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LEONARDO SORIANO DE MELLO SANTOS

"MECHANICAL EVALUATION OF TRAUMA IN HUMAN EDENTULOUS MANDIBLE"

"AVALIAÇÃO MECÂNICA DE TRAUMAS EM MANDÍBULA HUMANA DESDENTADA"

PIRACICABA

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Orientador: Prof. Dr. Felippe Bevilacqua Prado

"AVALIAÇÃO MECÂNICA DE TRAUMAS EM MANDÍBULA HUMANA DESDENTADA"

Tese apresentada à Faculdade de Odontologia de Piracicaba da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de doutor em Biologia Buco-Dental, na área de Anatomia.

Thesis presents to the Piracicaba Dental School of the University of Campinas in partial fulfillment of the requirements for the degree in Dental Biology, in Anatomy area.

Este exemplar corresponde à versão final da tese defendida por Leonardo Soriano de Mello Santos e orientada pelo professor Dr Felippe Bevilacqua Prado.

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RESUMO

O objetivo deste estudo foi analisar a distribuição de tensões de cargas aplicadas em sínfise de mandíbula desdentada humana de idoso por meios de análise fotoelástica e de elementos finitos. Foram analisadas correlações entre as cargas aplicadas e as tensões registradas. Os testes de carga em resina fotoelástica foram realizados em uma máquina acoplada a um polariscópio e uma câmera digital. Cargas perpendiculares foram aplicadas em sínfise. Cargas variaram de 50 a 723 Newtons. Uma tomografia computadorizada foi realizada para gerar um modelo digital da mandíbula macerada. Os modelos computadorizados para a análise de elementos finitos (AEF) foram caracterizados de acordo com as propriedades mecânicas da resina epóxi e do osso. As áreas 1, 2, 3 e 4 exibiram franjas isocromáticas de ordem 2 em cargas 150 a 300N, e franjas de ordem 3 em cargas de 350 a 700N. Os stresses de von Mises se distribuíram similarmente em ambos os modelos caracterizados como resina epóxi e osso. Houve uma excelente ($rP > 0.9$) e significante ($p < 0.05$) correlação entre as cargas aplicadas e as respostas obtidas em todas as áreas apesar de algumas delas como as 9 e 10 no corpo mandibular que demonstraram correlações muito boa ($rP > 0.7$) e significante ($p < 0.05$) respectivamente.

Palavras-chave: mandíbula; trauma; análise de elementos finitos; idoso.

ABSTRACT

The aim of this study was to analyze the distribution of stresses from loads applied on symphysis in human elderly edentulous mandible by photoelastic analysis and FEA. Correlations between the applied load and stress tension at each evaluated area were evaluated. Load tests on the photoelastic resin model of edentulous macerated hemimandible were performed in a testing machine equipped with polariscope and a digital camera. Perpendicular loads were applied on symphysis area. Loads ranged from 50 to 723 N. CT was performed on the same mandible used to generate the photoelastic resin model. Computational models to the FEA were characterized according to the mechanical properties of epoxy resin and bone. 1, 2, 3 and 4 areas showed fringes order 2 in loads of 150 to 300N, and fringes order 3 in loads of 350 to 700N. von Mises stress were distributed similarly in both characterized models, epoxy resin and bone. There was an excellent ($r_P > 0.9$) and significant ($p < 0.05$) correlation between the loads applied and the responses obtained in all areas, regardless of the area considered but areas 9 and 10 for the mandibular body, which showed very good ($r_P > 0.7$) and significant ($p < 0.05$)correlation.

Keywords: mandible; trauma; finite element analysis; aged

SUMARIO

DEDICATÓRIA

Dedico este trabalho à minha esposa Isis pelo amor, força, carinho e compreensão durante minha caminhada.

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"Benditos os que conseguem se deixar em paz ... Os que não se cobram por não terem cumprido suas resoluções ... que não se culpam por terem falhado ... não se torturam por terem sido contraditórios ... não se punem por não terem sido "PERFEITOS"... Apenas fazem o melhor que podem"

Martha Medeiros

INTRODUÇÃO

Com os avanços na medicina e na expectativa de vida prolongada, a proporção de pessoas idosas continuará a aumentar. Em muitos países em desenvolvimento ocorrerá o aumento de até 300% da população idosa em 2025 e em 2050, haverá aproximadamente dois bilhões de pessoas com idade superior a 60 anos. Esse crescimento da população representa enormes desafios nos cuidados com este envelhecimento populacional (WHO, 2008).

Para a Organização Mundial de Saúde, os idosos são um grupo de indivíduos com mais de 65 anos de vida (WHO, 2008). Em 1981 havia seis indivíduos idosos para cada grupo de 12 crianças com até a idade de 5 anos no Brasil. Em 2004, havia seis indivíduos idosos para cada grupo de cinco crianças com até a idade de 5 anos. O número de pessoas com idade acima de 60 anos aumentou de 6,07 % em 1980 para 9,49% em 2008 (IBGE, 2008). Além do aumento no tempo médio de vida, a expectativa de vida no Brasil passou de 66,57 anos em 1990 para 72,48 anos em 2007. Com as melhorarias na qualidade de vida, os idosos se tornaram mais ativos fisicamente, e portanto, mais susceptíveis ao risco de lesão (IBGE, 2008).

Nos últimos anos aumentou a incidência de trauma maxilo-facial em idosos, consequentemente, o trauma apareceu como a quinta causa de morte mais comum em pessoas como mais de 65 anos de idade (Schwab & Kauder, 1992). Diferentes estudos mostraram as frequências dos pacientes com trauma maxilo-faciais de 4,81% (Marciani, 1999), 6,16% (Kloss et al., 2007) e 9,9% (Gerbino et al., 1999). Com essa progressiva exposição dos idosos aos agentes agressores da vida moderna, mais eles se tornaram alvos de traumatismos bucomaxilofaciais, aumentando a necessidade de cuidados diferenciados e mais complexos (Marciani, 1999).

Existem diferenças substanciais na resposta ao trauma entre o idoso e o jovem. Comprometimento das vias aéreas, redução da complacência pulmonar, alteração na homeostase cardiovascular, prevalência de doença pré-existente, tudo contribui para o aumento da morbidade e mortalidade em pacientes com reservas fisiológicos já limitados. Mesmo que os princípios do tratamento de fraturas sejam praticamente os mesmos, fatores especiais como a atrofia óssea, diminuição da capacidade de reparação tecidual, e condições patológicas frequentemente encontrados nos idosos, influenciam o tratamento no idoso (Gerbino et al., 1999).

O individuo idoso apresenta, na maioria das vezes, mandíbula desdentada, logo um trauma de força mínima pode resultar uma fratura. Muitas vezes, o corpo da mandíbula pode estar reduzido à metade de sua altura, deixando regiões, como os colos dos côndilos mandibulares extremamente frágeis (Marciani, 1999; Scolozzi & Richter, 2003).

Essas mudanças na morfologia das mandíbulas desdentadas estão diretamente relacionadas às alterações funcionais ósseas (Merrot et al., 2005), consequentemente as funções mecânicas de arquitetura óssea e as respostas celulares envolvidas necessitam cada vez mais serem compreendidas (Lanyon & Rubin, 1985).

Devido às propriedades estruturais ósseas as fraturas mandibulares podem ser divididas em dois grupos principais de acordo à etiologia como fraturas patológicas ou traumáticas. Tumores, osteoporose e doenças afetam a estrutura óssea direta/ indiretamente são as causas das fraturas patológicas. Entretanto, as mais frequentes causas de fraturas mandibulares são traumas relacionados a acidentes de trânsito, quedas, violência interpessoal, e atividades esportivas (Goldschmidt et al., 2005).

Apesar de a mandíbula ser o osso mais pesado e mais forte do crânio, as áreas mandibulares como o côndilo, parassínfise e sínfise da mandíbula, são geralmente os locais mais frequentemente acometido nas fraturas da mandíbula. A parassínfise, corpo, côndilo e a sínfise da mandíbula são os locais mais frequentemente afetados em fraturas da mandíbula decorrentes de traumas mandibulares em individuais com idade acima de 50 anos (Goldschmidt et al., 1995).

Gallas Torreira e Fernàndes (2004) realizaram estudo em modelo tridimensional de mandíbula simulando duas situações de trauma mandibulares. Na região de sínfise da mandíbula, foi aplicada pressão de 107 N/m^2 sagital e perpendicular ao plano sagital mediano durante 1 segundo, onde constataram tensão máxima em sínfise (onde o impacto foi produzido) e na região retromolar em ambos os côndilos. Neste estudo, a mesma força de impacto foi simulada no corpo mandibular postero-anteriormente, direcionado para cima e perpendicular ao plano transversal, resultando em zonas de máxima tensão no côndilo e no corpo mandibular ao lado ipsilateral ao qual a energia foi inserida (lado direito). Os autores concluíram que, nestas duas situações de trauma, duas áreas se destacam como potenciais zonas de fragilidade: colo da mandíbula e ângulo mandibular devido à espessura da cortical óssea nestes locais.

Bujtár et al (2010) realizaram análise comparativa de três mandíbulas de faixas etárias diferentes pelo Método de Elementos Finitos (MEF) e demonstraram valores mais altos de flexibilidade para a mandíbula mais jovem no sentido de deformação máxima e absolutos em termos de deslocamento. As forças de reação às tensões se tornam máximas com o envelhecimento, com picos de tensão e deslocamento significativamente inferiores no paciente idoso, denotando maior rigidez com a idade.

O uso de ossos para testes mecânicos têm várias limitações: é impossível de se obter o mesmo tamanho em amostras, visto que para cada amostra haveriam variações de tamanho; a obtenção de ossadas é mais oneroso devido ao suprimento limitado; o uso de ossos de animais significa ter que extrapolar os resultados para seres humanos; há sempre risco biológico aos pesquisadores, mesmo com todos os cuidados em biossegurança; variações nas propriedades materiais dos ossos, que necessitam ser utilizados ainda frescos, visto que a preservação pode alterar suas propriedades, e; testes de fadiga em geral são demorados, estando os ossos sujeitos à desidratação, o que culmina por alterar suas propriedades (Wong et al, 2011). O MEF é uma técnica numérica utilizada em engenharia que nos últimos anos vêm tomando seu espaço dentro da área da saúde. Nesse contexto ele proporciona a resolução de um sistema de multiplicidade de forças que atuam sobre o sistema mandibular, enquanto leva em consideração o formato mandibular e as propriedades deformacionais dos vários componentes estruturais (Huiskes & Chao, 1983)

Uma vez que as fraturas mandibulares em pacientes idosos são pouco estudadas e compreendidas mesmo com o aumento da longevidade e a maior exposição de pacientes na terceira idade aos riscos de traumas, o presente estudo permitirá compreender o comportamento das energias nas fraturas em mandíbulas de idosos desdentados por meio do método dos elementos finitos. Diante destas considerações, o objetivo geral deste estudo foi avaliar a distribuição de tensões em mandíbula humana desdentada a partir de cargas aplicadas em regiões mais comuns de traumas.

CAPÍTULO 1*

PHOTOELASTIC AND FINITE ELEMENT ANALYSES OF STRESS IN HUMAN ELDERLY EDENTULOUS MANDIBLE UNDER SYMPHYSIS LOADS

Autores: Santos LSM, Freire AR, Correr-Sobrinho L, Caria PHF, Groppo FC, Prado FB.

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ABSTRACT

The aim of this study was to analyze the distribution of stresses from loads applied on symphysis in human elderly edentulous mandible by photoelastic analysis and FEA. Correlations between the applied load and stress tension at each evaluated area were evaluated. Load tests on the photoelastic resin model of edentulous macerated hemimandible were performed in an testing machine equipped with polariscope and a digital camera. Perpendicular loads were applied on symphysis area. Loads ranged from 50 to 723 N. CT was performed on the same mandible used to generate the photoelastic resin model. Computational models to the FEA were characterized according to the mechanical properties of epoxy resin and bone. 1, 2, 3 and 4 areas showed fringes order 2 in loads of 150 to 300N, and fringes order 3 in loads of 350 to 700N. von Mises stress were distributed similarly in both characterized models, epoxy resin and bone. There was an excellent (rP> 0.9) and significant ($p < 0.05$) correlation between the loads applied and the responses obtained in all areas, regardless of the area considered but areas 9 and 10 for the mandibular body, which showed very good (rP> 0.7) and significant ($p <0.05$)correlation.
Keywords: mandible; trauma; finite element analysis; aged.

INTRODUCTION

Mandibular fractures are one of the most common facial injuries[1]. The most mandibular fractured areas are mandibular neck, symphysis, mandibular body and mandibular angle, respectively. Despite the differences in etiology, these fractures are basically caused by vehicular accidents, injuries, robbery, falls, sports and work accidents[2].

Epidemiological surveys on causes and incidence of maxillofacial fractures may vary according to geographic region, socioeconomic status, culture[3] and age[4, 5].

Bujtár et al.[6] performed a finite element analysis (FEA) and demonstrated different distribution of stress in human mandibles in three different stages of life. These authors observed the highest stress on the mandibular neck in an older edentulous mandible (67 years), probably due to the bone stiffness in that area.

Mandibular fractures in elderly are not fully studied and understood. Due to longevity, elderly patients are exposed to trauma, being the general trauma the 5th major cause of death in this age[7]. Elderly people present a unique and complex physiologically of aging process, especially considering bone.

Finite element model could be a valuable method to understand the biomechanics of human head injuries. Stress analysis in elderly human edentulous mandible could be useful to understand the biomechanics of the different fractures and to help surgical planning, providing less traumatic and invasive procedures[5]. Schwartz-Dabney & Dechow[8] stated that stress distribution can be demonstrated through different methods, especially photoelastic and FEA.

The aim of this study was to analyze the distribution of stresses from loads applied on symphysis in human elderly edentulous mandible by photoelastic analysis and FEA. In addition, possible correlations between the applied load and stress tension at each evaluated area were evaluated.

MATERIALS AND METHODS

This study was approved by the Committee for Ethics of Research of the State University of Campinas (Protocol: 134/2012) (ANEXO 2).

Photoelastic analysis

A photoelastic resin model (Araldite epoxy resin - Araltec Chemicals Products Ltda - Hunstman) of edentulous macerated hemimandible was obtained by replication of natural 65 years-old hemimandible.

Load tests on the model were performed in an Instron Model 4411 (Instron Corp, Norwood, MA) universal testing machine equipped with polariscope (white light source and polarizing filter) and a digital camera (Sony Model Handy cam DCR-SR300 6.1 MP - Sony Corporation, Japan). The model was placed in a support set by the equipment load testing.

For the load test, perpendicular loads were applied on symphysis area. Loads ranged from 50 to 723 Newtons (N), in 50N intervals. The model fractured under 723 N load.

To evaluate the stress generated on the medial face of edentulous hemimandible, images showing isochromatic fringes of each load application were obtained using a digital camera with an optical filter lens. During each loading sequence isochromatic fringes in resin were observed and photographed. White light polarized optical effects manifested as colored fringes, which have a fringe order according to the load intensity. Fringe order is related to the level of stresses in the model[9].

Qualitative analysis of the fringes was performed as previously described by Cehreli et al.[10]. The number and order of the fringes indicate stress intensity whereas the proximity between them represents stress concentration that is observed through the isochromatic fringes. Each fringe order was counted by the transition of colors (Figure 1) according to the following order:

- fringe of order = 0 (transition white/black)
- fringe of order = 1 (transition red/blue)
- fringe of order = 2 (transition red/green)
- fringe of order = 3 (transition pink/green)

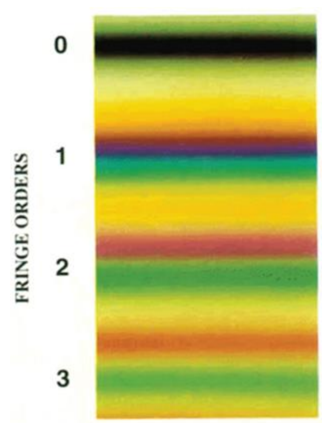

Figure 1. Isocromatic fringes order (Ozkir & Terzioglu, 2012).

FEA

Computerized tomography (CT) (GE HiSpeed NX / iCT scanner - General Electric, Denver, CO, USA) was performed on the same mandible used to generate the photoelastic resin model. CT slices had 0.25 mm of thickness to increase the accuracy in geometry.

Bone structure was selected according to the color of pixels using threshold values in HU (Hounsfield Units) in the InVesalius 3.0b software (Center for Information Technology "Renato Archer", São Paulo, Brazil).

Hemimandible structure was converted into three-dimensional models (3D) with stereolithographic format (STL), which were the basis for modeling the geometry CAD (Computer-Aided Design) for FEA[11], by using Rhinoceros 5.0software (McNeel& Assoc., USA).

FEA was performed in the Ansys v14 (Ansys Inc.)software. The geometry (CAD model) edentulous hemimandible was imported in the Ansys v14software in order to construct the finite element mesh in which the split occurred on the solids surface. The finite element mesh presented 528,010 tetrahedral elements and 759,787 nodes.

The models were characterized according to the mechanical properties of epoxy resin and bone (Table 1), both as isotropic and linear elastic structures.

Table 1. Mechanical properties of the anatomical structures.

Material	Young'sModulus (MPa)	Poisson'sratio
Epoxy resin*	3102,6	0,30
Bone[12]	14000	0,30

(*Araltec Chemicals Products Ltda- Hunstman®).

Mechanical properties of the epoxy resin were considered in order to reproduce the analogue situation of the mechanical testing in the computer simulation. We could assess the reliability of the analysis settings (boundary conditions and loading) in the computational simulation related to the experimental analysis[12, 13].

Restrictions were applied in the posterior region of the condyle and posterior border of the mandibular ramus preventing free movements in x, y and z axes during simulation, as occurs due to the presence of masticatory muscles, to avoid high displacements at its regions of insertion. Perpendicular loads were applied on symphysis. Similarly to photoelastic analysis, the loads ranged 50 to 723N in intervals of 50N.

Stress analyses

For both FEA and photoelastic analyses the medial face of hemimandible was divided into 10 areas. These areas were determined according Schwartz-Dabney & Dechow[8] method and numbered as shown in Figure 2.

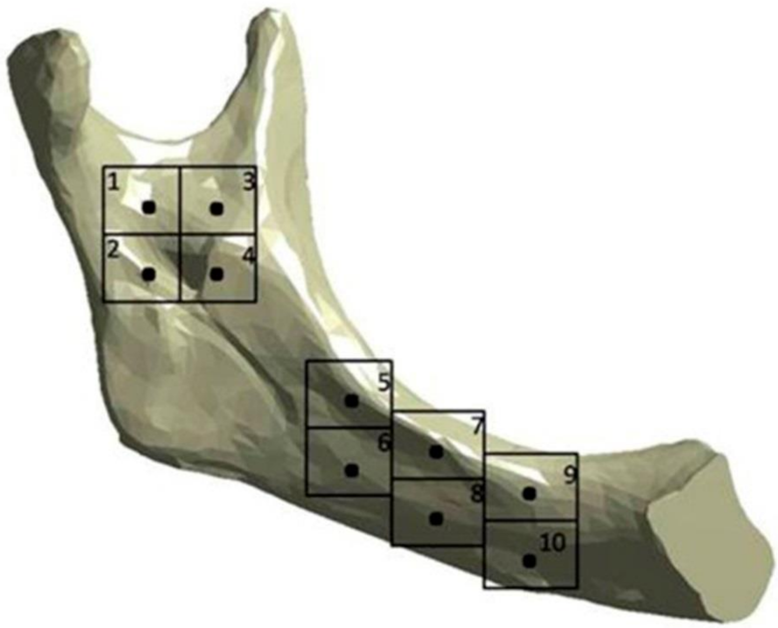

Figure 2. Schematic representation of the division and numbering of the areas evaluated in the medial face of the hemimandible.

von Mises stress represented the effective stress in a material under determined loading conditions[5].Stress values of von Mises were obtained at each area, three times in each load, by one examiner. Reproducibility was obtained by the Intraclass Correlation Coefficient (ICC) in BioEstat 5.0 software (Mamiramuá Foundation, Pará, Brazil).

In each studied area, Pearson correlation (rP) test was used to correlate the force applied and the tension for resin and bone in FEA. The significance level was set at 5% and the software was GraphPad 6.0.

RESULTS

The orders patterns of isochromatic fringes generated in each area are shown in Table 2.

Table 2. Isochromatic fringes order values (*F- Fracture).

Area	**Load(N)**														
	50	100	150	200	250	300	350	400	450	500	550	600	650	700	723
1	1	1	2	2	2	2	3	3	3	3	3	3	3	3	F
2	1	1	1	1	2	2	3	3	3	3	3	3	3	3	F
3	1	1	1	1	1	1	1	1	1	1	2	2	3	3	F
4	1	1	1	1	1	1	1	1	2	2	2	2	3	3	F
5	0	1	1	1	1	1	1	1	1	0	0	0	0	0	F
6	0	1	1	1	1	1	1	1	1	0	0	0	0	0	F
7	0	1	1	1	1	1	1	1	1	0	0	0	0	0	F
8	0	1	2	2	2	2	2	2	2	1	1	0	0	0	F
9	0	1	1	2	2	2	2	2	2	1	0	0	0	0	F
10	0	1	1	2	2	2	2	2	2	1	1	1	1	0	F

Under initial load of 50N, stress was concentrated only in 1, 4, 5 and 7 areas with order fringes of 1.

Increasing loads generated concomitant increased isochromatic fringes orders in 1, 2, 3 and 4 areas. These areas showed fringes order 2 in loads of 150 to 300N, and fringes order 3 in loads of 350 to 700N.

In both epoxy resin and bone FEA the reproducibility was excellent 1.000 ($p < 0.0001$), for all loads and areas.

The von Mises stress were distributed similarly in both characterized models, epoxy resin (Figures 3, 4 and 5) and bone (Figure 6, 7 and 8). High stress occurred in 1, 2, 3 and 4 areas (Tables 3 and 4).

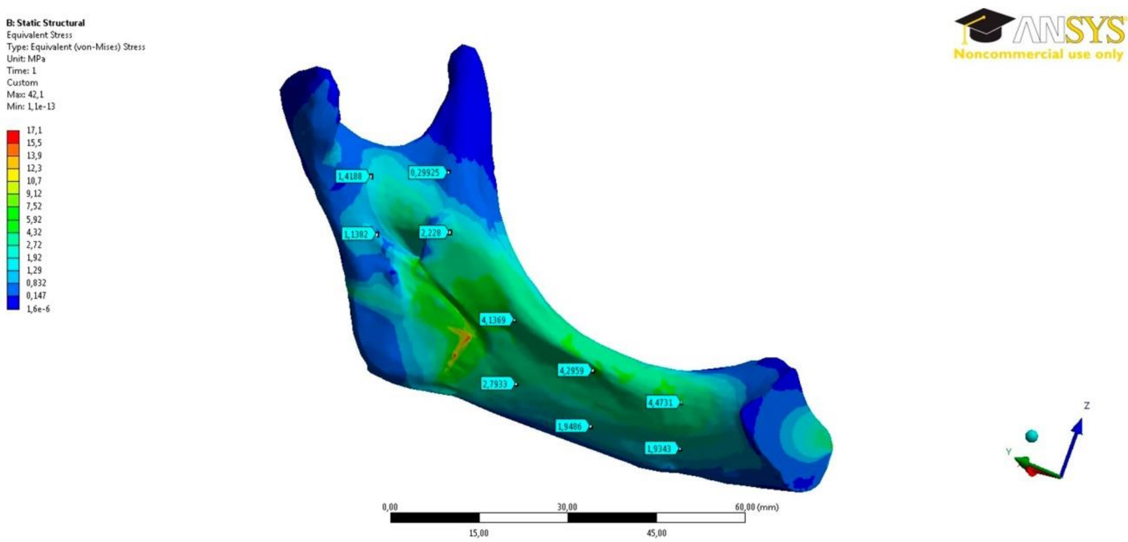

Figure 3. Von Mises stress of model characterized as epoxy resin under load of 50N.

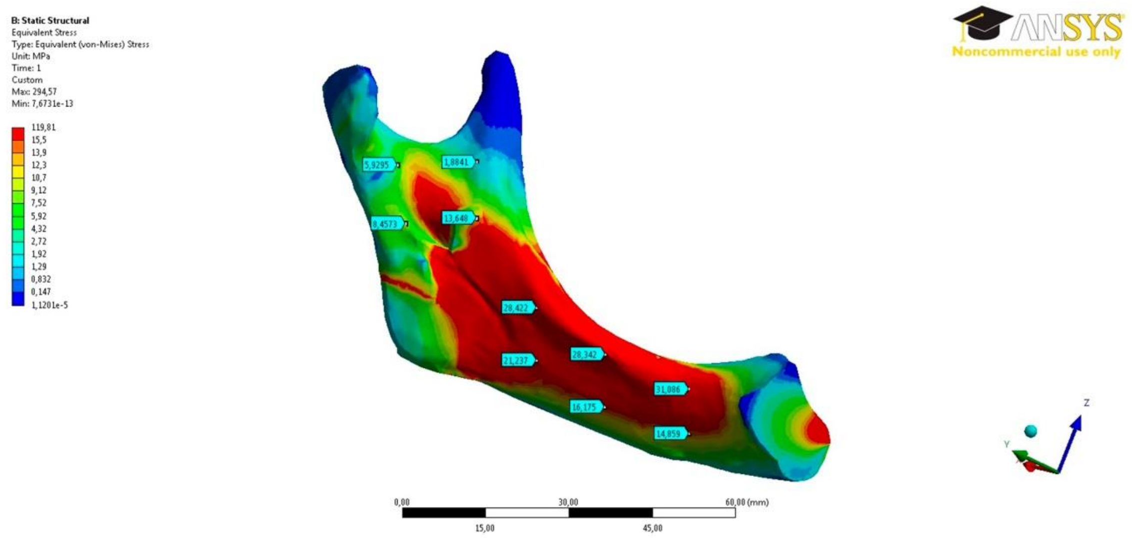

Figure 4. Von Mises stress of model characterized as epoxy resin under load of 350N.

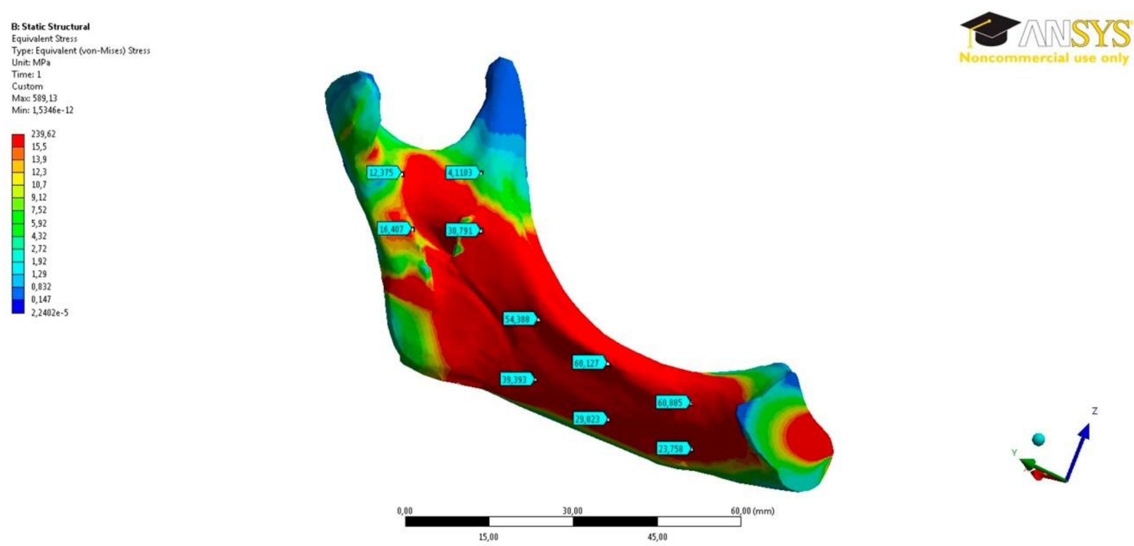

Figure 5. Von Mises stress of model characterized as epoxy resin under load of 700N.

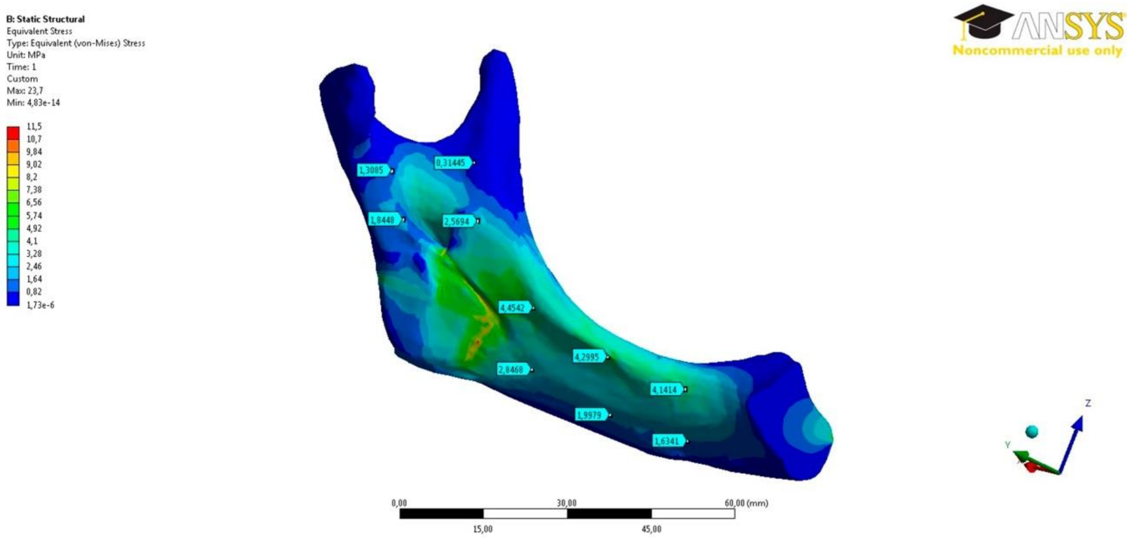

Figure 6. Von Mises stresses of model characterized as bone under load of 50N.

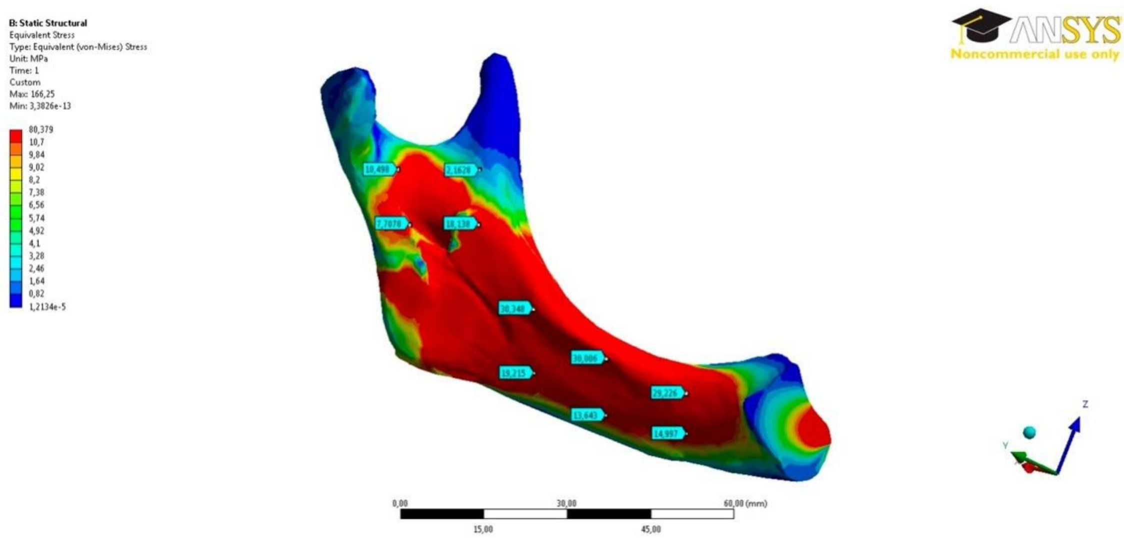

Figure 7. Von Mises stresses of model characterized as bone under load of 350N.

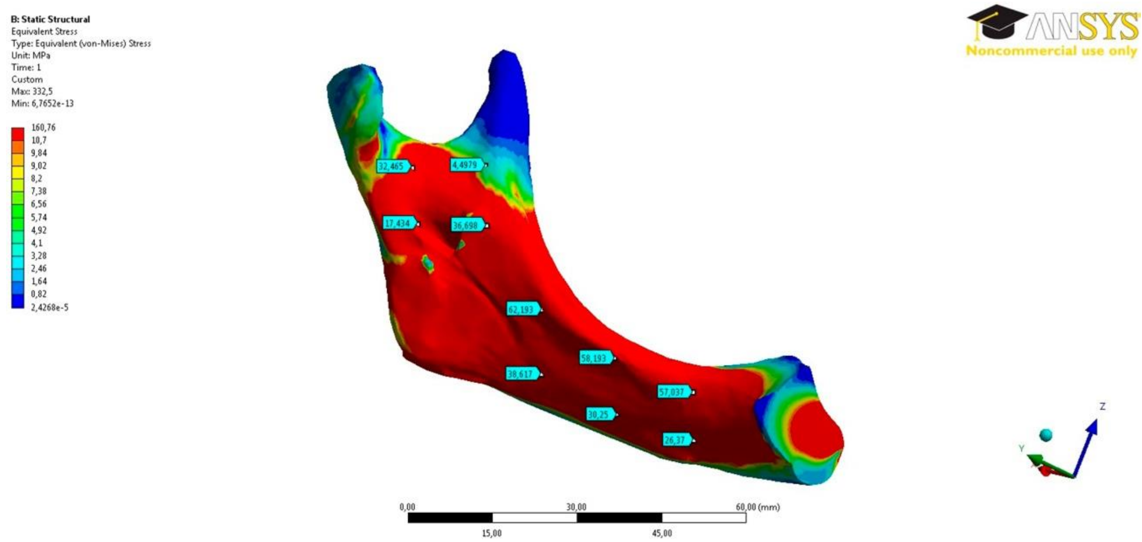

Figure 8. Von Mises stresses of model characterized as bone under load of 700N.

In the FEA model characterized as bone, stress showed low values (Table 3), probably due to the physical properties of bone, which presented more rigidity than the epoxy resin.

Table 3. von Mises stress (in MPa) to computational model characterized as epoxy resin.

Area	**Load N**														
	50	100	150	200	250	300	350	400	450	500	550	600	650	700	723
1	1.43	2.1	3.12	5.98	6.99	6.91	5.84	7.63	7.15	9.28	9.69	9.35	12.8	12.5	13.
2	1.14	2.43	3.67	4.77	6.31	7.48	8.52	9.63	10.59	8.34	12.50	9.78	15.13	16.48	-
3	0.30	0.51	0.80	1.10	2.12	2.08	1.88	2.50	3.30	3.13	3.02	5.36	3.55	4.14	-
4	2.24	4.39	7.42	8.96	11.41	9.30	13.53	16.53	17.79	21.67	24.26	26.80	28.74	30.73	-

5	4.14	8.23	11.67	15.30	21.21	22.98	28.33	33.30	39.47	39.79	47.60	57.41	55.72	54.56	-
6	2.79	6.42	8.17	11.33	16.26	17.17	21.32	23.56	26.56	27.60	31.45	35.82	36.84	39.31	-
7	4.30	8.38	13.76	18.02	22.17	27.03	28.53	33.13	38.79	42.21	48.05	50.82	54.69	60.10	-
8	1.96	4.48	5.76	7.34	9.21	11.18	16.14	16.47	16.99	20.69	23.10	23.40	28.18	29.15	-
9	4.47	8.82	12.44	17.39	22.20	26.04	31.07	33.85	37.61	43.31	48.89	53.31	54.54	60.60	-
10	1.94	4.02	5.28	6.72	9.83	10.18	14.69	14.98	15.82	18.26	22.42	21.08	22.64	23.66	-

Table 4. von Mises stress (in MPa) to computational model characterized as bone.

Area	**Load N**														
	50	100	150	200	250	300	350	400	450	500	550	600	650	700	723
1	1.31	4.2	3.85	7.84	8.96	8.42	10.5	10.6	11.6	14.6	14.3	16.5	20.5	32.4	32.
2	1.85	3.2	5.24	5.41	7.38	10.4	7.88	13.3	14.7	15.1	17.4	18.9	20.2	17.3	-
3	0.32	0.74	1.02	1.25	1.62	1.88	2.15	2.56	2.98	3.22	3.44	4.55	4.69	4.50	-
4	2.58	5.92	9.12	11.74	13.82	15.44	18.24	20.83	24.40	27.09	28.60	31.12	34.20	36.76	-
5	4.45	9.74	13.75	18.10	21.73	24.49	30.28	35.25	38.17	41.26	48.19	53.54	55.37	62.26	-
6	2.85	5.84	8.38	10.95	14.13	16.82	19.24	22.03	24.65	27.71	29.78	33.55	36.99	38.66	-
7	4.30	8.56	13.31	17.06	21.27	25.17	29.99	33.84	36.20	42.23	46.24	50.34	54.60	58.31	-
8	2.00	3.73	5.92	7.84	11.08	12.16	13.49	16.28	19.31	21.20	22.52	22.51	26.73	30.21	-
9	4.15	8.55	12.69	16.17	22.75	25.65	29.29	32.58	36.84	40.34	45.39	49.81	54.95	57.04	-
10	1.63	4.01	5.92	7.74	9.02	10.52	14.93	13.33	16.15	21.53	19.75	21.73	21.89	26.19	-

Figure 9 had shown the relationship between the applied load and stress in each of 10 areas examined.

There was an excellent (rP> 0.9) and significant ($p < 0.05$) correlation (Figure 8) between the loads applied and the responses obtained in all the studied areas, regardless of the area considered but areas 9 and 10 for the mandibular body, which showed very good (rP> 0.7) and significant (p <0.05)correlation. These results indicate that increasing loads produce proportional increases of the stress in each area tested. This observation is valid for both bone and resin models.

Correlation between bone and resin models, considering each area separately, is presented in Figure 10. Figure 10 shows an excellent and significant correlation between the two models, independently of the observed area. This shows that both models could be considered interchangeable, particularly considering the areas 4 to 10 (mandibular body mostly).

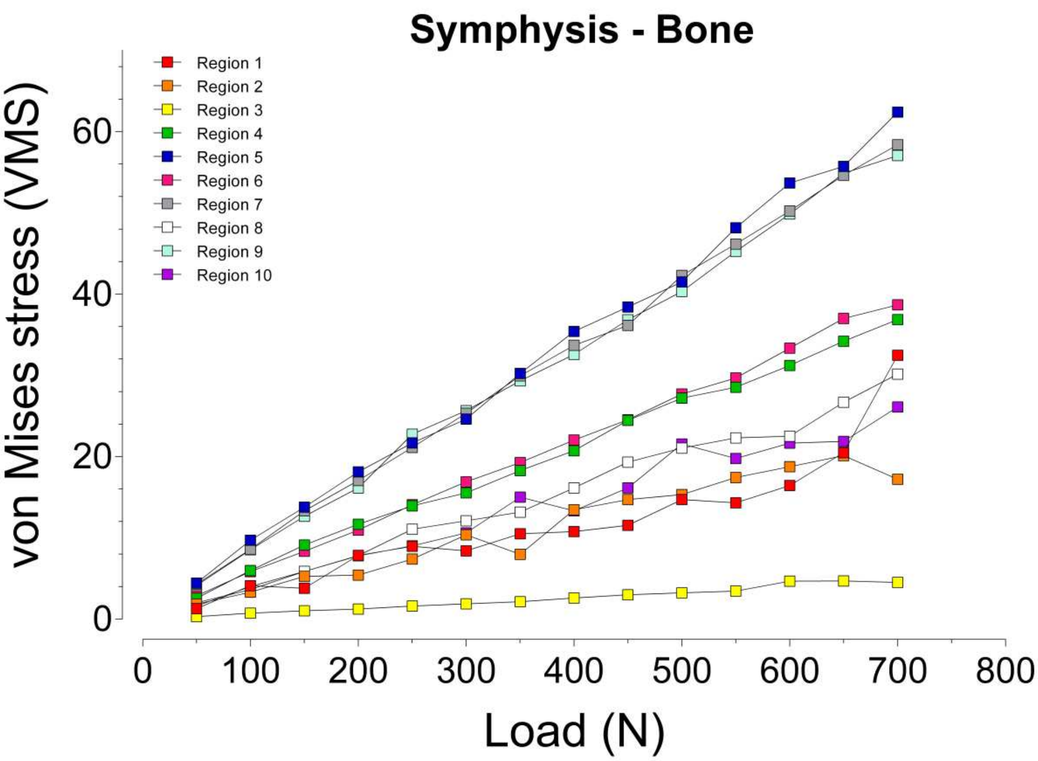

Figure 9. Correlation between applied loads and stresses observed along the 10 areas.

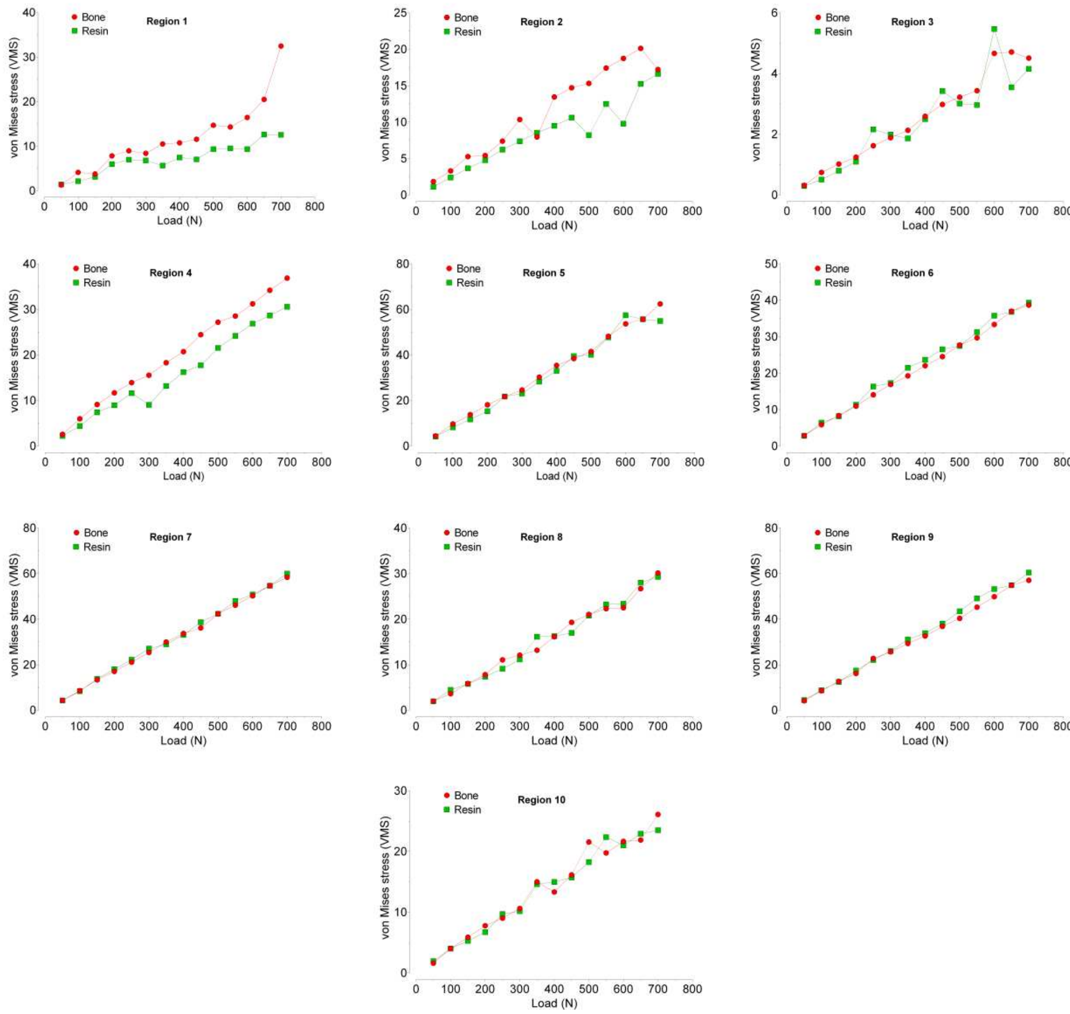

Figure 10. Correlation between applied loads and stresses observed along the 10 areas in the bone and epoxy resin models.

DISCUSSION

The increase in population longevity contributes to a more active life in old age and, therefore, more they are more expose to trauma[14]. The association between teeth loss and aging enhances the importance to understand the distribution of stress occasioned by trauma in elderly edentulous mandible.

FEA model is a valid and non-invasive method to predict different parameters of the complex biomechanical behavior of human mandibles[15]. Our study showed that both FEA and photoelastic analyzes were useful to evaluate the functional mechanical response of elderly edentulous mandible under symphysis loads according to the material properties.

In the present study, mechanical responses occurred initially in areas with high bone strength, thickness and density, mainly the mandibular body, in agreement with Schwartz-Dabney and Dechow[8]. Stress distribution in our study was probably determined not only by strength, thickness and density of mandibular bone, but also by the geometric form of the human mandible.

Differences on mechanical properties in both models may have influenced the results[16, 17, 18]. Since the present study was regarding to structural responses related to morphology, numerical values were applied to the bone structure. This concept has been determined from experimental studies applied to the FEA in human skulls which determined that only the geometry was sufficient for understanding the craniofacial biomechanics[12]. Previous studies suggested that no general stress patterns, neither loads, are greatly affected by material properties variation[17, 18, 19].However, increased precision regarding properties will lead to more accurate predictions of actual stress magnitudes.

Experimental and computational analysis in biomechanical studies showed that bones geometries have major sensibility to mechanical stimuli since morphology is an important factor in this response[16]. In the present study areas showing the higher stress concentration (areas 1, 2, 3 and 4) showed similar results in both models. This relationship was demonstrated by the similarity between the stress distribution in the FEA with model characterized by resin and model characterized as bone. However, the differences between the values were not considered for the comparison among the analysis since the model was simplified in relation to the different materials present in the human jaw (compact bone and cancellous bone).

In our study, both analyzes enabled the evaluation of regions of high stress after application of loads on symphysis. Ellis et al.[20] and Adi et al.[21] reported that motor vehicle accidents cause fractures in the mandibular neck due to trauma caused by anterior displacement of the passenger after the accident. For this reason, loads at the symphysis region was simulated to produce corresponding (indirect) fractures in the condylar process, and direct ones in the symphyseal area[22]. In our study, the loads applied in the symphysis region produced the highest stress values in both analyses, in the condylar neck areas (1 and 2).

Mandible arch shape geometry and its variations throughout the bone structure contribute to the stresses from traumatic loads on symphysis to distribute to mandibular neck (area 1) and nearby regions (2, 3 and 4 areas). These characteristics were considered in this study, in both analyzes, to understand the variations in isochromatic fringes stress and the von Mises stress. The relevance of these variations has been demonstrated in studies of computational simulations by FEA in bones of the human skull[12, 23, 24, 25].

Besides the geometry of the mandible, this mechanical response is related to bone strength, which is indicated by the mechanical property involving thickness, density and stiffness of the bone, which has variations along the mandible[8]. Therefore, bone thickness is decreased in the mandibular neck region, causing reduced strength in this region and, therefore, more tendencies to fracture.

CONCLUSIONS

Both analyses allowed the evaluation of the stress distribution in human edentulous mandible. The stress was distributed to the mandibular body and the mandibular neck of the mandible. There was an increased stress direct correlated with increasing increased applied load in all areas evaluated.

Independently of the area considered both bone and resin models showed an excellent correlation between load and tension.

Both photoelastic and finite element analyses of stress in human elderly edentulous mandible under symphysis loads could be useful to understand the biomechanical behavior of the human mandible and describe the outlined and existence of potentially weak areas in the mandibular geometry (mandibular neck and mandibular body) under common trauma situation.

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CAPÍTULO 2*

EFFECT OF THE REGION BONE AND INTENSITY OF APPLICATION OF LOADS IN THREE SITUATIONS IN TRAUMA OF HUMAN EDENTULOUS MANDIBLE BY FINITE ELEMENT ANALYSIS

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ABSTRACT

The aim of this study was to analyze the distribution of stress from loads applied on symphysis, parasymphyseal region and mandibular body in human edentulous mandible by FEA. In addition, verify the correlation between the load applied and the stress obtained at each area evaluated. CT was performed at totally edentulous macerated hemimandible with approximate age to 65 years. The bone structure was selected and was converted in a three-dimensional model with STL file format which was the basis for modeling the geometry CAD for FEA. The geometry was imported from the software Ansys v14.to construction of the finite element mesh. The model was characterized as the mechanical properties of bone as isotropic and elastic structure. Vertical loads were applied on symphysis, parasymphyseal region and mandibular body, in three separate simulations. The load was 700N. The traumatic load at the mandibular symphyseal region resulted in stress concentration with low values in the mental area and extended to the mental foramen level. At the mandibular neck and part of condyle the stress concentration occurred with high values in two sides. In the parasymphyseal load, near to the mental foramen, the stress concentrated around the load region. The load in the body was applied at the retromolar level, which resulted in an extensive stress concentration in the mandibular body, angle and ramus. In conclusion, FEA allows described the complex stress distribution in the human edentulous mandible and outlined the existence of potentially weak areas in the mandibular geometry (mandibular neck and mandibular body) under three common traumas situations.
Keywords: mandible; edentulous; traumas; finite element analysis.

INTRODUCTION

More accurate description of mandibular fractures biomechanics will have relevance in resolving the paradox of similar clinical success obtained with use of reconstruction plates and the small plate techniques on the same fracture scenarios. Understanding the science of biomechanics is necessary to optimize current treatment systems of fractures and direct decisions regarding future steps needed to significantly improve outcomes[1].

Principal trauma regions are located in the symphysis, parasymphyseal region, mandibular body and mandibular angle, and tend to vary according many factors[2]. One of these factors is age[2]. Mandibular fractures in older patients are poorly understood. Due to the increase in longevity in older people, patients remain at risk for trauma, which became the fifth leading cause of deaths in this age group, because the elderly have a unique and complex aging process[3].

Finite element analysis (FEA) is a useful tool to predict the biomechanical response of the mandible to various loads[4]. This method allows simulating the biomechanical behavior in standard trauma situations[5].

Thus, the aim of this study was to analyze the distribution of stress from loads applied on symphysis, parasymphyseal region and mandibular body in human edentulous mandible by FEA.

MATERIALS AND METHODS

This study was approved by the Committee for Ethics of Research of the State University of Campinas (Protocol: 134/2012) (ANEXO 2).

Computerized Tomography (CT) (GE HiSpeed NX / i CT scanner - General Electric, Denver, CO, USA) was performed at totally edentulous macerated mandible with approximate age to 65 years. To increase the accuracy in the geometry, the CT slices had 0.25 mm of thickness.

The bone structure was selected according to the color of pixels, using threshold values in units HU (Hounsfield Units) using InVesalius 3.0b software (Center for Information Technology "Renato Archer", São Paulo, Brazil).

The structure was converted in a three-dimensional model with stereolitographic file format (STL), which was the basis for modeling the geometry CAD (Figure 1) for FEA[6]. For this purpose we used the software Rhinoceros 5.0 (McNeel & Assoc., USA).

The FEA was performed in the software Ansys v14. The geometry (CAD model) (Figure 1) of the edentulous mandible was imported from the software Ansys v14. The construction of the finite element mesh resulted in 528010 tetrahedral elements and 759787 nodes.

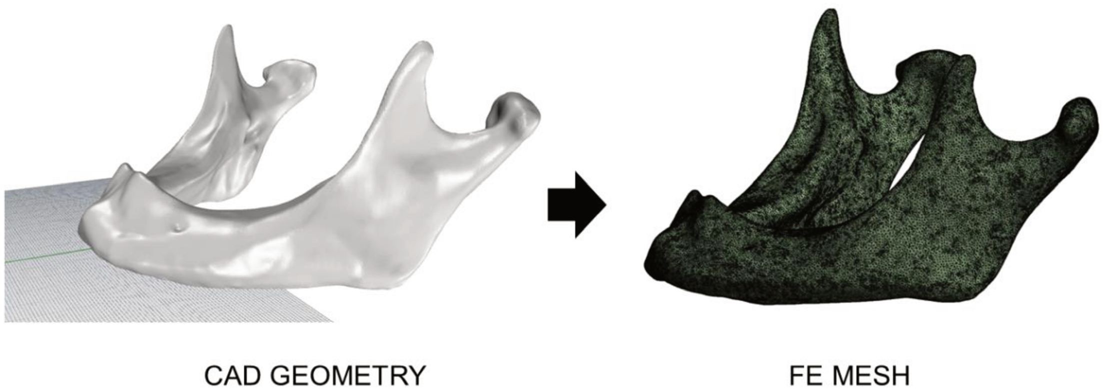

Figure 1. Geometry (CAD model) and finite element mesh of the edentulous mandible.

The model was characterized as the mechanical properties of bone[7] (Table 1), as isotropic and elastic structure.

Table 1. Mechanical properties of the model.

Material	**Young'sModulus (MPa)**	**Poisson'sratio**
Bone	14000	0,30

The condyles were constrained to prevent free movements in the x, y and z axis during the simulation (simulating the presence of masticatory muscles supporting the mandible, with the aim of approaching the condition of the presence of muscle during trauma) (Figure 2). Vertical loads were applied on symphysis (Figure 2A), parasymphyseal region (Figure 2B) and mandibular body (Figure 2C), in three separate simulations. The load was 700N according Gallas Torreira & Fernandez[5].

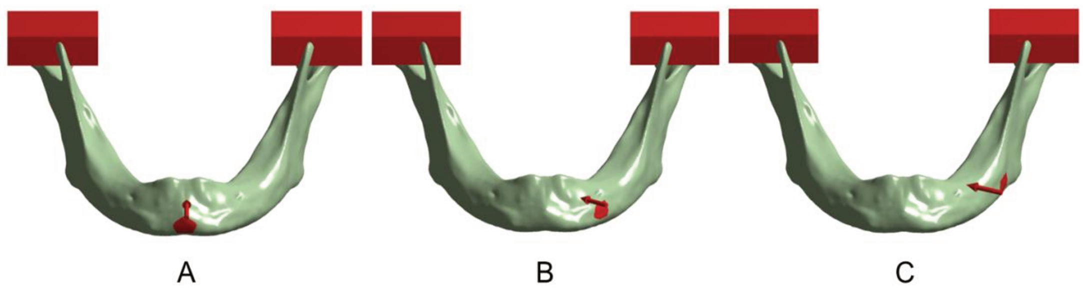

Figure 2. Boundary and load conditions showing the symphyseal load (A), parasymphyseal load (B) and Lateral load on the mandibular body (C).

The von Mises stresses are a representation of the effective stress in a material under determined loading conditions[5]. In this study, the energy flow resulted in a critical stresses, which occurred failure in some regions of edentulous mandible, was caused by three traumas simulated.

RESULTS

The traumatic load at the mandibular symphyseal region (Figure 3) resulted in stress concentration with low values in the mental area and extended to the mental foramen level. In posterior area of body, angle and inferior third of mandibular ramus were not found stress concentration and very low values. At the mandibular neck and part of condyle the stress concentration occurred with high values in two sides.

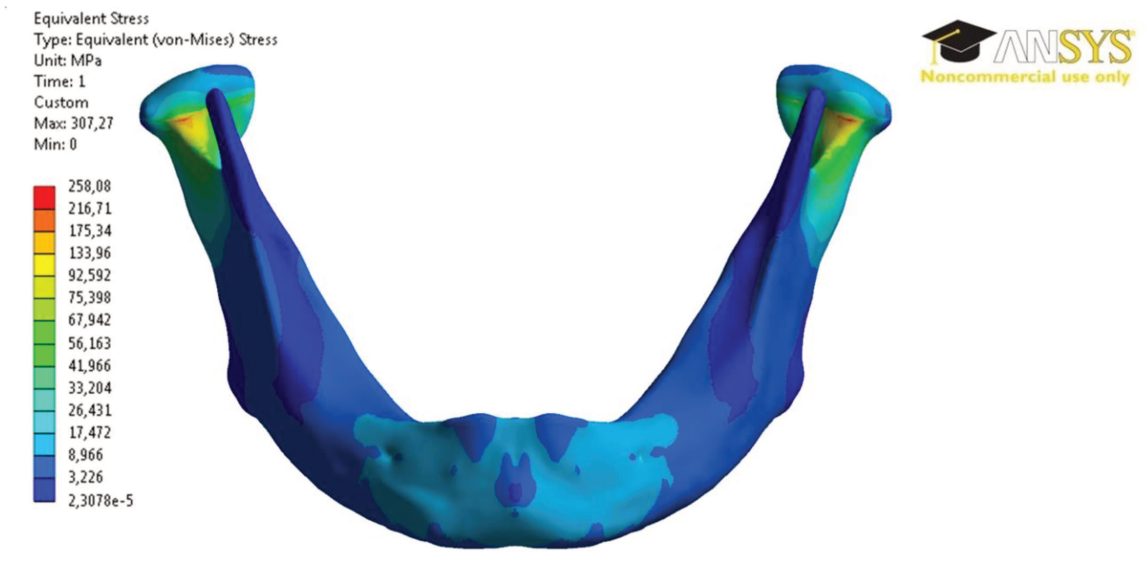

Figure 3. von Mises stress distribution from symphyseal load.

In the parasymphyseal load (Figure 4), near to the mental foramen, the stress concentrated around the load region. A minor stress area also occurred in the body, opposite to the load. At the mandibular neck, high stress occurred mainly on the medial surface. The mandibular neck on the opposite side presented minor stress concentration compared to the side of the load.

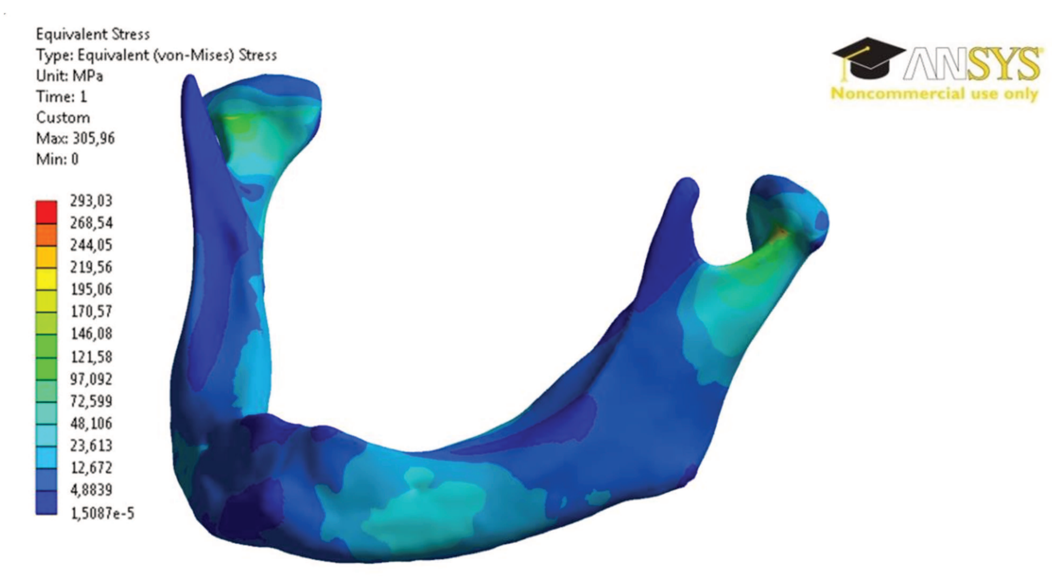

Figure 4. von Mises stress distribution from parasymphyseal load.

The load in the body was applied at the retromolar level (Figure 5), which resulted in an extensive stress concentration in the mandibular body, angle and ramus. The mandibular neck presented high stress concentration at the same side of the load, involving medial and lateral surface. The opposite mandibular neck occurred minor stress concentration.

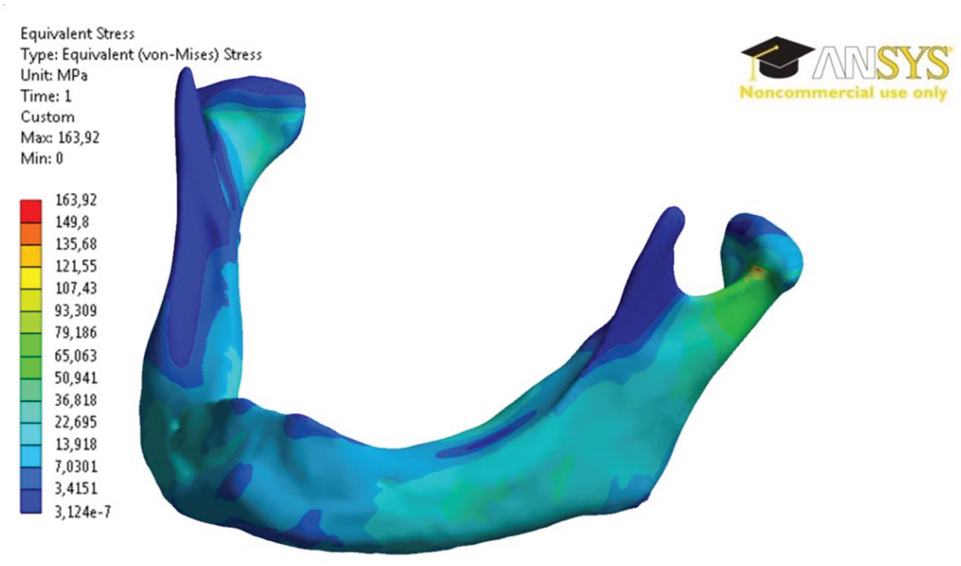

Figure 5. von Mises stress distribution from lateral load on the mandibular body.

DISCUSSION

In craniomaxillofacial trauma, older people are prone to fractures (increasing at 4.4%/year of age). In addition, population life expectancy increased, with more active in old age and, therefore, more traumas in general, which highlights the relevance of this study for understanding the behavior of these stresses from traumas in edentulous mandible[9].

The mandibular fractures are produced either by direct application of a load in the impacted area, or induced stress in specific areas. We analyzed the distribution of stresses by FEA on mandibular lateral face. According to Viaño et al.[10] the trauma from these three regions of trauma (symphysis, parasymphyseal region and mandibular body), generate the force line on the lateral face (region of open fracture). Clinical evidence suggests that there is a need for stress in a region of fracture healing for adequate maturation of the bone to occur. The evaluation of a repair strategy includes the identification of consistent parameters of stress distribution. Techniques for repair can be too weak or too stiff, altering the stress distribution and resulting in system failure[1]. Thus, this study exposed a basic knowledge about the stress distributions for contribute to the repair of fractures.

We verify that the symphysis load generated higher stresses than load on parasymphyseal region. Thus, the stresses were dependent of the region load (symphysis, parasymphyseal region and mandibular body) and of the intensity of load. The accurate geometry of the mandible and its variations throughout the bone structure contribute to the stresses from traumatic loads on symphysis and parasymphyseal region (but with lower intensity) to distribute to mandibular neck and nearby regions. The geometry and its morphologic variations were considered in this study, to interpret the von Mises stress[7, 11, 12, 13]. This mechanical response is related to bone strength, which is indicated by the mechanical property involving thickness, density and stiffness of the bone, which has variations along the mandible[8]. Thus, according to Schwartz & Dabney-Dechow[8], the bone thickness is smaller in the mandibular neck, so that this region having less bone strength and therefore more tendency to fracture.

In this study, there was an excellent correlation between the applied loads and the responses obtained in three regions simulated. We verified that the mechanical response by FEA on mandibular body load occurred in areas with major bone strength, thickness and density mainly, in agreement with the data showed by Krüger[14], Viaño et al.[10] and Schwartz-Dabney & Dechow[8]. This adaptation is associated to the concept that areas of major strength with minimum presence of materials are presents in the bony structures[15].

There are inherent limitations of this study. The mandible model was all assumed to be homogeneous and isotropic and to possess linear elasticity, although the bone of the mandible is transversely isotropic and non-homogeneous in living tissue. Furthermore, there is a difference in cortical thickness, bone density, and buccolingual width in the mandible. The loads applied in this study were not dynamic, but static, although in previous studies, the stress distribution and magnitude by static analysis were almost consistent with those by dynamic analysis. Any theory on mandible behavior will be incomplete if it ignores the effects of soft tissue, including the effects of the facial and periosteal attachments, and the effects of muscle contraction in traumas. The forces are transmitted not only through bone but through soft tissues, creating circuits of force[16].

CONCLUSIONS

In conclusion, FEA allows described the complex stress distribution in the human edentulous mandible and outlined the existence of potentially weak areas in the mandibular geometry (mandibular neck and mandibular body) under three common traumas situations.

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CONCLUSÃO

Ambas as análises permitiram a avaliação da distribuição das tensões em mandíbula humana desdentada. As tensões foram distribuídas ao corpo mandibular e ao côndilo mandibular. Houve um aumento das tensões diretamente correlacionado com o aumento das cargas aplicadas em todas as áreas avaliadas.

Ambas as análises (fotoelástica e de elementos finitos) das tensões em mandíbula humana desdentada de idoso, mostraram-se úteis na compreensão do comportamento biomecânico da mandíbula humana e descreveram a distribuição e existência de áreas potencialmente fracas na geometria mandibular (côndilo mandibular e corpo mandibular) quando submetidos a situações de traumas comuns.

Em conclusão, AEF permite descrever complexas distribuições de tensões em mandíbulas humanas desdentadas, ressaltando a existência de áreas de fragilidade em potencial na geometria mandibular (côndilo mandibular e corpo mandibular) sob três situações comuns de trauma.

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* De acordo com a norma da UNICAMP/FOP, baseadas na norma do International Committee of Medical Journal Editors – Grupo de Vancouver. Abreviatura dos periódicos em conformidade com o Medline.

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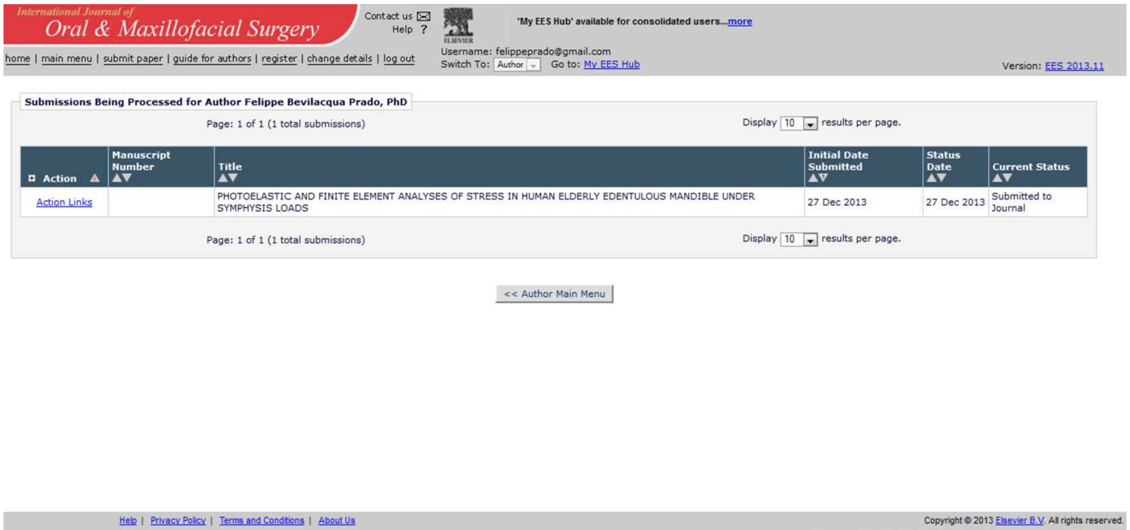
ANEXO 1



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ANEXO 2

COMITÊ DE ÉTICA EM PESQUISA
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CERTIFICADO

O Comitê de Ética em Pesquisa da FOP-UNICAMP certifica que o projeto de pesquisa **"Dissipação de tensões em traumas de mandíbula humana desdentada pela análise dos elementos finitos: Análise comparativa entre modelos isotrópicos e ortotrópicos"**, protocolo nº 134/2012, dos pesquisadores Leonardo Soriano de Mello Santos e Felippe Bevilacqua Prado, satisfaz as exigências do Conselho Nacional de Saúde - Ministério da Saúde para as pesquisas em seres humanos e foi aprovado por este comitê em 15/05/2013.

The Ethics Committee in Research of the School of Dentistry of Piracicaba - State University of Campinas, certify that the project **"Tension dissipation associated to edentulous mandible trauma by finite element analysis: Comparative analysis between orthotropic and isotropic models"**, register number 134/2012, of Leonardo Soriano de Mello Santos and Felippe Bevilacqua Prado, 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 05/15/2013.

Prof. Dr. Felippe Bevilacqua Prado
Secretário
CEP/FOP/UNICAMP

Livia M. A. Tenuta
Profa. Dra. Lívia Maria Andaló Tenuta
Coordenadora
CEP/FOP/UNICAMP

Nota: O título do protocolo aparece como fornecido pelos pesquisadores, sem qualquer edição.
Notice: The title of the project appears as provided by the authors, without editing.