The Finite Element Analysis and Its Application in Pediatric Dentistry. A Narrative Review

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ABSTRACT

BACKGROUND: The finite element analysis (FEA) or the finite element method (FEM) is a numerical method that is used to solve problems in engineering and mathematical physics. It has been introduced to the dental field and has been used in different dental specialties for the reason of scientific research, in order to test for stress and strain on different dental materials. It has been also used to test for different loads applied on hard and soft tissues in the oral cavity.

PURPOSE: The purpose of this review will be to understand the FEM and how it is used in different research fields including its application in dentistry.

CONCLUSION: Operating the FEM in dentistry has given it a big leap forward. Researchers could test virtually the stresses exerted upon any of the craniofacial structures. This may give rise to yet considerable evidence and may lead to the invention of new materials and appliances serving all scopes of pediatric dentistry. However, further clinical trials will be needed to support the results from this simulation software and provide evidence-based results.

KEYWORDS: finite element analysis, finite element method, dentistry, pediatric dentistry, numerical method.

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INTRODUCTION

Dentistry is a fast-growing branch of health care. It deals with many materials which are placed in a complex and hostile oral environment that encounters multiple forces and stresses from different perspectives. However, almost all these materials need to be tested in terms of stress and strain before their application in the oral cavity. For this to be achieved finite element analysis (FEA) can be used. (1)

The FEA or the finite element method (FEM) is a numerical tool for solving problems in engineering and mathematical physics. The FEM is primarily used to analyze the stress and strain of different materials and structures that cannot be measured in real conditions, for the reason, it can virtually mimic the natural process through computer technology. (2)

The basic concept is dividing complex problems into simpler ones to give more realistic results. To perform analysis with FEM, the computer is fed with certain data which are: the geometrical model (domain), the material behavior (Young's modulus of elasticity, Poisson's ratio, and density), forces of loading, and finally, the boundary conditions. Once the model is completely defined and meshed, a stress analysis is performed and stress distributions are obtained. (3)

HISTORICAL BACKGROUND

The FEM is the latest form of analyzing complex structures. The idea was introduced by Courant in 1943. (4) The full development of the FEM was then introduced by Clough in 1960 (5) in solving problems in the field of aeronautical engineering and aircraft industries. Ever since, the method has made rapid progress in solving engineering problems. Moreover, in recent years, fluid flow and heat transfer modeling have been accomplished successfully through this method. (6)

Considering the use of FEM in the medical field, Farah et al, in 1973 (7) were the pioneers to use the FEM in dentistry when they published their paper entitled "Finite element stress analysis of a restored axisymmetric first molar". They compared the results of the stresses applied to the static axisymmetric model to the FEM model. They concluded that the finite element approach provides a more detailed evaluation of the complete state of stress in the model. Later, in 1976, Weinstein et al (8) used this technique in implant dentistry to evaluate various loads of occlusion on the implant and adjacent bone. Since then, the FEM has been used in different branches of dentistry to test for the stresses and strains exerted on dental restorations, dental prosthetics including dental implants or even living tissues such as bone and periodontal ligaments (PDL). (2)

IMPORTANCE

The FEM is a very useful tool for researchers to test for different designs of objects or bodies dynamically under stress, without the need to create a physical working model. It can be used on wide scales to test for the different loading conditions in different structures, therefore, increasing public safety. This can be the case when designing buildings, aircrafts, spacecrafts, sports arenas, and bridges. The advantages of the FEM are: allowing the modeling of bodies with multiple layers and having multiple material types, testing of complex bodies with different shapes, and the ability to capture local effects acting on a small area of the design. Another important advantage of using the FEM is that studies performed with the FEM can be comparable to studies on real models, and the tests are repeatable with accuracy and without ethical concerns. (9)

LIMITATIONS

Stress analysis using the FEM is done by inserting certain numerical values into the software, which will result in the same outcome for the same test repeatedly, therefore, the results may only be acknowledged qualitatively. (10) In other words, the numerical values applied to the FEM model could only give the same numerical results if the original numerical value of the load is not changed. This is why the results are only descriptive and cannot be compared quantitatively unless the original numerical loads are changed every time the test is done. Another limitation of the FEM highlights its use in the medical and dental fields. Practically, the FEM is a computerized tool for in-vitro studies in which clinical conditions and elements, such as bacteria and saliva, may not be completely replicated. This is because, in this numerical method, the hostile elements of the oral cavity cannot be replicated or translated into numbers. However, Szwedowski et al (11) compared the experimental loading mimicking that of the masseter muscle of real specimens of cadaveric human craniofacial skeleton using strain gauge measurements with finite element (FE) models. They found that the 2 models agreed well with each other. But again, these cadaveric models did not include bacteria, saliva, other elements, which failed to be replicated in the numerical method. Moreover, pain or fatigue which can be experienced by the patient cannot be also replicated by the FEM.

How does FEM work?

It takes certain steps to create a model and analyze the stress and strain exerted upon it. These steps are; imaging, discretization, applying the boundary conditions, inserting the materials' properties, then applying the loads on the model, and finally obtaining a solution displayed on the computer screen. (12)

1. Imaging

Computerized tomography (CT), magnetic resonance imaging (MRI), and confocal microscopy have made it possible to create 3D images of any structure by virtually sectioning it. The resultant 3D image can be then imported into the FE tool and can be successfully discretized and meshed.[12] Imaging can also be done by computer-aided designs (CAD), laser scanners, or even by simply describing the geometry or the anatomy of the object to be tested. (12)

FEA of 2D models can be done on old-fashioned computers, but they may produce less accurate results, whereas the FEA for 3D models can yield more accurate and realistic results but they need to be run by more sophisticated and fast processing computers. Despite being simpler and less time-consuming, the 2D models are nowadays less used by researchers owing to the fact that currently available computers are of high-end technologies and are capable of processing 3D models using the FEA software, therefore yielding more realistic and reliable results. (12)

2. Discretization and meshing

In reality, problems are solved by the continuous approach, while in the numerical world, these problems are solved by the discrete approach. That is to say that a numerical digital model (domain) can be divided into known number of elements, where these elements are the result of the connection of a finite number of nodes predetermined on the domain. Solving a certain problem related to that numerical model can be done by calculations at these nodes where the results are interpolated for all elements. (12)

3. Boundary conditions

A boundary condition is the application of force and constraint at the outermost boundaries of the model to be tested. Zero displacement constraints must be placed on some boundaries of the model where nodes at these boundaries have no freedom of rotation or movement in either of the three planes of rotation (x, y, and z axes). They are placed at the nodes which are furthest away from the point of interest (loading). (12)

4. Material properties

After transferring a model to the FEM software, the properties of the material, or different layers of different materials, which form the model have to be also fed to the program. These properties include the Young's modulus of elasticity, the Poisson's ratio, and the density of the material. [12] These values are known numbers for any given material and thus can be extracted from literature and directly inserted in the FEM program. (12)

4. Applying the desired loads

They are the loads (forces) that will be exerted on the object (model) during function. To accurately understand potential failure modes, the applied forces should be set as the largest expected loads that the object could experience during its lifetime, rather than the average loads. In dentistry, the desired load can be acquired from literature and fed to the computer. (12)

6. Applying a solution

Once all the needed data is provided, the computer program runs a series of calculations that translate the principal stresses acting on the model in the x, y, and z directions. These stresses ideally should not exceed the yield stress of the material which is the maximum stress that can be developed in a material without causing plastic deformation. (13)

The information is represented in the software as a series of colors and values that indicate different stress areas. The highest stress on the model is coded in red and the value of the force is referred to as the Von Mises stress. The Von Mises stress (criterion) indicates the failure point which occurs when the energy of distortion reaches the same energy for yield in uniaxial stress. The von Mises criterion is a formula for combining three principal stresses in the 3 axes of rotation into an equivalent stress, which is then compared to the yield stress of the material. (13)

FEM software

There are many software available in the market for the application of the FEM such as ANSYS™, SimScale™, COMSOL Multiphysics™, OpenFoam™, ABAQUS™, Altair HyperWorks™, Autodesk CFD™, IVRESS™, Nastran™, SAMCEF™, LS-DYNA™. (14)

Application in dentistry

One of the important biomedical applications of FEM is in the different fields of dentistry. Remarkably, FEM can also be associated with clinical evaluations as a further tool for diagnosis and treatment planning, consequently, providing the clinician with the required information about the choice of therapy. (15)

For decades, FEA has been extensively used to predict the biomechanical performance of various dental implant designs, as well as the effect of clinical factors on its success. (16,17) Many authors used the FEM to describe and test different loading conditions in different clinical scenarios. (18-19)

Orthodontics also benefited greatly from the FEM. (20) The method was used to study the biomechanics of tooth movement, reactions of the teeth, and their supporting tissues when loaded with an orthodontic force, as they could not be measured in-vivo. (21,22)

The FEM can also be applied to optimize the design of dental restorations which can withstand the different forces as well as measure the stresses produced by polymerization shrinkage of resin composites on the tooth. (23-25)

It can be also used in investigating the stress distribution in a tooth upon cavity preparation and biomechanical preparation during root canal treatment as well as analyzing the mechanical behavior and the cyclic fatigue resistance of the endodontic instruments subjected to dynamic loads can be done by the FEA. (26-28)

In prosthetic dentistry, the FEM has been used by different authors to understand the stresses created by restoration and post-application on the endodontically treated teeth which are compromised by coronal destruction from dental caries, fractures, previous restorations, and endodontic access. Nonetheless, evaluating the influence of the type of material as well as the external configuration of the post on the stress distribution of teeth restored with varying post systems after endodontic treatment. (29) In addition, the FEM has been used to study the stress distribution in the teeth and their supporting structures in relation to different designs of fixed and removable prosthesis. (30-33)

Periodontists can also make use of the FEM to measure different stresses on the periodontal ligaments (PDL), cementum, and bone. (34)

Applications in pediatric dentistry

Finite element method can be applied in pediatric dentistry research methodology, and help in the innovation of new restorative materials, appliances, and protocols for the prevention of traumatic injuries and dealing with such cases.

Growth and development

Knowing that abnormal oral habits can affect the growth and development of the facial skeleton, the FEM can help in determining the loads that can affect these bones adversely. In 2020, Borges et al (35) studied the influence of the mouthguard to reduce the stress magnitude created by bruxism in children using the FEM. They concluded that mouthguard use is beneficial for decreasing the generated stresses in bone, dentin, enamel, and PDL. Consequently, this optimizes the growing patterns and improves the development of the craniofacial bones and muscles. Likewise, in 2021, Al Zubaidi et al (36) studied the effect of the buccinator during normal and abnormal function on the size and shape of the mandible. They determined the forces that could cause mandibular malformations and they stated that abnormal function of buccinators during growth and development could result in size and shape variation of the mandible with unfavorable malocclusion.

Interceptive orthodontics and space management

The finite element method can be put in use for optimizing forces and designs of appliances used in interceptive orthodontics. (37,38) It can also be used to test for the forces that cause displacement of the teeth in case of premature loss of their adjacent neighboring teeth. (39) Thus, describing the forces needed for ideal benefit of space regainers. Moreover, altering the design, shape, and materials of space maintainers can be achieved with the aid of FEM.

Designing pacifiers

Since their appearance in the market, pacifiers witnessed changes in terms of size, geometry and production materials. With time, new specific shapes have been designed and their dimensions have been increasingly adapted to the infant’s age with the help of FEM. (40)

Cleft lip and palate

The finite element method made studying the effects of stresses on the bone in patients with cleft lip and palate more applicable. (41) This in turn can give researchers the opportunity for augmenting the appliances used in these cases for obtaining more desirable growth patterns and results.

Improving restorations

Many authors evaluated the different forces experienced by teeth and the restorations in different clinical case scenarios for the sake of describing the best material which can be used in every specific case. (42-46) Moreover, further research using the FEM could be performed in order to design the optimum material for every specific restorative situation in children.

Trauma

Trauma is commonly experienced in children. Analysis of the forces that lead to avulsion, luxation, and fracture of the teeth can be achieved using the FEM. Moreover, enhancing the trauma protocols and the splint types for different traumatic scenarios to the teeth can also be accomplished by the FEM technology. (47)

Nonetheless, forces leading to bone fractures in the craniofacial region, as well as protocols for their treatment can also be described by further research using FEM. (48-51)

CONCLUSION

Operating the FEM in dentistry has given it a big leap forward. Researchers could test virtually the stresses exerted upon any of the craniofacial structures. This may give rise to yet considerable evidence and may lead to the invention of new materials and appliances serving all scopes of pediatric dentistry. However, further clinical trials will be needed to support the results from this simulation software and provide evidence-based results.

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