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A three-dimensional model of the human masticatory system, including the mandible, the dentition and the temporomandibular joints

Gaivile Pileicikiene, Edvinas Varpiotas, Rimas Surna, Algimantas Surna

SUMMARY

The objective of this study was to create a three-dimensional mathematical model of a human masticatory system, including the mandible, the dentition and the temporomandibular joints.

Object of research was one 20 year old dead man. The research was approved by Committee of bioethics (Kaunas University of Medicine). Required extent of computed tomography scanning and required high amount and high resolution of images increased X-ray radiation for the object and made this research impossible to perform on alive human. Spiral computed tomography scanning was performed to achieve two-dimensional images, necessary for creating three-dimensional model. The 3D modeling was done using the "Image pro plus" and "Imageware"software.

A three-dimensional physiological (normal) model of a human masticatory system, simulating the mandible, the dentition and the temporomandibular joints was generated. This model system will be used subsequently in stress analysis comparison for the physiological and pathological systems after improvement of its physical properties. We suggest that computer simulation is a promising way to study musculoskeletal biomechanics of masticatory system.

Key words: masticatory system, modeling, three dimensional models.

INTRODUCTION

Analysis of the mechanical behavior of the human mandible, its associated structures, and attached artificial devices is relevant for basic and clinical researches in oral biology and dentistry. Whereas the analysis of mandibular biomechanics helps us to understand the interaction of form and function, it also aids in the improvement of the design and the behavior of restorative devices placed on the structures of the jaws for rehabilitative purposes, thus increasing their treatment efficiency [1]. The masticatory system is a complicated combination of several paired anatomically complex muscles and a mandible supported by two interlinked joints. Relationships between muscle tensions, jaw motions, bite and joint forces, and craniofacial morphology are not fully understood, and critical information is often difficult or impossible to obtain in experiments on living humans [2]. Different direct [3, 4, 5, 6, 7, 8] and indirect [9, 10, 11] researches have been accomplished in order to determine the biomechanical behavior of the masticatory system. The number of direct studies of the masticatory system is limited, because its components are difficult to reach and the applications of experimental devices inside the structure introduce damage to its tissues, which influence their mechanical behavior [4].

Therefore, the mechanical forces and their distribution in most structures of the masticatory system cannot be measured directly in a non-destructive way. To study the mechanical function of the masticatory system is necessary to create a representation of the system, or a model. According to Webster's Dictionary, a model is defined as "a system of postulates, data, and inferences presented

[1]*Clinic of Prosthodontics, Kaunas Medical University, Lithuania*
[2]*Kaunas University of Technology, Lithuania*

Gaivile Pileicikiene[1] *– D.D.S., assist. prof.*
Edvinas Varpiotas[1] *– D.D.S., assist. prof.*
Rimas Surna[2] *– assoc. prof.*
Algimantas Surna[1] *– D.D.S., PhD., assoc. prof., Head of Clinic of Prosthodontics, Kaunas Medical University, Lithuania*

Address correspondence to Gaivile Pileicikiene, Clinic of Prosthodontics, Sukileliu 51, Kaunas, Lithuania.
E-mail: gaivile@gmail.com

as a mathematical description of an entity or state of affairs" [12]. By creating a model we are trying to determine the relationships between the forces at work in the masticatory system. It is hoped that this will eventually lead to the characterization of how the complete system, such as joint and mandible loads, responds to variations in morphology, occlusal load magnitude, and position. These factors are clinically significant since they are regularly modified in surgery, prosthodontics and orthodontics. Earlier described mathematical models of the masticatory loading system present several representations of the following individual subsystems:

1) the physical structures that form the mandible, articular eminence, and potentially all the structures of the scull;

2) the temporomandibular joint loads, including their location, direction, magnitude, frequency, and duration;

3) the muscle forces, including their location, direction, magnitude, frequency, and duration;

4) the surfaces of the dentition to apply and distribute generated occlusal forces.

The purpose of this investigation was to create a three-dimensional model of the human masticatory system, including the mandible, dentition and temporomandibular joints, which could be used to simulate and study the biomechanical events in the entire masticatory system.

MATERIALS AND METHODS

Skeletal morphology

In creation of three-dimensional mathematical model first step is to acquire two-dimensional images of subject. To get two-dimensional images, computed tomography scanning was chosen because the object of research was hard tissues of stomatognathic system – bone and teeth.

Required extent of CT scanning, i.e. upper and lower jaws, zygomatic bone, also required high resolution and amount of images, increased X-ray radiation for the object. It made this research problematic to perform on alive human. By choosing dead person for the study the precision of CT examination increased – voluntary and involuntary movements of research object were excluded (like breathing or muscle tonus movements). Disadvantage of CT scanning of cadaver vs live subject may be related with superior conditions of scanning and more precise results achieved, which sometimes could be impossible to achieve on live subject. Real disadvantage in scanning of cadaver is lack of control on positioning of mandible, because muscles that are responsible for positioning are in rigor. And also rigor could be the cause of unusual position of mandible. Anyway, CT scanning of dead person is first step in understanding how much precision can be achieved in scanning of human masticatory system. And only then, the dose of X-ray can be diminished to acceptable range for alive human, for instance, increasing the slice thickness, with expected accuracy of results. The problem with positioning of mandible can be solved later with computer manipulations in three dimensional models.

The research was approved by Committee of bioethics (Kaunas University of Medicine).

The following criterions were included to determine suitability of person to take part in research:

1) age of the person should be between 18 and 40 years, i.e. lowest limit ensures that permanent bite is already formed and highest limit - occlusal anatomy of teeth could be expected had insignificant changes;

2) no trauma in stomatognathic complex;

3) full dentition (the presence of wisdom teeth is optional) without signs of caries and periodontitis;

4) orthognathic type of bite;

5) no fixed prosthesis, that can disfeature CT scanning data, present in the mouth;

6) no morphological abnormalities should be found in the mandibular head or the mandibular fossa.

The sample consisted of one dead 20 year old male person. Sample size was based on goal of study – to create physiological (normal) mathematical model, which could be changed into various pathological situations (like loss of teeth, changes in occlusal anatomy) by taking or adding details to it. Object of research met high requirements, it was nearly ideal conditions arranged and because of it the object could be called physiological. As it was documented in case-record the cause of death was brain lesion as result of trauma. No damage of skull, mandible or teeth was detected in CT scans done before study and in study. General status of health - before death, patient was unconscious for several days; no concomitant diseases to trauma were presented in case-record. Dental status was examined before CT scanning: it was orthognathic (physiological) type of bite, no fillings or any prosthetic restorations present, occlusal surfaces of teeth had cusps and grooves, i.e. no signs of bruxism, attrition, erosion, abfraction or other lesion of hard tissues as also soft tissues too.

Multisection spiral computed tomography was performed (General Electrics) in the area from infraorbital region to the mandible and 1500 slices within thickness of 0,625 mm were gained. A CT scanning protocol and reconstruction parameters are presented in Table 1.

Model generation

Computer-aided techniques like CAD or CAM requires an efficient coordinate measuring technique in order to achieve precise correlation between the numerical model and the actual masticatory system. Surfaces of the human masticatory system models were created from spiral computed tomography two-dimensional images (Fig. 1). It was then possible to visualize the components of masticatory system from arbitrary directions and sections with computer graphics. The CT 16 bit DICOM format images were converted into 16 bit TIF format. Media Cybernetics' software "Image-Pro Plus" was used for collecting 3D contour coordinates and placed in a text file, which is suitable for Electronic Data Systems Corporation software "ImageWare". 3D modeling starts from one separate bone or just a fragment of bone. The number of points is optimized by reducing it that much that model can stay fairly accurate. The areas of point clouds poligonized and their mathematical chatacteristics are presented in Table 2. The accuracy of the model was not estimated. Image size of CT 512x512 pixels, each point of the contour of investigative object was used for this model. The resolution of the CT: for common view – DX=0.6 mm, DY=0.6 mm, DZ=0.1 mm; for separate parts of the model we used the maximum resolution of the CT – DX=0.1 mm, DY=0.1 mm, DZ=0.1 mm.

RESULTS

A finite element model of the masticatory system including the jaws, the dentition and the TMJ from a dead person was created. The model simulates these structures: maxilla, mandible, articular eminence of temporal bone, maxillary and mandibular teeth. Poligonized left and right temporal mandibular fossae (grey) and mandibular condyles (dark grey) are shown in Fig. 2. These wiev series represent elements of the TMJ in different spatial positions. Poligonized mandible is presented in Fig. 3. Such 3D mathematical model characterised with referenced parametres can be used in the mathematical analysis of strain and stress distributionn in the human masticatory system, however, improvement of its physical properties is required for more accurate outcomes.

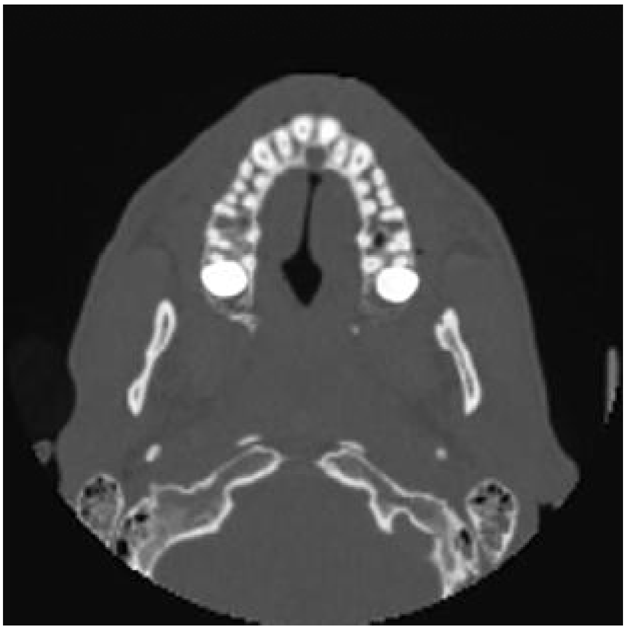

Fig. 1. 2D tomography scanning image

Table 1. Technical characteristics of CT scanning

Tube voltage	120 kV
Tube current	650 mA
Slice thickness	0,625 mm
Table movement speed	1 mm/sec
Image size	512 * 512 pixels

DISCUSSION

Different experimental approaches have been used to investigate biomechanical events in the human masticatory system. Unfortunately, most of the methods have meaningful limitations. The invasive nature of the direct methods decrease their reliability, since the insertion of experimental devices, such

Table 2. Areas of point clouds poligonized and their mathematical chatacteristics

	Data points	Poligons	Points as vertices	Size X	Size Y	Size Z
Mandible	153529	34740	17167	196.43 mm	167.60 mm	90.01 mm
Left mandibular fossa of temporal bone	1335	2584	1335	42.14 mm	38.05 mm	10.10 mm
Right mandibular fossa of temporal bone	1054	2045	1054	40.21 mm	35.62 mm	10.24 mm
Left mandibular condyle	19149	3897	1980	26.81 mm	19.19 mm	7.71 mm
Right mandibular condyle	6394	12522	6331	29.04 mm	17.87 mm	8.29 mm

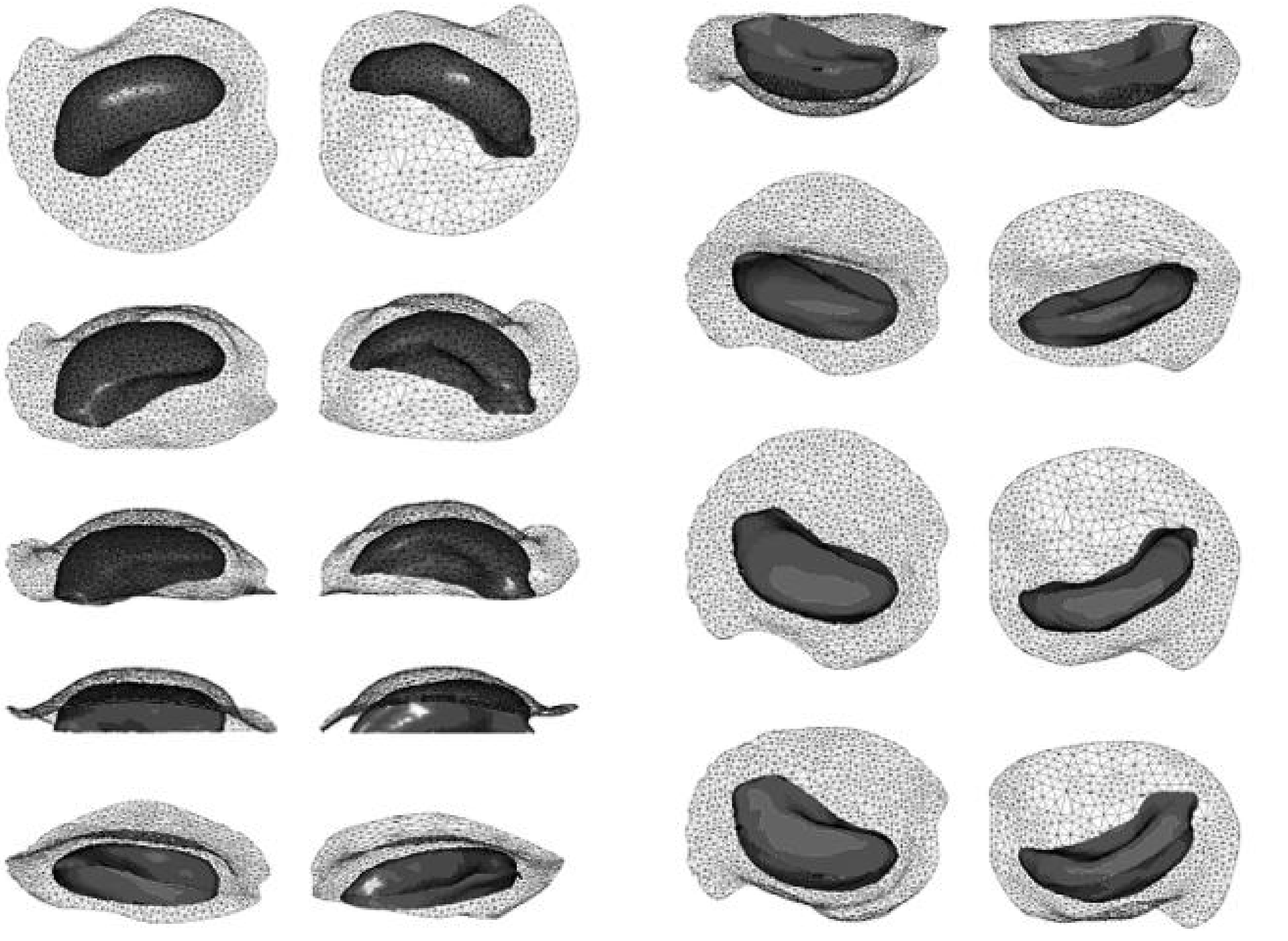

Fig. 2. Poligonized left and right mandibular fossae of temporal bone (grey) and mandibular condyles (dark grey)

as strain gauges, inside the structure bring damage to its tissues [4], while placing the measuring device in or between the dental arches [5, 6, 7] disturb normal physiological function which influence their mechanical behavior. Besides, the direct experimental techniques deliver only local measurements of specific points [8], giving only an approximation of the biomechanical behavior. In previous studies, several indirect techniques were tried to evaluate mandibular biomechanics. Descriptive or comparative studies [9] are good in deriving macroscopic information, but do not estimate specific masticatory loads. Humanoid robotic approach has some significant limitations because these measurements are performed on a dry skull, where dentition does not have the periodontal ligaments, so the mechanical properties and simulation conditions are far away from physiological state [10, 11]. Indirect studies, based on physical modeling techniques, such as mandibular [13] and dental [14] photoelastic systems, Moire fringe technique [15], and laser holographic interferometry [16], also had limited success, evaluating only surface stress of the model but did not reproduce its mechanical properties. Eventually, the mathematical modeling technique, based on finite element analysis, is used widely in biomechanical studies for given advantages: it enables simulation of geometry and mechanics of a real object, the me-

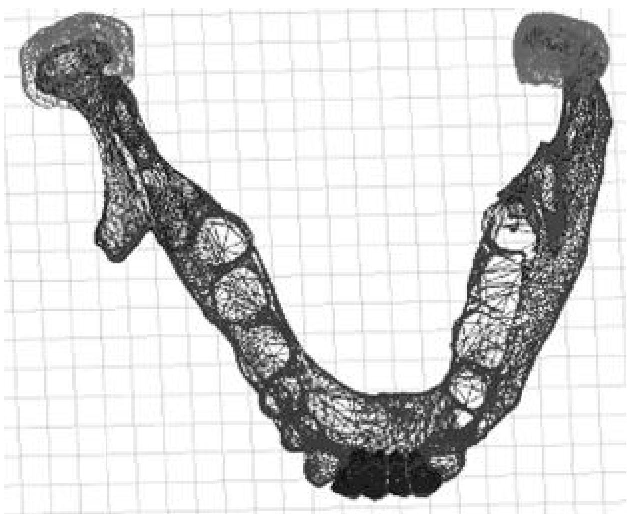

Fig. 3. Poligonized mandible

chanical behavior of the model is similar to that of the real object, internal stresses can be quantified in the model, and the point of exertion, magnitude and direction of any given force can be easily changed in order to simulate different functional situations [21]. Many studies, based on three-dimensional FEM have been performed and published. Some of them were based on computed tomography [27, 28, 29] and others on photographs of sections of different specimens [24, 25, 26]. Computed tomography scanning has the limitations to apply on a living object due to high X-ray radiation, which increases with the accuracy of examination. Also CT scanning is not usable when an object of research has any metal restorations in the mouth, because metal artifacts may appear in the CT images, and in particular the precision of the model construction for tooth shape may deteriorate [29]. The technique of sectioning the specimen has substantial limitations regarding the technical difficulty in obtaining sections with a uniform thickness, destruction of a specimen and the time and effort required in its preparation. A method of magnetic resonance imaging is commonly applied to reconstruct the soft tissue geometry, but it also has the detection limit of imaging [30].

The present study represents an initial stage of research to evaluate the loading in the human masticatory system in different simulated physiological and pathological situations. Development of this 3-D FE model to include more elements, finer mesh details, differential osseous moduli, teeth and periodontal membranes, implants and prosthetic appliances, will provide future insight into strain distribution in the masticatory system and potential clinical application. Tomography scanners are improving; dozes of radiation are decreasing and scanning only particular areas of jaw bones and skulls the amount of radiation can be minimized till acceptable size.

CONCLUSIONS

1. Acquisition of the 3-dimensional shape of the human masticatory system, including the jaws, the dentition and the temporomandibular joints is necessary for mathematical analysis of strain and stress distribution in the human masticatory system. Such analysis may be useful for quantitative evaluation of the diagnosis and treatment of occlusal disorders.
2. The inaccessibility of the mandible and its related structures is a major obstacle to measure their internal forces and stresses, and understanding their effects. Computer modeling offers an alternative method for doing this. Despite its limitations, modeling can provide a useful conceptual framework for developing hypotheses regarding the role of stresses during human masticatory system function.

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