

Finite element analysis of the mechanical behavior of a partially edentulous mandible as a function of cancellous bone density

Análise por elementos finitos do comportamento mecânico de uma mandíbula humana parcialmente edêntula em função da densidade óssea trabecular

Abstract

Purpose: To present a methodological procedure to obtain the geometric and discrete models of a human mandible for numerical simulation of the biomechanical behavior of a partially edentulous mandible as a function of cancellous bone density.

Methods: A 3D finite element method was used to assess the model of a partially edentulous mandible, Kennedy Class I, with dental implants placed at the region of teeth 33 and 43. The geometric solid model was built from CT-scan images and prototyping. In the discrete model a parametric analysis was performed to analyze the influence of cancellous bone density (25%, 50%, 75%) on the development of mandibular stress and strain during simulation of masticatory forces in the anterior region.

Results: Maximum von Mises stress and equivalent strain values in cancellous bone were found close to the loading area (masticatory forces). The peak stress and strain values occurred in the mandibular anterior region, and for the same masticatory force the equivalent stresses increased with bone density.

Conclusion: The results suggest that the stresses and strains developed in the mandibular model were affected by cancellous bone density during the simulation of masticatory activity.

Key words: Finite element analysis; mandible; stress analysis; mechanical behavior; bone density.

Resumo

Objetivo: Apresentar uma metodologia para modelamento geométrico de uma mandíbula humana e obtenção de um modelo discreto para simular numericamente o comportamento biomecânico de uma mandíbula parcialmente edêntula em função de diferentes densidades do osso trabecular.

Metodologia: Utilizou-se o método de elementos finitos 3D para realizar um estudo numérico sobre um modelo de mandíbula humana, desdentada parcial tipo Classe I de Kennedy, com implantes nas regiões dos dentes 33 e 43. O modelo sólido geométrico foi determinado por tomografia computadorizada e prototipagem. No modelo discretizado foi realizada uma análise paramétrica para verificar a influência da densidade óssea do osso trabecular (25%, 50%, 75%) no desenvolvimento de tensões e deformações da mandíbula durante a aplicação de forças mastigatórias na região anterior.

Resultados: As tensões máximas de von Mises e deformações equivalentes no osso trabecular foram desenvolvidas próximo às regiões de aplicação das forças de mordida. Os picos de valores de tensões/deformações localizaram-se na região anterior da mandíbula, sendo que, para o mesmo valor de esforço de mordida, as tensões equivalentes aumentaram com a densidade óssea.

Conclusão: Os resultados sugerem que as tensões e deformações desenvolvidas no modelo mandibular testado foram afetadas pelo grau de densidade do osso trabecular durante simulação de atividade mastigatória.

Palavras-chave: Análise por elementos finitos; mandíbula; análise de tensões; comportamento mecânico; densidade óssea

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Introduction

The mandible is a complex structure that plays an important role in facial esthetics and many functional activities, such as mastication, swallowing, facial expression, and speech (1). The mandibular system is composed of different tissues, such as bone (cortical and cancellous types), teeth (enamel, dentin, and pulp), ligaments, and muscles (1). This sophisticated combination of anatomic structures is related to the physiological phenomena of bone remodeling, resorption, and apposition that may influence stomatognathic functions and prosthetic rehabilitation. Wolff (2) initially suggested an interdependent relationship between bone internal architecture and functional loads, but the present view shows a multi-factorial complexity in bone response related to mechanical processes and biological cellular remodeling (3).

The main components of bone tissue are type I collagen, minerals, and water, with a variable composition. For example, bone density increases with age, and partially edentulous mandibles often have highly mineralized areas (4). During lifetime bone is subjected to a remodeling process with areas of different mineralization and density grades (4). It is also important to consider that the main function of the stomatognathic system, mastication, is dependent on four major muscle groups (masseter, temporal, medial and lateral pterygoid). Suprahyoid and infrahyoid muscles also contribute to the mandible stabilization and equilibrium (5).

Computational applications in Dental Medicine include highly precise image-guided surgeries and the identification of structural problems by using medical images (6). Model development in biomedical engineering allows the simulation of stresses and deformation in bone, teeth, dental prostheses, and implants (6). In order to correctly understand mandibular functions and to optimize a dental prostheses design it is possible to use stress analysis techniques commonly used in mechanical engineering, such as holographic interferometry, photoelasticity, strain gauges, and finite element method (7).

Finite element method (FEM) is a numerical technique that can be used to analyze stress and strain in structures with any given geometry. It is based on the discretization of a continuous media maintaining the same properties of the original model (8,9). The first 3D model of a human mandible was developed by Gupta in the '70s using a non-structured model with few finite elements (10). In 1987, Ben Nissan developed the first 3D dental model with a complex geometry but only 1106 nodes and 258 solid elements (11). In 2005, Reis Campos (7) presented a prototyping technique named "plane slicing" for 3D reconstruction of a human mandible. Some other models were reported in the dental literature aiming to achieve the real behavior of structures and materials, but their geometry usually was structurally over-constrained and had poor anatomical characteristics (1). FEM requires a precise description of the geometry of the structure to be analyzed and should allow calculation of

displacement, strain, and stress values. Recent developments in the characterization of muscle activity and tissue properties provided better conditions for numerical simulation using FEM.

This study reports the methodological procedures to obtain the geometric model of a human partially edentulous mandible with dental implants and its discrete model used for the numerical simulation of the mandible mechanical behavior as a function of cancellous bone density.

Methodology

The research was conducted according to international standards. A human partially edentulous mandible, Kennedy Type I, with dental implants placed at the teeth #33 and #43 regions (Fig. 1A) was scanned by means of computer tomography. The mandibular image (Fig. 1B) was subjected to a segmentation and filtering process using an image processing software (ScanIP™, Simpleware Ltd., Exeter, United Kingdom) (Fig. 1C,D). The geometric model was then imported to a finite element analysis software (Ansys v11™, ANSYS, Inc. Software Products, Canonsburg, PA, USA) where the mastication conditions were simulated. The discrete model used the finite element Solid45 regular geometry that can degenerate into a tetrahedral or triangular prism. This finite element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. This model was determined to differentiate mandibular bone tissue and all the prosthesis components and implants. Figure 2 depicts the finite element model with geometric symmetry. Properties were considered to have linear behavior and were previously reported by Al Sukhun (12) (Table 1); cancellous bone density was defined to 25, 50, and 75% (13).

Forces involved in the model loading should obey to the equilibrium conditions of the mandible. Figure 3 presents a free body diagram used to adjust the mastication forces to reference values (14). The masticatory load was equally divided by the six remaining teeth present in the anterior section of the mandible, considering the articulated model in the convex shape of the condyle and the negligible effect of the digastric muscle for the equilibrium of the remaining muscle forces, assuming symmetric load conditions in relation to the saggital plane. Table 2 shows the muscle force values used in the simulation; the value of the bite load was estimated by using a moment equilibrium equation relative to the condyle (15).

The strength criteria used in this study to analyze the mechanical behavior of the model was the maximum distortion strain energy criterion, or Von Mises, through which a global view of the stress magnitude is calculated, e.g., the "stress average" in all directions, obtaining stress peaks. This approach allows the prediction of the plastic strain quantity under a tri-axial load from the results of a simple test of uni-axial stress (16).

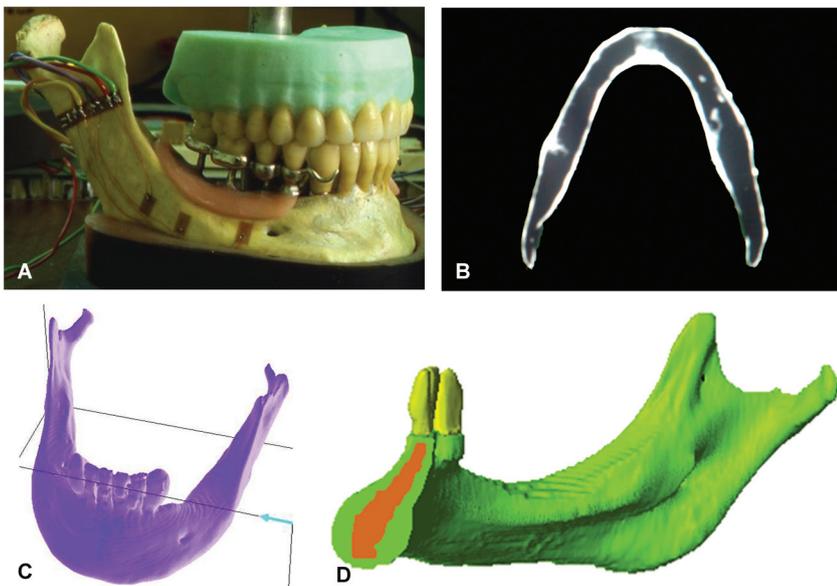


Fig. 1. A) Real human mandible. B) Mandible image by computer tomography, cross-section. C) Three dimensional model of the resulting human mandible. D) Mandibular anatomic model with implants and artificial teeth.

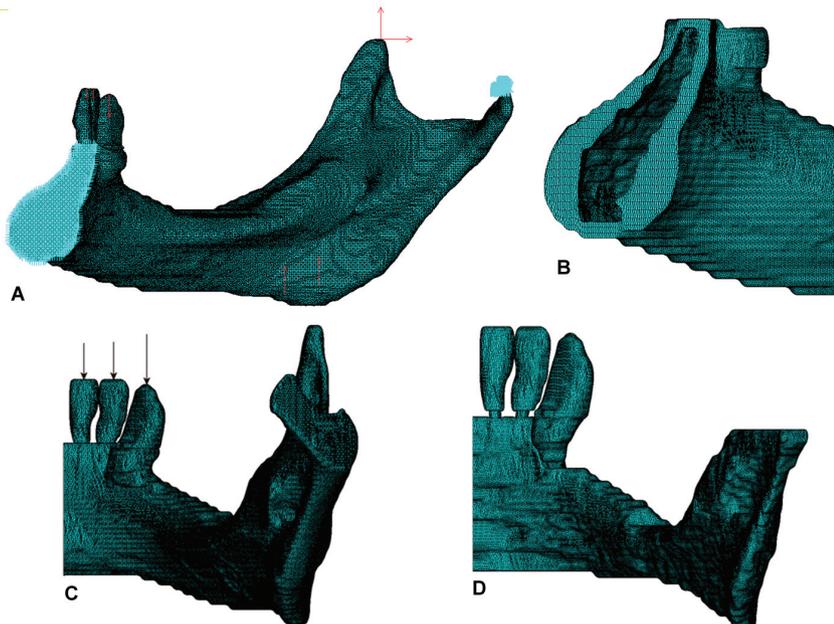


Fig. 2. A) Finite element model. B) Cortical bone tissue. C) Complete model with implants and artificial teeth. D) Mandible model with implants and artificial teeth, without cortical bone tissue.

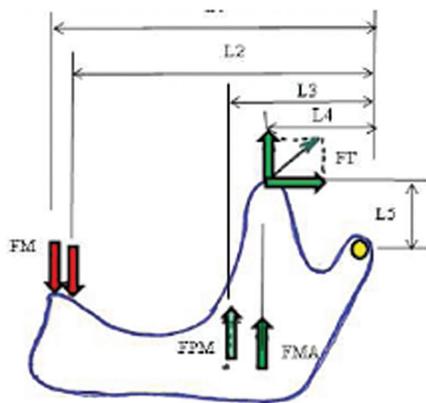


Fig. 3. Free body diagram with simulated mastigatory activity [selected from Inou et al. (14)]. FM = Bite force, FPM = Medial Pterygoid muscle force, FMA = Masseter muscle force, FT = Temporal muscle force (see Table 2).

Table 1. Elastic properties used for materials in the tested model.

Material	Elastic Module [GPa]	Poisson's Ratio
Titanium implants	110.00	0.35
Artificial teeth	2.26	0.45
Cortical bone	13.60	0.30
Cancellous bone (d=25%)	1.36	0.45
Cancellous bone (d=50%)	4.00	0.45
Cancellous bone (d=75%)	8.00	0.45

Table 2. Loads applied in the model (unilateral).

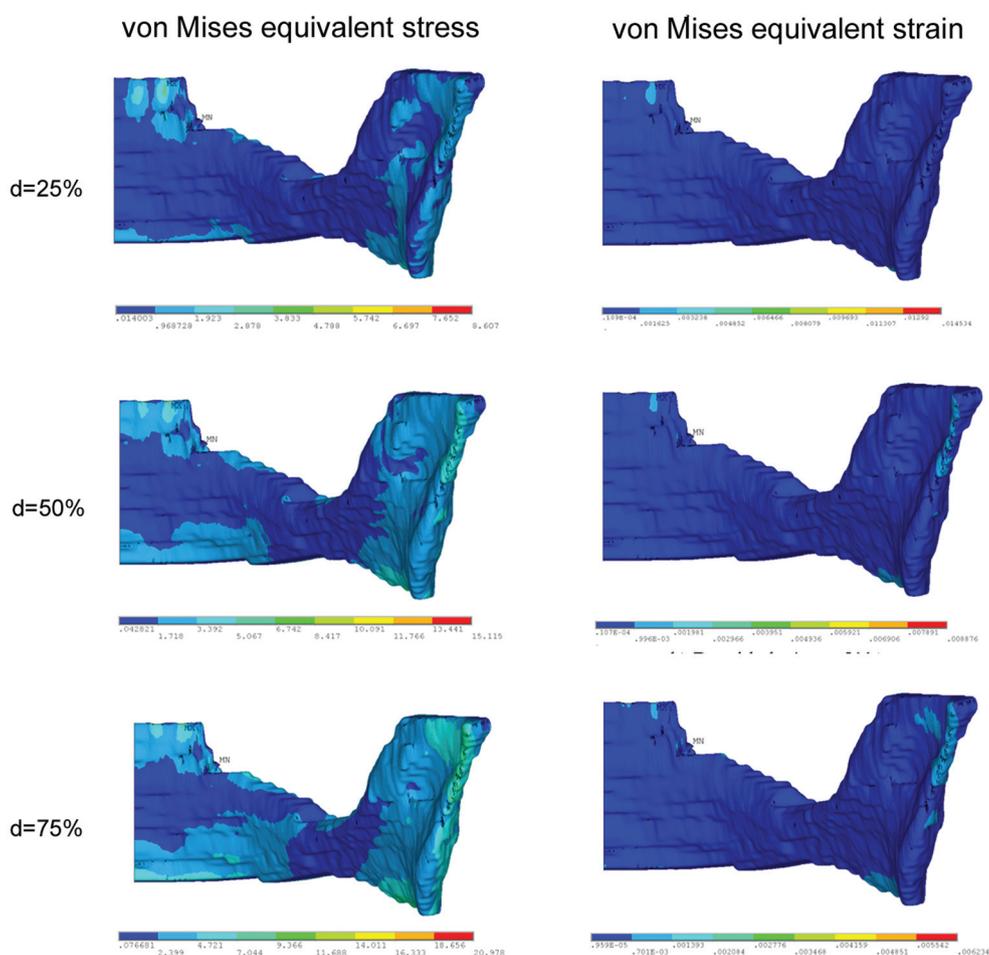
Muscle Forces	Value [N]
Bite (3 points) = FM	220
Temporal = FT	235
Masseter = FMA	151
Medial Pterygoid = FPM	145
Lateral Pterygoid	Not considered

Results

The results are presented as a function of the cancellous bone density. The von Mises maximum stresses in the cancellous bone were developed near the loading region of the mandibular anterior section. Similarly, the distribution of the maximum strain levels in the bone tissue was also located in the anterior region. Different results occurred as a function of the cancellous bone density (Fig. 4). Table 3 presents the maximum von Mises strain values in cancellous bone. The stress peaks were located in the anterior mandible, where dental implants were placed.

Table 3. Maximum values for von Mises strains.

Material	Strain
Cancellous bone (d=25%)	0.014
Cancellous bone (d=50%)	0.009
Cancellous bone (d=75%)	0.006

**Fig. 4.** Graphic representation of equivalent stress and strain (von Mises), developed in cancellous bone tissue with bone density (d) equal to 25%, 50%, and 75%.

Discussion

The 3D model of this study was developed from the real geometry of a partially edentulous mandible with teeth and dental implants in the anterior region, whose image was obtained through computer tomography. A 3D reconstruction of a human mandible can be acquired by different methods (1,7,17). Fütterling (17) presented a 3D reconstruction technique of a mandible from 2D segments obtained by computer tomography. His major difficulty was the differentiation between the bone tissues, and the solution adopted was the identification of seven bone types according to the material density. Reis Campos (7) made a 3D reconstruction of a human mandible using the “plane slicing” technique, in which a conventional scanner is used to obtain the outer borders of a human mandible in a polyester resin model. The digital files were pre-processed using the I-DeasTMSDRC software, and the 3D mandible model and its mesh were reconstructed using the NastranTM and StrandTM softwares. The final model obtained by Campos (7) had 258 tetrahedral elements and 1,635 nodes, and differentiates only the cortical and cancellous bone.

In the present study the model was obtained using computer tomography, image processing and finite element softwares, which reproduced with accuracy the mandibular morphology and geometry. Cone-beam CT scans provides a radiation dose inferior ($\approx 15x$) to the conventional computer tomography units (36,9-50,3 μSv) and have been increasingly used in Implantology, Oral Surgery, Oral Pathology, Orthodontics, Occlusion, and other dental areas (18). This technology combined with specialized software may represent a valuable contribution to the individual biomechanical study of each patient.

Similarly to previous studies on human mandible stress analysis (19-21), this research showed stress around implants and in the mandible, which may be related to the biological values of bone regeneration and strength limits of each material. Bone tissues, usually adapted to the mechanical conditions and respective muscle activities, present strain peak values that must be framed in the biological and mechanical equilibrium range, necessary for the bone

remodeling process and far from the typical reference value for the material collapse ($\epsilon=0.025$) (22).

Likewise the study by De Santis (23), the present results show that during the simulation of masticatory loading the stress/strain peaks were located in the anterior region of the mandible, where the dental implants were inserted. The strain values observed in the implants area could assist the increase of the bone mass. The strain analysis in the mandible is important for oral rehabilitation with dental implants, where the bone-implant interface is subjected to the rigid connections of osseointegration, responsible for the occurrence of stress peaks. This process is dependent on the strain range values developed during the functional activities in the posterior area of the mouth, which justifies the importance of the relationship between strain and density of cancellous bone. Excessive mandibular deformation and the resulting strains around implants could lead to implant loss. This research presents a parametric solution based on the density of cancellous bone, and the results suggest that the bone remodeling process expected around implants would be more efficient with cancellous bone of high density.

The use of computational models in biomedical engineering may help to study the most appropriate solutions for each clinical case after collection of individual data using image exams. For example, strain analysis may be useful for the solution of some impression problems, and fast three-dimensional prototyping systems with 3D data from CAD software allow the production of a real physical model (24). Accurate modeling is fundamental to achieve proper computer simulations of the mandibular activity, in particular the characterization of different tissues and materials. With this methodological analysis and clinical tools, dental practitioners may offer better treatment with oral implants, maxillo-facial reconstruction, osteogenic distraction, temporomandibular joint surgery, and other procedures for complex cases, reducing risks for the patient.

Conclusions

The stresses and strains developed in the mandibular model tested were affected by the degree of cancellous bone density during simulated masticatory effort.

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