FELIPPE BEVILACQUA PRADO

DISSIPAÇÃO DE TENSÃO MECÂNICA PELO PILAR ZIGOMÁTICO HUMANO DURANTE A OCLUSÃO MOLAR - ANÁLISE DE ELEMENTO FINITO

Tese apresentada à Faculdade de Odontologia de Piracicaba, da Universidade Estadual de Campinas para obtenção do Título de Doutor em Biologia Buco Dental, área de concentração Anatomia.

Orientador: Prof. Dr. Paulo Henrique Ferreira Caria

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MENTE·MANV·CORDE

A Comissão Julgadora dos trabalhos de Defesa de Tese de Doutorado, em sessão pública realizada em 15 de Junho de 2010, considerou o candidato FELIPPE BEVILACQUA PRADO aprovado.

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Resumo:

Introdução: As tensões mastigatórias são absorvidas pelos processos alveolares e são dissipadas do pilar zigomático para o restante do crânio. A análise por elementos finitos é útil para avaliar a dissipação da tensão e simular o comportamento mecânico de estruturas biológicas. **Objetico:** O Objetivo deste estudo foi analisar a dissipação da tensão principal máxima na região do Pilar Zigomático de um crânio humano, ao simular a oclusão dos molares. **Material e Método:** Um modelo dos ossos faciais foi construído a partir de imagens tomograficas computadorizadas com 0,25 mm de espessura de um crânio humano dentado pertencente ao Departamento de Morfologia da FOP - UNICAMP. O modelo geométrico foi construído com base na modelagem por meio do software Rhinoceros 4,0 (modelagem tridimensional por superfícies NURBS), utilizando a técnica de BioCAD e software MSC / Nastran ® 4.5 para Windows (The Corporation MacNeal-Schwendler, Savannah, GA, E.U.A.) que reproduziu o modelo de elementos finitos com as propriedades mecânicas da estrutura original. **Resultados:** Durante a aplicação da carga nos molares superiores, surgiram na superfície interna do seio maxilar duas linhas tensão maxima principal a partir do assoalho do seio maxilar, a primeira em direção ao pilar zigomático e a segunda para a região póstero-lateral do seio maxilar. Na região de transição entre a maxila e a crista zigomático maxilar foi observado uma área de tensão máxima principal nula. **Conclusão:** A tensão máxima principal durante a oclusão molar não é transferida diretamente ao pilar zigomático, mas sim para estruturas adjacentes.

Palavras-chave: Biomecânica; Crânio; Análise de Elemento Finito

Abstract

Introduction: Masticatory stress are absorbed by the alveolar processes and dissipated from the Zygomatic Pillar for the hole skull. The finite element analysis is useful to evaluate the stress dissipation and simulate the mechanical behavior of biological structures. **Objective**: The objective of this study was to analyze the dissipation of maximum principal strain in the region of the Pillar Zygomatic of a human skull during molars occlusion. **Material and Methods:** A model of the facial bones was constructed from computed tomography images with 0.25 mm thickness of a dentate human skull from the Department of Morphology, FOP - UNICAMP. The geometric model was built based on modeling using the Rhinoceros 4.0 software (three-dimensional modeling by NURBS surfaces), using the technique of BioCAD and MSC / Nastran for Windows ® 4.5 software (The MacNeal-Schwendler Corporation, Savannah, GA USA) which reproduced the finite element model with the mechanical properties of the original structure. **Results**: During application of the load on the upper molars two lines of maximum principal strain appeared on the inner surface of the maxillary sinus from the maxillary sinus floor, the first toward the Zygomatic Pillar and the second to the posterior of the maxillary sinus. **Conclusion**: The maximum principal strain during molar occlusion is not transferred directly to the Zygomatic Pillar, but to adjacent structures.

Key words: Biomechanics, Skull, Finite Element Analysis.

SUMÁRIO

INTRODUÇÃO GERAL

De acordo com a lei de Wolff, as mudanças na função e na intensidade das forças mecânicas aplicadas podem modificar externa e internamente a morfologia óssea (Wolff 1882). Esse conceito da biomecânica permite avaliar a influência das forças mecânicas mastigatórias sobre o osso alveolar e estruturas de suporte (Sicher 1965; Koppe et al., 2005) embasados pela na remodelação óssea (Misch & Bidez 1997).

A relação entre forma e demanda funcional mastigatória (Prossinger & Bookstein 2003; Mavropoulos et al., 2004), vem provocando um aumento nas discussões sobre a variabilidade morfológica das estruturas craniofaciais nas diferentes populações humanas, já que tal aspecto é apontado atualmente como um dos principais responsáveis pela remodelação do crânio (Hylander & Johnson 1997; Ravosa et al., 2000).

As forças mastigatórias são dissipadas pelos pilares canino, zigomático e pterigóideo, assim denominados devido a sua localização e por serem áreas de reforço ósseo capazes de suportar as tensões mecânicas (Hilloowala & Kanth 2007). Tanto a forças oclusais como as de tração muscular geram forças de tensão e compressão que se dissipam a partir desses pilares por todo o crânio, determinando secundariamente seu arranjo ósseo estrutural (Sicher 1965; Standlee & Caputo 1987).

Estudos experimentais realizados em primatas demonstraram essa relação entre forma e demanda funcional mastigatória com base na dissipação da tensão mecânica e da remodelação da região supra-orbital e dos seios paranasais, uma vez que essas estruturas absorvem as tensões mecânicas mastigatórias e sofrem alterações dimensionais de acordo com a quantidade de estímulos que recebem (Preuschoft *et al,* 2002).

Para avaliar a disipação e os efeitos das cargas mecânicas funcionais e parafuncionais sobre dentes e estruturas craniofaciais, diferentes metodologias podem ser utilizadas (Tappen 1953; Standlee & Caputo 1987; Knoell 1977; Caputo, Chaconas, Hayashi 1974; Hylander & Johnson, 1997; Kawarizadeh, Bourauel, Jäger 2003), dentre as quais pode-se destacar as análises por elementos finitos (Boryor et al, 2010).

As análises por elementos finitos possibilitam a obtenção de informações sobre o deslocamento e o grau de tensão mecânica gerado durante a atividade muscular e mastigatória sobre as estruturas craniofaciais, permitindo a reprodução matemática da arquitetura do crânio por meio de sua modelagem (Panagiotopoulou et al., 2009; Panagiotopoulou, 2010). Nas últimas décadas a região zigomática vem se destacando como uma das áreas do crânio de maior importância funcional em termos biomecânicos (Herring 1972; Hylander & Johnson 1997; Rayfield 2005). Além de permitir a inserção muscular, essa região faz a junção entre o viscero e o neuro-crânio por meio da sutura zigomático-temporal o que aumenta o interesse sobre essa estrutura sob o ponto de vista funcional e evolucional (Hylander & Johnson 1997; Rafferty et al., 2000; Witzel et al., 2004).

Baseados nesses princípios foram desenvolvidos dois artigos científicos, um referente à literatura que aborda a aplicação do método em analises da biomecânica do crânio aplicadas a odontologia e outro experimental onde foi avaliado distribuição da tensão mastigatória da região dos molares pelo pilar zigomático.

CAPÍTULO 1*

Title: STRESS DISTRIBUTION IN HUMAN ZIGOMATICMAXILLARY PILLAR AFTER MAXILLARY MOLARS LOADING: A THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS.

Article Type: Research Paper

Keywords: Finite element, biomechanics, skull, stress, strain, functional morphology.

Corresponding Author: Paulo Henrique Ferreira Caria,

First Author: Felippe B Prado, MSc

Order of Authors: FB Prado1, AR Freire 2, AC Rossi 2, PY Noritomy 3, F Heiter-Neto 4, PHF Caria 5.

1. PhD Student - Department of Morphology, Anatomy Area, Piracicaba Dental School - State University of Campinas –UNICAMP.

2. Undergraduate student - Department of Morphology, Anatomy Area, Piracicaba Dental School - State University of Campinas –UNICAMP.

3.Mechanical Engineering, MSc, PhD. Center for Information Technology Renato Archer - CTI - Campinas - Brazil.

4 DDS, MSc, PhD, Full Professor, Department of Clinical Odontology, Radiology Area, Piracicaba Dental School - State University of Campinas –UNICAMP.

5 DDS, MSc, PhD, Full Professor, Department of Morphology, Anatomy Area, Piracicaba Dental School - State University of Campinas –UNICAMP.

***Submetido para Journal of Anatomy (Anexo 1)**

Abstract

The morphology of the craniofacial skeleton reflects the functional demand. Tensions generated by chewing are mainly absorbed by the zygomatic bone and dissipated across the skull from the zygomaticomaxillary pillar (ZMP). Finite element analysis (FEA) is a useful tool to evaluate the dissipation of strain and to simulate the mechanical behavior of biological structures. The aim of this study was to analyze the dissipation of maximum principal strain (MPS) in the ZMP region of the human skull simulating a maxillary molars loading. Sequential computed tomography images with 0.25 mm thickness were obtained by a dentate human skull from the Department of Morphology, Piracicaba Dental School - UNICAMP, which was modeled geometrically using the Rhinoceros 4.0 (three-dimensional modeling by NURBS surfaces), by BioCAD technique and MSC/Nastran® 4.5 for Windows (The MacNeal-Schwendler Corporation, Savannah, GA, USA) software that replicated the model to finite elements with the mechanical properties of the original structure. After the application of maxillary molars loading on the internal surface of the maxillary sinus was observed two lines of MPS from the floor of the maxillary sinus toward the ZMP and after was distributed towards the posterolateral surface of the maxillary sinus. An area of zero MPS in the transition between the maxilla and zygomatic maxillary crest was recorded. The MPS during simulated maxillary molars loading is not transferred directly through the lateral surface of ZMP, however its focuses on the body of the zygomatic bone and dissipated not directly to the ZMP but for different directions on adjacent structures.

Introduction

Functional morphology is an important subject because can help to explain how the anatomical structures are modified by the action of external mechanical loads, how structures such as bone can resist stressful loadings and figure out the relationship between form and function of the morphological structures (Turner, 1998; Huiskes, 2000; Pavalko et al. 2003; Silva et al. 2005, Kupczik et al. 2007).

The fundament of the skull biomechanics is based on the dissipation of the masticatory occlusal forces through the alveolar bone and afterward through other bone structures named pillars and trajectories (Sicher & Tandler 1928; Sicher 1965; Caputo & Standlee, 1987). It is believed that one of those pillars, the zygomaticomaxillary pillar (ZMP), dissipates the mechanical forces toward the zygomatic arch, frontal process of maxilla, passing by the lateral border of the orbit (Dubrul, 1988; Hilloowala & Kanth 2007).

The zygomatic bone has been studied biomechanically by stereological analysis (Teng et al. 1997), in vivo analysis of the mechanical stress (Oyen et al. 1996; Hylander & Johnson, 1997; Herring et al. 2005) employing animals as experimental models like monkeys and pigs. The finite element analysis (FEA) also has been used to evaluate functionally the zygomatic bone in non-human models (Hylander & Johnson, 1997; Rafferty et al. 2000; Witzel et al. 2004; Kupczik et al. 2007), despite the structural similarities, morphological differences limit the correlation with humans.

Finite element analysis is enable to evaluate the mechanical stress on biological structures (Brekelmans et al. 1972; Hosey & Liu, 1982) and figure out the dissipation of occlusal forces through the teeth and support pillars of the skull, as well make easier the diagnosis of functional and parafunctional masticatory changes and to plan oral rehabilitation (Jaffin & Berman, 1991; Fugazzoto et al., 1993; Misch & Bidez, 1997). Nevertheless, previous researches using FEA did not evaluate the action of masticatory forces on the ZMP, then the reason the purpose of this study was to analyze and characterize the dissipation of mechanical tension through the ZMP by tridimensional FEA.

MATERIAL AND METHOD

A dried male human skull, 38 years old without any skeletal pathology and normal dental relationship was selected from the anatomical collection of the Department of Morphology – Anatomy Area of Piracicaba Dental School – UNICAMP. The selected skull presented maxillary first molars positioned right below the ZMC and it maxillary morphology totally preserved with sufficient bony support around both molars. This research was approved according to the Local Research Ethics Committee (no.175/09).

Sequential CT images acquisition of the skull was performed in a DICOM (Digital Imaging Communications in Medicin) format using a GE HiSpeed NX/i CT scanner (General Electric, Denver, CO, USA) in the axial plane, parallel to the Frankfurt plane, with slice thickness and scan increment both of 0.25 mm, resulting in 392 slice images. The physical and geometric parameters (within safety limits) yielding the best results with respect to image quality, were obtained using 120 kV, 150 mA, a 640 × 640 matrix, a

14×14 cm field of view and a slice thickness of 0.25 mm. Those parameters generated a 0.273 mm pixel size.

The anatomical structures of interest were obtained from the resetting of a CT scan of the skull, transferred to the program InVesalius (CTI, São Paulo, Brazil). Segmented topographic images of the skull without mandible were evaluated to considering the discontinuation of craniofacial structures, so that their geometry and anatomical details were reproduced by a triangle mesh surface, called "Stereolitography" format (STL) and imported into the Mimics software / MedCAD 8.0 software (Materialize, Leuven, Belgium), where the images were segmented by thresholding for the maxilla and zygomatic bone and the first and second upper left molars, as distinct parts.

The BioCAD geometric models of the study were initially necessary to checks on its quality, especially about the consistency of the areas resulting from the processes of import tools for pre-processing of finite element analysis. Inconsistencies of the surface can not be easily detected but can influence negatively on the final quality of the meshes, contacts and, especially the final results.

After the segmentation of anatomical structures of interest and three-dimensional virtual models in STL format were subsequently transferred to the Rhinoceros ® 3D 4.0 (NURBS Modeling for Windows, USA) program, an engineering computer-aided design (CAD) software used to detail the surface structure from mapping the major anatomical landmarks with specific geometric entities. It technique is called BioCAD, and the structures of interest are modeled separately and incorporated into the same model, creating three-dimensional isocurves and isosurfaces. Rhinoceros 4.0 program uses the file format 214 STEP (*.stp), that presents good compatibility with the program FEMAP® (Siemens PLM Software) pre-processing, used in conjunction with the NeiNastran ® (Noran Engineering, Inc, Westminster, CA, USA) who is responsible for generating the finite element model.

From the three-dimensional models was initiate the mesh generation for finite element analysis. We used mesh controlled by quadratic tetrahedral elements, characterized by a triangular base pyramids, with a node at each corner and one node in the center of each edge, a total of 10 nodes per element. The number of triangles describing the outward forms were reduced (Fig. 2). The mesh generation resulted in a total of 112,000 elements and 177,000 nodes. The average size of elements was 3.8 mm for the model. Added to this, another important factor related to the control loop consisted in understanding the phenomena of study, so that high density of the mesh were carried out in regions of greatest relevance of the mechanical behavior of structures. Later were incorporated into the mechanical properties for each material, the Young's modulus and Poisson's ratio (Table1), which were determined from values obtained in the literature. All materials were considered isotropic, linearly elastic, and homogeneous (Meijer et al. 1993).

Table 1 – Mechanical Properties of the anatomical structures.

Material	Young Módulus	Poisson Ratio
Cortical bone (Oliveira, 2000)	1,37 x 10^4 MPa	0,30
Dentin (Rubin et al, 1983)	1,9 x 10^4 MPa	0,30

Regarding to boundary conditions, restrictions were placed symmetrical motion in the region of the median sagital plane (palate). The load consisted of the application of nodal force of 200 N (Fig. 1) In suture areas as zygomatic frontal suture and zygomatic temporal suture (fig 2 and 3) has imposed a restriction condition, to simulate the presence of the others parts of the skull. equally distributed on the vertices of the first and second left upper molar. In regard to boundary conditions, movement was restricted symmetrically to the midsagittal plane. For the top of cutting plane, the restraint was defined to simulate the other part of the skull.

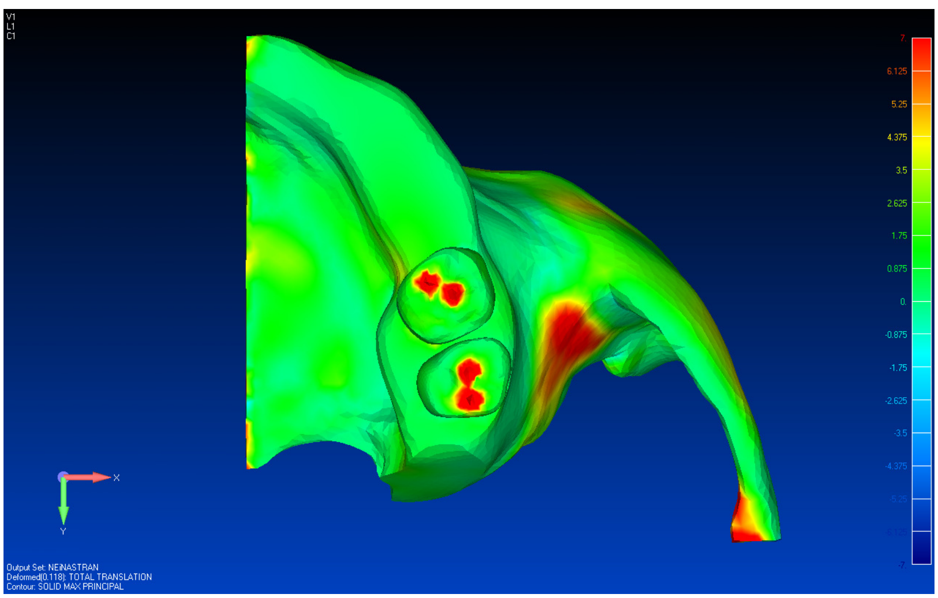

Figure 1 - Boundary conditions for the application of nodal force of 200 N, equally on the slopes of the cusps of the first and second left upper molar.

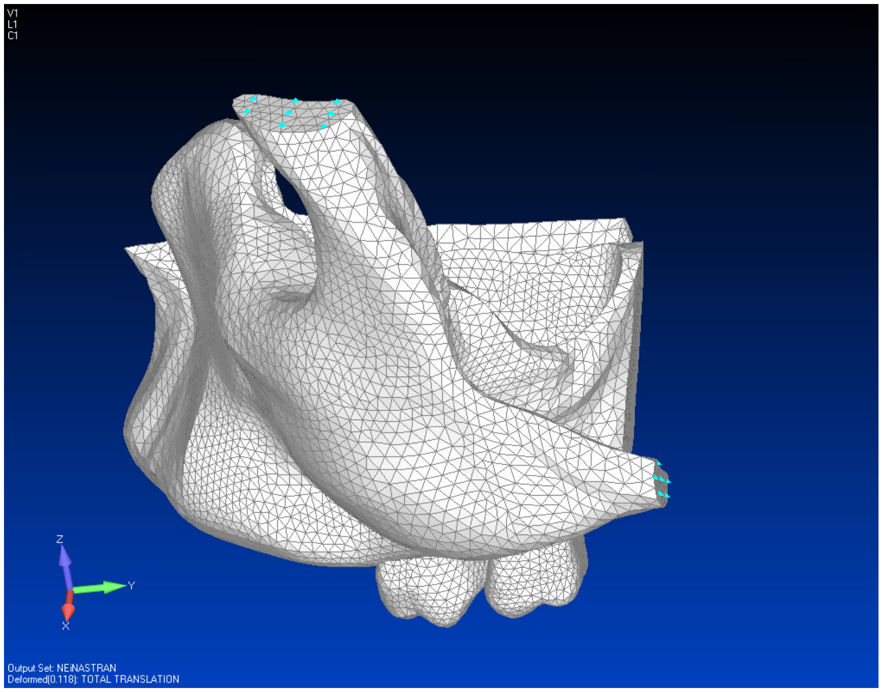

Figure 2 Boundary conditions and restrictions of movement on the faces of cutting in the frontal zygomatic and zygomatic temporal sutures.

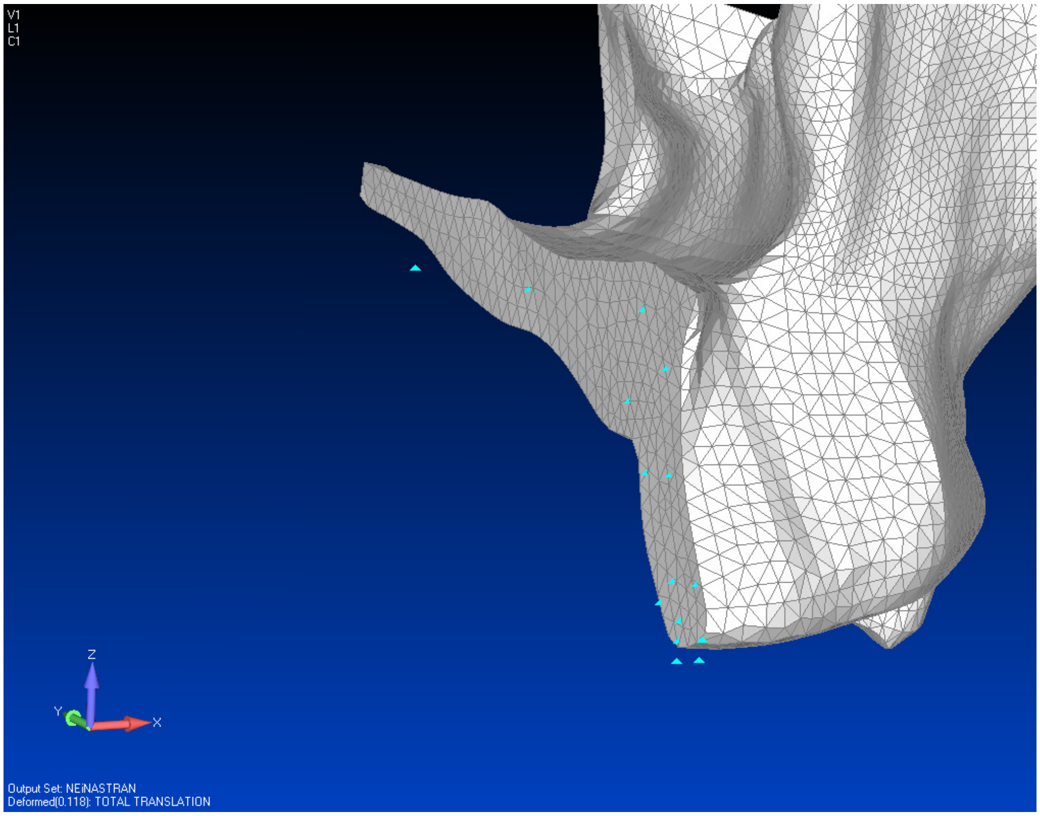

Figure 3 Symmetry conditions imposed in the median sagital plane.

RESULTS

In the interior of the maxillary sinus model, after the application of mechanical loading on the left maxillary molars, were recorded two lines of maximum principal strain (MPS) from the floor of the maxillary sinus. One line from the anterior wall of the maxillary sinus (yellow and red) toward the ZMP and other one posteriorly, distributed to the posterolateral wall (yellow) of the maxillary sinus (Fig 4).

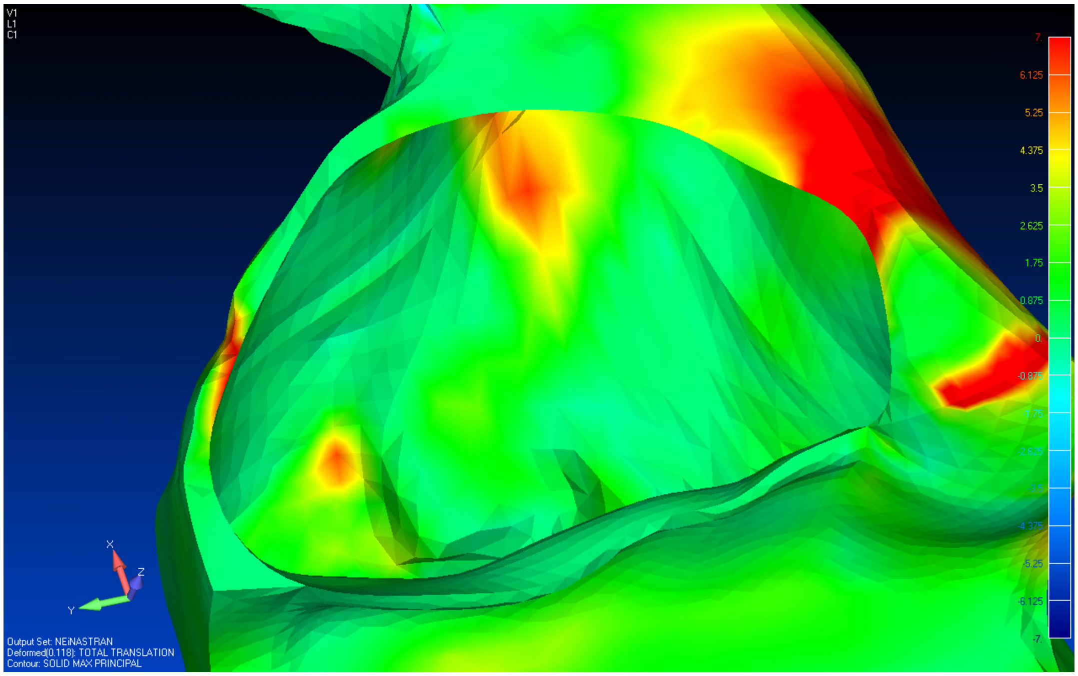

Figure 4. Analysis of the distribution of MPS, after the application of a simple force. Supero-medial view of the maxillary sinus model.

At the inferolateral external view of the maxillary model (Fig. 5), there was an area of zero MPS (near to zero) just below the ZMP. At the posterior region, however, the ZMP shows a MPS concentration camp (red) significantly longer. In the infer lateral margin of the piriform aperture, an area of MPS concentration (yellow) was dissipated by the canine pillar toward the upper orbital rim below, where another part of MPS (red) can be observed. The same image was also observed in the region that would be occupied by the infra-orbital foramen, an area of zero MPS (light green).

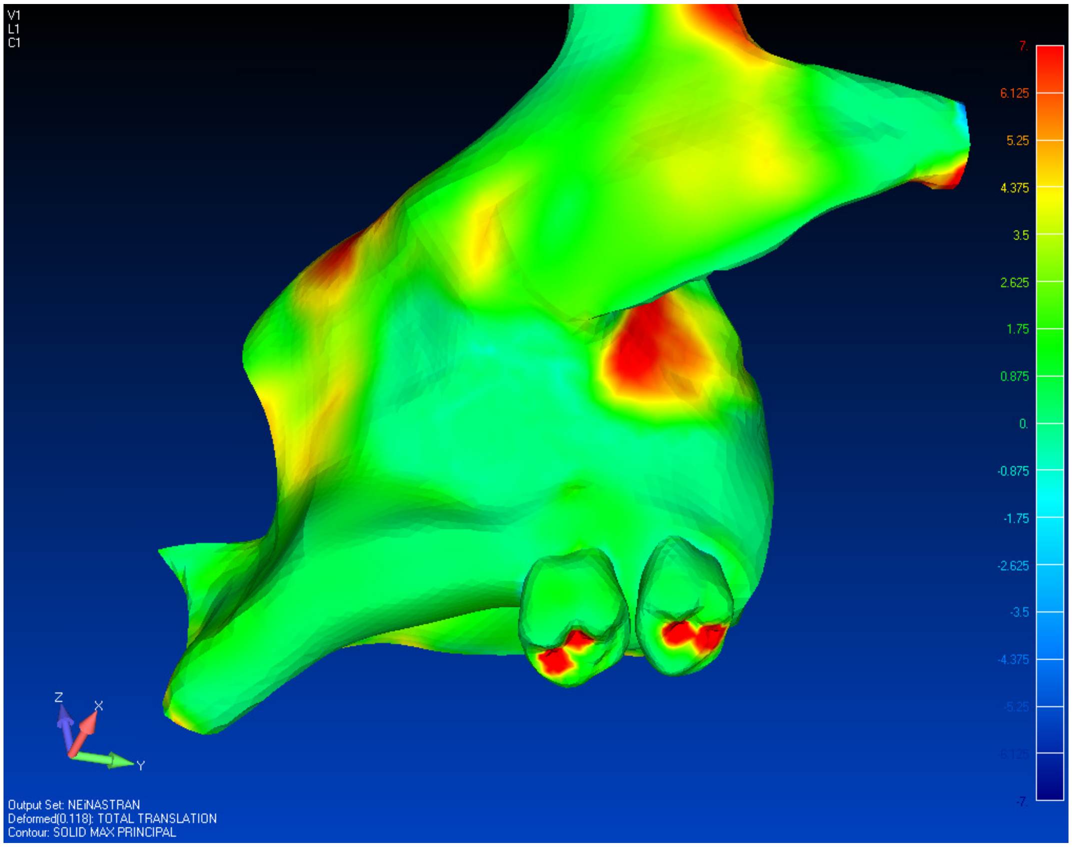

Figure 5. Analysis of the distribution of MPS, after the application of a simple force. Inferolateral view of the model.

Above the first and second upper left molar, mechanical strain has acquired a semicircular shape and dissipated to the anterior (canine pillar) and posterior (maxillary tuberosity) face of the maxillary model (Fig. 5 and 6). Above the semicircle in the transition region between the maxilla and ZMP, there was an area of mechanical tension close to zero, according to the values of MPS.

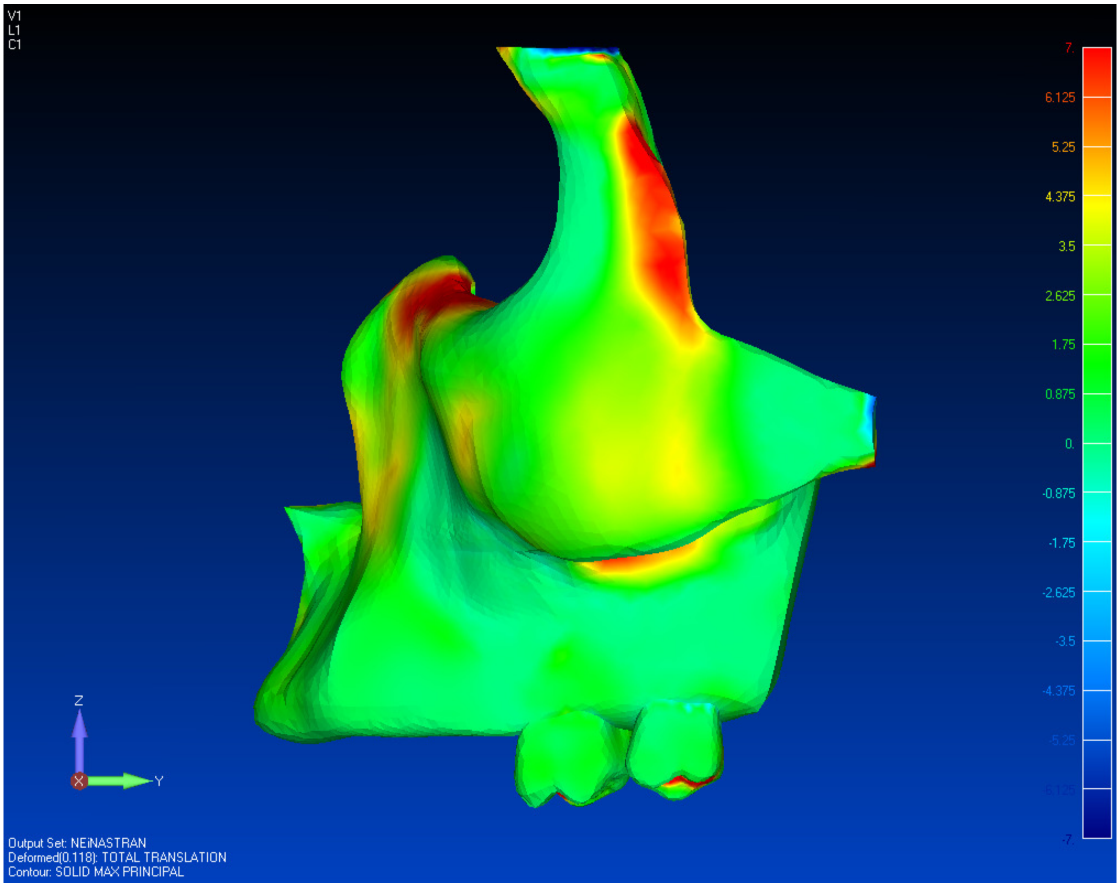

Figure 6. Analysis of the distribution of MPS, after the application of a simple force. Lateral view of the maxillary model, with the zygomatic pillar.

An inferior view of the maxillary model (Fig. 7), show (green and yellow) a tension line MPS dissipated respectively to the anterior and posterior regions of the hard palate from the palatal root of the maxillary left first molar and an area of MPS concentration along the entire region of the sutures.

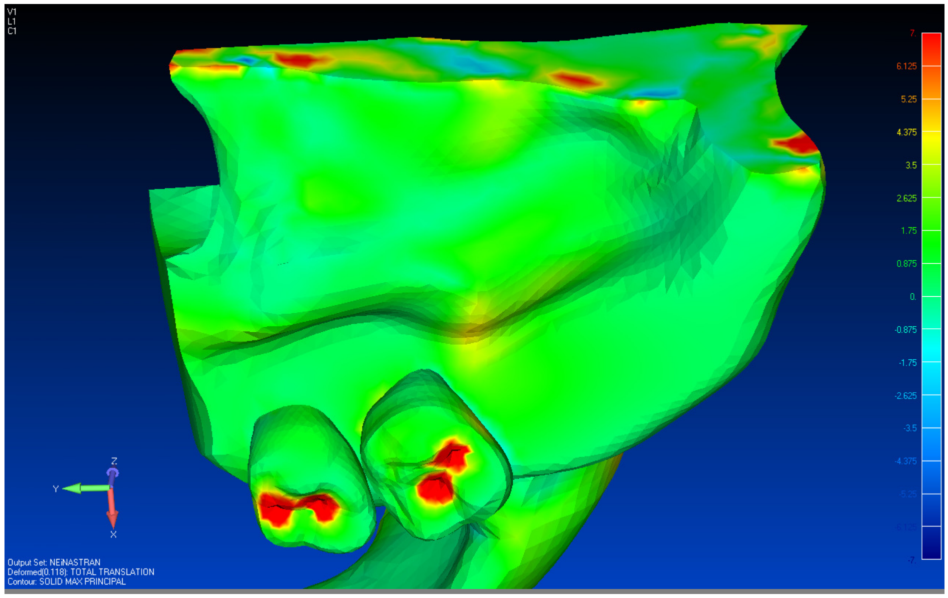

Figure 7. Analysis of the distribution of MPS, after the application of a simple force. Bottom view of the hard palate of the maxillary model.

DISCUSSION

The BioCAD's models used on this study were initially evaluated based on quality of the geometry of study, mainly to the consistency of the areas resulting from the processes of import tools for pre-processing of finite element. Surface inconsistencies undetected can negatively influence on the final quality of the meshes, contacts and the final results.

The generation of finite element meshes in organic three-dimensional complex geometry requires a careful and highly intensive labor. Although the complexity of the geometric structure, it is necessary to obtain satisfactory discretization of the model so that the quality of results not be compromise by the coarse and distorted meshes.

Some researches present limited finite element models on anatomical details because give importance only to interpretation of results, since engineering software used to process its analysis can evaluate rudimentary models. This study used a model built respecting strictly every anatomical details, reference points, structures and contours. On the other hand, in the functional morphology contexts, the creation of experimental models is the most time-dependent phase (Richmond et al. 2005). For this reason the shape of the modeled skull is important to obtain accurate results (Boryor et al. 2010), once fail on this step can produce artificial results.

The results of this study showed a large area (dark green) from the MPS zero, just below the ZMP (Fig. 5 and 6), which characterizes the region of insignificant bone mechanics exigency, so this region does not present significant functional activity in the craniofacial skeleton, contrary to the fundamentals of skull biomechanics that's empathized this lateral masticatory pillar, as one of the most important structures related to the process of masticatory stress distribution (Sicher & Tandler, 1928; Sicher 1965; Caputo & Standlee, 1987; Hilloowala & Kanth 2007). On the other hand, Cattaneo et al. (2003), by means of the Von Misses stress found maximum stress on the ZMP. However, the Von Misses stress highlights the shearing stress, and the region of greatest distortion but bone tissue is not a structure sensitive to shear. Bone is sensitive to tensile stress, which is most suitable parameter for this type of analysis.

First molar is considered the key occlusion and has a favorable natural anatomical functional relationship with the zigomatic maxillary crest and ZMP (Atkinson, 1951). For this reason, we selected a skull who the upper left first molar was located just below the ZMC (Angle, 1907; Helman, 1920) to this aspect not influenced our results. The FEA confirmed that the position of first molar can directly influence the dissipation of mechanical tension to the ZMP (Gross et al. 2001), it can provoke significant impacts for the success or failure of orthodontic treatment in anchorage implants (Benzing et al. 1995; Clelland et al. 1995) and the placement of prosthesis (Kregzde, 1993; Benzing et al. 1995).

During the application of mechanical loading was recorded the emergence of two lines of MPS from the interior of the maxillary sinus floor. The first line toward the ZMP (yellow and red) on the anterolateral surface of the maxillary sinus and other one to the posterolateral wall (yellow) of the maxillary sinus (Fig 4). The sinus wall are areas of lower bone density of the facial skeleton, formed by thin compact substance (Blaney, 1990; Prossinger & Bookstein, 2003), located between the craniofacial pillars (Endo, 1965; Preuschoft et al. 2002), that respond to the biomechanical demands (Blanton & Biggs, 1969; Witmer, 1997), and resist the masticatory efforts counterbalancing the forces of tension and compression to which they are subjected (Schumacher, 1997).

Posteriorly to the ZMP was observed a concentration MPS (red) significantly longer. It, suggest an efficient dissipation of tension to the posterior wall and tuberosity of maxilla. Those characteristics were also obtained by the results of MPS reported by Gross et al. (2001), suggesting that MPS is dissipated into the pterygoid pillar. The pterygoid pillar, is one of the most remarkable pathways of stresses which distributes its abruptly from the upper molars to the skull base (Witzel & Preuschoft. 2004).

In the present study, despite the mechanical loading have been carried out in the upper left molars, there was efficient dissipation of mechanical strain to the anterior wall of maxilla, zygomatic arch and fronto-zygomatic suture. Other authors have show the concentration of mechanical stress during experiments in animals, demonstrating the biomechanical importance of these craniofacial skeleton areas (Hylander & Johnson, 1997; Herring, 2007). The MPS (yellow) in the canine pillar, infra orbital rim (yellow) and inferior-lateral margin of the piriform aperture (yellow) (fig 6 and 7) were previously analyzed by strain gauges (Endo, 1966; 1970) and FEA (Gross et al. 2001) during incisive mastication.

The cancellous bone, periodontal ligament and enamel were not modeled and included in this study. The aim of this research was to describe the transference ofmechanical strain on the ZMP in a wide scale model, according to Cattaneo et al., (2003) this type of model does not receive direct influence of mechanical stress dissipation. "The effect of the periodontal ligament on bone rupture at high forces was assumed negligible as found in pre-experiments, where toothless specimen ruptured in the same region by similar force magnitudes" (Boryor et al. 2010). This information's corroborates with the decision of not modeling the periodontal ligament in this study. On the other hand, the elastic properties of mandibular and maxillary cancellous bone are still unknown, isotropic values determined from other similar tissue material are often used in craniofacial finite element models (Korioth & Versluis, 1997). The accurate structural and behavioral incorporation of all cortical, trabecular, dento-alveolar, and articular components into complete 3D finite element models of the masticatory system with necessarily highly refined meshes is still probably an utopian (Korioth & Versluis, 1997).

Our results do not allow to affirm that the greatest tension areas are under more bone biologically adaptation. But its suggest that those areas reflect structural adaptation to mechanical stresses applied. Bone tissue is highly organized and complex (Carter & Orr, 1992), providing structural strength to the functional demand. Thus, it adapt remarkably well to the functional changes through its plasticity (Humphrey et al, 1999; Vioarsdóttir et al, 2002). Craniofacial skeleton works in synergy with the masticatory muscles, joints, teeth and the mechanical stress is a key element able to increase or decrease bone formation (Van Eijden, 2000). Those aspects are possibly related to the mechanical stress areas, leading this study to related it with dentistry clinical aspects. Computer simulation can predicted this process and can help us to unravel its secrets (Huiskes, 1983).

CONCLUSION

The MPS during simulated maxillary molars loading is not transferred directly through the lateral surface of ZMP, however its focuses on the body of the zygomatic bone and dissipated not directly to the ZMP but for different directions on adjacent structures.

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CAPÍTULO 2*

Title: THE APPLICATION OF FINITE ELEMENT ANALYSIS IN THE SKULL BIOMECHANICS AND ON DENTISTRY

Article Type: Review Paper

Keywords: Finite Element Analysis; Biomechanics; Skull; Dentistry; Teeth; Implant.

Corresponding Author: Felippe Bevilacqua Prado,

First Author: Felippe B Prado, MSc

Order of Authors:
Felippe Bevilacqua Prado, DDS, MSc. – Post Graduate student, Department of Morphology, Anatomy, State University of Campinas.
Ana Cláudia Rossi, DDS, MSc. – Post Graduate student, Department of Morphology, Anatomy, State University of Campinas.
Alexandre Rodrigues Freire, DDS, MSc. – Post Graduate student, Department of Morphology, Anatomy, State University of Campinas.
Paulo Henrique Ferreira Caria, DDS, MSc, PhD. - Associate Professor, Department of Morphology, Anatomy, State University of Campinas.

***Submetido para Indian Journal of Dental Research (Anexo 2)**

ABSTRACT

INTRODUTION: Empirical concepts describe the direction of the masticatory stress dissipation in the skull. The scientific evidence of the trajectories and the magnitude of stress dissipation can help in the diagnosis of the masticatory alterations and the planning of oral rehabilitation in the different areas of the Dentistry. The Finite Element Analysis (FEA) is a tool that may reproduce complex structures with irregular geometries of natural and artificial tissues of the human body, because it uses mathematical functions that enable the understanding of the craniofacial biomechanics. **OBJECTIVES:** The aim of this study was to review the literature on the advantages and limitations of FEA in the skull biomechanics and Dentistry study. **DATA AND SOURCES:** Were selected original research articles with the keywords: finite element analysis, biomechanics, skull, Dentistry, teeth, and implant. The literature review was performed in databases: PUBMED, MEDLINE and SCOPUS. Were selected books and articles between years 1928 and 2010. **CONCLUSION:** The FEA is a assessment tool that the application in different areas of the Dentistry had gradually increase over the past 10 years, but its application in analysis of the skull biomechanics is scarce. The main advantages of the FEA are the realistic mode to approach and the possibility of results being based on analysis of only one model. On the other hand, the main limitation on the FEA studies is the lack of anatomical details in the modeling phase of the craniofacial structures and the lack of information about the material properties.

Keywords: Finite Element Analysis; Biomechanics; Skull; Dentistry; Teeth; Implant.

1. INTRODUCTION

The FEA is a technique that reconstructs and evaluates the stress, strain and deformation of structures. This methodology is a representation of a structure that is readily resolved by mathematical analysis as a series of subdivisions, i.e., a method that reduces a complex geometry into a finite number of elements with simple geometries, with the same properties of the origin model. All finite elements are described by differential equations and solved by mathematical models from which results are obtained.

The success of the applications of FEA depends on the processing power of computers. However, the great challenge of FEA is the difficulty to establish a model that respects, with reliability, the morphological characteristics of the cranial structures. The limited availability of information about the craniofacial tissues properties, as well as of dental materials, is another complicating factor in interpreting results[1, 2, 3, 4, 5.]

Currently, the FEA is used in the medical area to assess the human musculoskeletal system [6, 7, 8], remodeling and ossification fields [9, 10] the skeleton biomechanics [11, 12], the functional morphology and the evolutionary anthropology [13].

In the Dentistry, the FEA has applications in various specialties [14, 15, 16, 17], it allows to assess tooth movement on Orthodontics area [18], the action of orthopedic forces on the craniofacial complex [4], the action of mechanical loads on implants[17] and the creation of models for forensic application [19] .

The aim of this study was to review the literature about the advantages and limitations of FEA in the study of the skull biomechanics and its application in different dental specialties. Were selected original research articles with the keywords: finite element analysis, biomechanics, skull, Dentistry, teeth, and implant. The literature review was performed in databases: PUBMED, MEDLINE and SCOPUS. Were selected books and articles between years 1928 and 2010.This review was divided into five topics: (1) Theories, Concepts and Fundamentals about the skull biomechanics; (2) The different methods used to assess the effects of mechanical loads on the skull; (3) The application of FEA in the skull biomechanics; (4) The use of FEA in the different specialties of Dentistry and (5) The main advantages, limitations and prospects of application of FEA in the skull biomechanics and in Dentistry.

1) Theories, concepts and fundamentals about the biomechanics of skull

The skull is a dynamical structure capable to suffer morphological changes in response to mechanical loads. The relation between functional load and bone morphology was described by Julius Wolff [20] whose law states that the bone are optimized mechanical structures which resists maximum forces with minimum weight, respecting mathematical rules [21] .

Theoretical fundaments of biomechanics explain the skull architecture based on bone pillars in the maxilla and trajectories of stress dissipations in the mandible. However, no scientific evidence of how the occlusal tensions generated by masticatory activities are transferred to alveolar bone and from this to the skull [22].

According to Sicher [22], the masticatory forces are dissipated from alveolar process to the three enhance bone pillars in the maxilla, located at each antimere and bypassed by nasal and orbital cavities. The canine and zigomatic pillars are horizontally connected along the supra and infra orbital edges, which acts as beams that resists the mechanical stresses. The pterygoid pillar is an enhance bone arched toward the skull base and hard palate, connecting the pillar systems on each side of the skull [23]. Following this concept, beyond dental occlusion, the traction of masticatory muscles also generate tension and compression forces which dissipate to mandible by three bone trajectories (marginal, temporal and alveolar) and posterior to the skull, given its bone structural arrangement [22].

Conceptual models are used to describe the trajectories of tension along the skull and its morphology, based in mechanical and architectonical analogies, as well as in the functional bone adaptation [22, 24, 25, 26, 27, 28, 29, 30, 31, 32].

If the Wolff's theory [33, 34, 35] and the concepts of skull biomechanics affirm that the masticatory stress are dissipated along the skull and interfere in its morphology through the bone remodeling, what kinds of experimental analysis would be able to assess these conditions?

(2) The different methods used to assess the effects of mechanical loads on the skull

The process by which the mechanical forces influence the morphology or form and the craniofacial geometry are known as mechanical adaptation. Many classic experiments have shown the bone remodeling in response to mechanical functional loads [36, 37, 38]. Different methodologies are used to evaluate the effects of the mechanical functional loads on the teeth and craniofacial structures [14, 39, 40, 41, 42] among which are highlighted the conventional methods, photoelastic models, holographic lasers, mathematical analytical models, experimental analysis in human and animals and FEA.

The difficulty to reproducing *in vitro* models similar to craniofacial structures is due the diversity of elements that compose them, and specially the anatomical irregularity of its shapes. Further these limitations, the necessity of sophisticated laboratories, equipments and instruments, become indispensable and difficult for analysis, generating doubts on the efficiency of some conventional methods [41, 43].

The photoelastic models provide widely [43], but not quantified illustrations of main tension concentration along the skull with a single elasticity modulus [44, 45]. However, these models are limited by simplifying of assumptions, since consider only two dimensional plain and reproducing idealized and unreal geometrical shapes, not analyzing the directional changes of mechanical tension [41]. In affirmation, the photoelastic methods are complex and the numerical results found could be more easily obtained by other methods [46].

The holographic laser should not be used for biomechanical purpose due to not consider all characteristics of materials, such as its nonlinearity, an aspect found in the live tissue. Other limiting is how the structure is simulated in this technique, which not allows the creation of materials with same responses of the natural structures and not allows variations in the geometrical shapes used [41]. The holographic laser requires complex equipments, which complicates their execution [16, 47, 48].

Mathematical analysis may represent *in vivo* situations, and express, through of mathematical equations compatible to real, the form, contour and function of model [49], however, the results obtained disrespect the aspects as width or area of the structure analyzed, simplifying and compromising the intended evaluation.

The experimental techniques in human/animals are limited by difficult access to parts of the skull, through the use of devices and eventually invasive analysis [50]. As for animal models, the limitations are in the capability for reproduction of same morpho-functional characteristics of humans, further of ethical aspects for the use of animals in experiments which use complex force systems [50].

Despite the advantages and disadvantages mentioned, the methodologies described above present limitations when applied for biomechanical as they are not effective to describe how mechanical masticatory forces act on the craniofacial skeleton.

(3) The application of FEA in the skull biomechanics

The FEA of skull made possible to obtain information on displacement, the degree of tension caused during chewing [41, 50, 51, 52] and the distribution of mechanical forces on craniofacial structures.

In recent years, few studies were developed about computer models of human craniofacial skeleton reproducing in detail the anatomical structures to study the dissipation of mechanical stresses during functional masticatory activity on the FEA [53, 54]. The FEA is being employed in various forms, in microscopic level [55, 56] aiming to characterize the mechanosensation and the mechanic transduction in cancellous and cortical bone (Beaupr´e et al. 1990), searches that have significantly improved the understanding of the fundamentals factors that control the morphology and bone remodeling [57].

Other uses of FEA is to evaluate the relationship between form and function in the musculoskeletal system of extinct species and test the theory that deals of the influence of the action of hard and soft tissues on mechanical function as a determinant of the viability of the structure and ontogeny [33, 34, 35, 58, 59, 60, 61, 62, 63, 64, 65].

The efficiency of the skeleton to perform specific mechanical functions and the understanding of whither which the shape is an adaptation to the mechanical action or is associated with the space requirements of non-skeletal factors, such as sexual dimorphism, dentition, facial orientation and phylogenetic constraints can be evaluated by FEA. Similarly it is possible to evaluate the adaptation of skeletal structures during evolution by comparative analysis between species of the same lineage to help understand why some features of the skeleton were kept and others disappeared during the evolution [13, 35]. It can be affirm that FEA is a promising tool able to promote understanding of the relationship between form, function and evolution of vertebrates and extinct species.

Considering the FEA as a tool able to evaluate the action of mechanical forces on the skull, as it is possible to apply this information to the various dental specialties?

(4) The FEA in the different specialties of Dentistry

Over the past 20 years, scientific articles have emphasized that knowledge of the process of dissipation of occlusal forces on the craniofacial skeleton can assist in the diagnosis of masticatory functional alterations in planning oral rehabilitation, as well as in the understanding of mechanisms involved in the dissipation of tension by teeth, implants and on the alveolar bone remodeling [66, 67].

The mechanical behaviors of the maxilomandibular complex and support structures are important information for the achievement of restorative treatments, rehabilitation, surgical and forensic procedures [5]. It's would consider and characterize the masticatory effort and the distribution of stress in different craniofacial structures, and the FEA can help carry out those tasks [2, 52, 68, 69, 70].

Two-dimensional models were used to assess patterns of mechanical stress in teeth healthy, restored and in alveolar bone support and others oral structures [71].

The FEA are useful for different areas of Dentistry, because allow to assess the mechanical behavior and the distribution of stress in dental elements, periodontal ligament and alveolar bone by applying force [15, 16, 68], simulating clinical conditions that could hardly be evaluated by other methodologies.

The Implantology, Dentistry, Prosthesis, Orthodontics, Oral and Maxillofacial Surgery and Forensic Dentistry are influenced by laws of skull biomechanics, because the mechanical masticatory forces muscles and dental that act on soft and hard tissues also act directly on dental materials such as resins, porcelain, metal and others such as prosthetics, implants and braces.

(4.1) Restorative Dentistry

In Restorative Dentistry, the FEA has been applied to assess patterns of mechanical stress in bonded restorations, retention pin [72], etiologies of abfraction, to investigate the stress distribution in the different systems of dental reconstruction or verify the fracture resistance of fixed prostheses [46].

The evaluation of the biomechanical behavior and dissipation of tension in the teeth in different restorative techniques with various restorative materials such as ceramic and gold, composite resins, combined polyethylene fibers, glass fibers or others materials can be performed with the FEA. Simulate clinical conditions similar to the oral cavity, such as alteration in the dental structure, inclination of cusps or compare the tensile strength of endodontically treated teeth or not, finally, the FEA provides a series of analysis [72, 73]. The mentioned analysis may favor the clinical treatments of restoration and rehabilitation.

(4.2) Orthodontics

The FEA has become useful in orthodontic research by presenting accurate results and that allow the simulation of orthodontic treatment and its effects unlikely to be clinically evaluated [74, 75].

The FEA allows evaluating the effect of orthodontic movement on the periodontal ligament and alveolar bone through the simulation of different types of stress [76], repeatedly and comparative, which would hardly be reproduced experimentally with the same accuracy *in vivo*. The relative facility of modeling complex geometric structures of biological tissues of different properties, and the ability of program to allow simulation of various magnitudes of force in different points of application are the advantages of this method [14].

The FEA generates information about the behavior of craniofacial tissues, including sutures, orthopedic action forces generated by extra or intraoral appliances, alterations in size, shape and position of facial structures after orthodontic treatment [77,78, 79].

Furthermore, it is possible to evaluate the resistance of orthodontic brackets simulating the displacements during the application of shear and torsional strength as well as the causes of success or failure of treatments [80]. The FEA has been used successfully in orthodontic to assisting the planning and results.

(4.3) Implantology

The Implantology is one of the specialties of Dentistry with more benefit the FEA, due to this method allows to evaluate the concentration and distribution of masticatory stress on the implant and adjacent bone tissue [81].

It is also possible to understand the events related to the osseointegration of implants, since the FEA allows to assess the biomechanical behavior of implants simulating clinica0l conditions that other analysis do not provide [82].

The development of computers allowed reproduction of biological structures in more detail. Another advantage to using this tool is to understand the actions of mechanical stresses along the surfaces of an implant and surrounding bone, favoring determining the design of the implant and its anchorage in the bone. The FEA also makes possible the manufacture of prostheses to minimize the mechanical stress [83].

The integration of dental implants in the maxilla is dependent on the resistance and dissipation of forces on the implant and the alveolar bone, the FEA allows defining these elements avoiding mechanisms that cause failures in clinical performance of implants [83].

(4.4) Periodontics

There is controversy whether the mechanical loads are absorbed and distributed throughout the periodontal ligament during mastication and occlusal contact affecting its integrity. Understanding the biomechanical behavior of the periodontal ligament under functional and non-functional loads is possible by means of FEA. Combining FEA with experimental research will facilitate the understanding of biological reactions of the periodontal ligament, the factors that affect the integrity of the periodontal structures and the causes of destruction of its fibers and cells, and alveolar bone resorption under mechanical influences [84].

(4.5) Oral and Maxillofacial Surgery

Simulate different types of surgical treatments for craniofacial injuries and anomalies, calculate and analyze the stability of fixation on maxillofacial fractures [74], evaluate the stability of the osteotomies, discover and predict the performance and efficiency of materials used for surgical fixation as the influence of masticatory activity [75], check the biomechanical behavior of bone tissue during mechanical compressions [75] are possible by means of FEA.

With the development of FEA, the craniofacial anatomical structures of each individual may be evaluated biomechanically to predict changes of soft tissues after craniofacial surgery, since the aesthetic is a fundamental aspect to be considered in maxillofacial surgery [85].

(4.6) Forensic Dentistry

The FEA is a tool that allows assessing the consequences of head impacts such as ballistic studies or other artifacts [19]. This method favors the forensic investigations, because it allows determining the effect of head injuries. It also enables to gauge the extent of an impact and report on the intensity of mechanical forces that acted on the skull showing the causes of the impact according to the distribution of mechanical stress [86].

The FEA develops according to the processing power of computers and software, but it is able to assist in practice and routine forensic [19]. However, knowledge of geometry and anatomy of the head during the modeling is essential to perform this type of analysis and to obtain precise information from the mechanical stresses of materials [86].

(5) The advantages, limitations and prospects of application of FEM in the skull biomechanics and Dentistry

The major difficulty in construction of craniofacial models for tridimensional finite element analysis is the anatomical complexity of these structures, as face sinus, variations in the alveolar topography and bone thickness [87].

Since 1977, finite element models of complex regions of craniofacial skeleton, as two-dimensional (2D) [71, 88, 89] as three-dimensional (3D) [2, 3, 70, 90, 91, 92, 93] were developed and applied in specific areas of Dentistry, without reproduction of anatomy of the skull with fidelity, specially the maxilla [92]. Some models are designed in an idealized way [90].

3D Models developed to assess the effects of orthopedic maxillary forces on the craniofacial complex may verify through FEA the different patterns of dissipation of tension, however lack of anatomical details, and presents as limiting factor the limited number of elements and nodes which the model was built [92] .

Other studies that described the tension distribution of occlusal forces on the teeth and implants show the importance of characteristics of support structures, position, size of implants for longevity and stability and the necessity of evaluate the response of the human bone on the mechanical tensions [90].

Importantly, the research employing the FEA results of a 3D analysis provide more accurate information of analysis than performed in 2D, since a 3D model allows a more comprehensive spatial evaluation [93].

Models developed to assess the concentration and the dissipation of tension around implants, using several clinical parameters such as implant-bone interface, the elastic properties of bone, the presence of the lamina dura, and shown to be sensitive to these parameters, but there are limitations on how reproducibility of the anatomical structures modeled, where the bone was modeled as a simplified rectangular configuration [81, 94].

The FEA is a realistic method to approach and the results are often based on analysis of only one model where there is not a natural variation. The reliability of analysis with the model is data dependent on the model incorporated the details of the geometric representation, and also the availability of data and materials on the reality of the load [13].

A major challenge with regard to modeling is the limited availability of data from dental materials, since there are few physical data and patterns for them, as their elastic modulus and strength. The lack of pattern is a complicating factor in interpreting the results of the analysis and conclusions related [13] requiring further study to determine patterns that may be used in all searches that use this tool.

Despite the simplification of parameters of material properties, method of verification, boundary conditions, and especially the geometry of the structures, these parameters are necessary to achieve confident results using 3D FEA [1, 2, 3, 77]. Therefore, the validity of this method and the necessity to define the effects of these parameters has been questioned by most researchers [56], mainly with the progress in computer technology, and this increase in dentistry and health area that ignore fundamental concepts of engineering.

The exact incorporation of the structure and behavior of all cortical bone, trabecular bone, dentoalveolar surface, articular components in 3D models of the masticatory system with highly refined meshes is still one of the solutions to the research in FEA [70]. In this case, detailed models are more useful for the investigation of the mechanical behavior as the specific conditions of a given region of interest is reproduced with accuracy and detail [13]. The ideal analysis through the FEA includes systematic changes in geometry, material properties, boundary conditions, and attention if some variables were changed [70].

The nonlinear FEA have gained space as they are able to simulate conditions of tension in the orofacial structures in more realistic than could be accomplished by conventional linear analysis. However its validity and reliability in dental research are not fully established [95].

With the continuous use of FEA in dental research and skull biomechanics, and the clarification of the advantages and limitations compared to other available methods, the knowledge of this methodology becomes important for its correct use provides benefits for dental and scientific craniofacial biology as a whole, due to researchers and clinicians will not only learn the basics of FEA, but to interpret accurately the results of the studies.

CONCLUSIONS

The use of FEA for evaluation in biomechanics of the skull is low, however, would be the solutions for this kind of study.

In Dentistry, FEA have applications in several specialties, it allows a series of evaluations to simulate conditions that would hardly be possible to be analyzed clinically or by other methodologies. Within Dentistry, Prosthesis, Implantology and Orthodontics are the areas that most used technique for FEA analysis.

The main limitations of studies by the FEA are the deficiency of anatomical details on the models reproduced, due the complexity of certain craniofacial structures and the lack of information on the properties of materials due to the necessity of expanding the use of this tool.

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CONCLUSÕES GERAIS

· Por meio das Análises de Elemento Finito foi possível avaliar a dissipação da tensão mecanica pelos ossos do esqueleto cranifacial e demonstrar que a tensão mecânica gerada pela oclusão molar não é transferida diretamente para a região do pilar zigomático, mas sim em direção a outras estruturas adjacentes.

. A principal limitação das Análises de Elementos Finitos está na qualidade dos modelos estruturais empregados para a analise.

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Dear Co-author,

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We thank you for submitting your valuable work to the Indian Journal of Dental Research.

Yours sincerely,
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Indian Journal of Dental Research

COMITÊ DE ÉTICA EM PESQUISA
FACULDADE DE ODONTOLOGIA DE PIRACICABA
UNIVERSIDADE ESTADUAL DE CAMPINAS

CERTIFICADO

O Comitê de Ética em Pesquisa da FOP-UNICAMP certifica que o projeto de pesquisa **"Avaliação dos padrões de dissipação de tensão mecânica na região do primeiro molar superior e estrutura de suporte maxilo-zigomático (pilar zigomático) por meio do método dos elementos finitos tridimensionais (MEF)"**, protocolo nº 175/2009, dos pesquisadores Felippe Bevilacqua Prado e Paulo Henrique Ferreira Caria, satisfaz as exigências do Conselho Nacional de Saúde - Ministério da Saúde para as pesquisas em seres humanos e foi aprovado por este comitê em 11/01/2010.

The Ethics Committee in Research of the School of Dentistry of Piracicaba - State University of Campinas, certify that the project **"Evaluation of the tensile force dissipation on superior first molar and zigomatic-maxillar support structure (zigomatic pillar) by three-dimensional finite element analysis (FEA)"**, register number 175/2009, of Felippe Bevilacqua Prado and Paulo Henrique Ferreira Caria, comply with the recommendations of the National Health Council - Ministry of Health of Brazil for research in human subjects and therefore was approved by this committee at 01/11/2010.

Prof. Dr. Pablo Agustin Vargas
Secretário
CEP/FOP/UNICAMP

Prof. Dr. Jacks Jorge Junior
Coordenador
CEP/FOP/UNICAMP

Nota: O título do protocolo aparece como fornecido pelos pesquisadores, sem qualquer edição.
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