages and the prior stages before the final run for the results to feed the correct input data for the expected outcome or results. It is highly difficult or impossible to be frank to replicate the exact living substance into mechanical models till date due to its complex nature [43]. The major limitation which you would have never guessed all through this chapter is that the cost of the FEM study. It should be highlighted that the FEM does not come with a reasonable price currently in many countries and it's used more for the research purposes. It's not a question to ask if FEM is considered in building bridges or dams or aircrafts but definitely when comes to field of dentistry or orthodontics, to use FEM for every single patient is never feasible.

17. Conclusion

The main fundamental in orthodontics is the movement of teeth or tooth within bones, which in other words means the movement of solid (tooth) in another solid (jaw bones bone) which is the toughest movement of all mediums and it's a slow process which consumes time. If we are smart enough to estimate the final position of the teeth form its initial one, it's like predicting the end result without the trial and error methods or without any unwanted disturbances which even if occurs could be foreseen and a right component of force. This ideology actually saves time and the pain to both the clinician as well as for the patient. The mechanical and biological/physiological reactions to orthodontic forces by the PDL and the alveolar bone are closely linked with each other. This coupling can be treated in biomechanical models, focusing on the mechanics and considering the phenomenological aspects of the biology. As a tool to describe the mechanics of orthodontic tooth movement due to remodeling, 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.

It is a very big question to ask that have we discovered or implemented the complete aspect of the FEM and is it been used in our field. 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 an FEM study for independently from person to person is also unique according to the author, which is not emphasized much in any of the literature ever before.

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Conflict of interest

The author declares no conflict of interest.

Notes/thanks/other declarations

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Appendix and nomenclature

*iges	The Initial Graphics Exchange Specification
*sat	Standard ACIS Text
HU	unit used in computed tomography (CT) (Dimension less unit)
E	Modulus of elasticity (Gpa)
S	Stress (Mpa)

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References

[1] Abu, A. R., Rashid, K., and Voyiadjis, G. Z. A finite strain plastic-damage model for high velocity impact using combined viscosity and gradient localization limiters: Part I-theoretical formulation. International Journal of DamageMechanics, 2006; 15(4):293.

[2] Adachi, T., Tsubota, K., Tomita, Y., and Hollister, S. J. Trabecular surface remodeling simulation for cancellous bone usingmicrostructural voxel finite elementmodels. Journal of Biomechanical Engineering, 2001: 123(5):403-409.

[3] Anshul Chaudhry, Maninder S. Sidhu, Girish Chaudhary, Seema Grover, Nimisha Chaudhry, and Ashutosh Kaushik. Evaluation of stress changes in the mandible with a fixed functional appliance: A finite element study. Am J Orthod Dentofacial Orthop 2015; 147: 226-34

[4] Adachi, T., Kameo, Y., and Hojo,M. Trabecular bone remodelling simulation considering osteocytic response to fluid-induced shear stress. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2010: 368(1920):2669

[5] Sarmah A, Mathur AK, Gupta V, Pai VS, Nandini S. Finite element analysis of dental implant as orthodontic anchorage. J Contemp Dent Pract. 2011;12:259-64.

[6] Akhtar, R.,Daymond,M. R., Almer, J. D., andMummery, P.M. Elastic strains in antler trabecular bone determined by synchrotron X-ray diffraction. Acta Biomaterialia, 2008:4 (6):1677-1687.

[7] Ammar, H. H., Ngan, P., Crout, R. J., Mucino, V. H., and Mukdadi, O. M. Threedimensional modeling and finite element analysis in treatment planning for orthodontic tooth movement. American Journal of Orthodontics and Dentofacial Orthopedics, 2011:139(1): e59–e71

[8] Shaw AM, Sameshima GT, Vu HV. Mechanical stress generated by orthodontic forces on apical root cementum: a finite element model. Orthod Craniofacial Res. 2004;7(2): 98-107.

[9] Jones ML, Hickman J, Middleton J, Knox J, Volp C. A validated finite element method study of orthodontic tooth movement in the human subject. Am J Orthod. 2001;28(1):29-38.

[10] Bailon-Plaza, A. and Van Der Meulen, M. A mathematical framework to study the effects of growth factor influences on fracture healing. Journal of Theoretical Biology, 2001:212(2):191-209

[11] Aversa, R., Apicella, D., Perillo, L., Sorrentino, R., Zarone, F., Ferrari, M., and Apicella, A. Non-linear elastic three-dimensional finite element analysis on the effect of endocrown material rigidity on alveolar bone remodeling process. Dental Materials, 2009:25(5): 678-690

[12] Arola, D. and Reprogel, R. Effects of aging on the mechanical behavior of human dentin. Biomaterials, 2005:26(18): 4051-4061

[13] MECHANICAL FINDER [Internet]. Available from: https://mechanical-finder.com/

[14] Bagge, M. A model of bone adaptation as an optimization process. Journal of Biomechanics, 2000:33(11): 1349-1357.

[15] Bailon-Plaza, A. and Van Der Meulen, M. A mathematical framework to study the effects of growth factor influences on fracture healing. Journal of Theoretical Biology, 2001:212(2): 191-209.

[16] Baïotto, S. and Zidi, M. Un modèle viscoélastique de remodelage osseux : approche unidimensionnelle. Comptes Rendus deMécanique, 2004:332(8): pp. 633-638.

[17] Beaupré, G. S. and Hayes, W. C. Finite element analysis of a three-dimensional opencelledmodel for trabecular bone. Journal of biomechanical engineering, 1985:107:249.

[18] Beaupré, G. S., Orr, T. E., and Carter, D. R. An approach for time-dependent bone modeling and remodeling-theoretical development. Journal of Orthopedic Research, 1990:8 (5):651-661

[19] Cattaneo, P. M., Dalstra, M., and Melsen, B. The finite element method: a tool to study orthodontic toothmovement. Journal of Dental Research, 2005:84(5):428-433.

[20] Cattaneo, P.M., Dalstra,M., andMelsen, B. Strains in periodontal ligament and alveolar bone associated with orthodontic tooth movement analyzed by finite element. Orthodontics & Craniofacial Research, 2009:12(2): 120-128.

[21] Chan, E. and Darendeliler, M. A. Physical properties of root cementum: Part 7. Extent of root resorption under areas of compression and tension. American Journal of Orthodontics and Dentofacial Orthopedics, 2006:129(4): 504-510.

[22] Charlebois, M. Constitutive Law for Trabecular Bone in Large Strain Compression. PhD thesis, Technische Universitat Wien, Institute of Lightweight Design and Structural Biomechanics, 2008.

[23] Committee, A. I.H. ASMHandbook: Properties and selection, volume 2. ASMInternational, 1990.

[24] Cowin, S.C. Themechanical and stress adaptive properties of bone. Annals of Biomedical Engineering, 1983:11(3-4): 263-295.

[25] Cowin, S.C. Themechanical and stress adaptive properties of bone. Annals of Biomedical Engineering, 1983:11(3-4): 263-295.

[26] Cowin, S. C. Tissue growth and remodeling. Annual Reviews of Biomedical Engineering, 2004:6: 77-107.

[27] Cowin, S. C. andDoty, S. TissueMechanics. Springer Verlag, 2007. Ch. 11 : Bone tissue.

[28] Cowin, S. C. and Hegedus,D. Bone remodeling I: theory of adaptive elasticity. Journal of Elasticity, 1976:6(3):313-326.

[29] Cowin, S.C. and Nachlinger, R. Bone remodeling III: uniqueness and stability in adaptive elasticity theory. Journal of Elasticity, 1978:V8(3):285-295.

[30] Cowin, S. C. Wolff's law of trabecular architecture at remodelling equilibrium. Journal of Biomechanical Engineering, 1986:108(1):83-88.

[31] Cowin, S. C., Hart, R. T., Balser, J. R., and Kohn, D. H. Functional adaptation in long bones: establishing in vivo values for surface remodeling rate coefficients. Journal of Biomechanics, 1985:18(9): 665-684.

[32] Crigel, M.-H., Ballig and, M., and Heinen, E. Les bois de cerf : revue de literature scientifique. Annales deMédecine Vétérinaire, 2001:145(1): 25-38.

[33] Cronau,M., Ihlow, D., Kubein-Meesenburg, D., Fanghänel, J., Dathe,H., and Nägerl, H. Biomechanical features of the periodontium: an experimental pilot study in vivo. American Journal of Orthodontics and Dentofacial Orthopedics, 2006:129(5):599. e13– 599.e21.

[34] Currey, J. Strain rate dependence of themechanical properties of reindeer antler and the cumulative damage model of bone fracture. Journal of Biomechanics, 1989:22(5):469– 475.

[35] de Bien, C. Analyse de la relation entre les propriétésmécaniques et lamicrostructure de matériaux cellulaires : contribution au développement d'une méthodologie basée sur le suivimicrotomographique de tests de compression. Master's thesis (in French), Université de Liège, Faculté des Sciences Appliquées, Département de Chimie Appliquée, 2010.

[36] de Giorgi, M., Carofalo, A., Dattoma, V., Nobile, R., and Palano, F. Aluminiumfoams structuralmodelling. Computers & Structures, 2010:88(1-2): 25-35.

[37] del Pozo, R., Tanaka, E., Tanaka, M., Kato, M., Iwabe, T., Hirose, M., and Tanne, K. Influence of friction at articular surfaces of the temporomandibular joint on stresses in the articular disk: a theoretical approach with the finite element method. Angle Orthodontist, 2003:73(3):319-327.

[38] Desmorat, R. and Otin, S. Cross-identification isotropic/anisotropic damage and application to anisothermal structural failure. Engineering Fracture Mechanics, 2008:75(11): 3446-3463.

[39] Dizier, A. Caractérisation des effets de température dans la zone endommagée autour de tunnels de stockage de déchets nucléaires dans des roches argileuses. PhD thesis, Université de Liège - Faculté de Sciences Appliquées - ArgEnCo, 2011.

[40] Doblaré, M. and García, J.-M. Application of an anisotropic bone-remodellingmodel based on a damage-repair theory to the analysis of the proximal femur before and after total hip replacement. Journal of Biomechanics, 2001:34:1157-1170.

[41] Frost, H. Bone "mass" and the "mechanostat": a proposal. The anatomical record, 1987; 219 (1):1-9.

[42] Frost, H. Skeletal structural adaptations to mechanical usage (SATMU): 1. Redefining Wolff's law: the bone modeling problem. The Anatomical Record, 1990; 226(4): 403-413.

[43] Gal, J. A., Gallo, L. M., Palla, S., Murray, G., and Klineberg, I. Analysis of human mandibular mechanics based on screw theory and in vivo data. Journal of Biomechanics, 2004;37(9):1405-1412.