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Reverse modeling of the human mandible 3D geometric model

Reverzno modeliranje 3D geometrijskog modela donje ljudske vilice

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Abstract

Background/Aim. The geometry of each bone in the human skeletal system is unique. The aim of this research was to present application of a new method, method of anatomical features (MAF), for the creation of the geometrical model (surface and solid) of the human mandible. **Methods**. The method was based on Referential Geometrical Entities (RGEs) which have been defined on mandible polygonal model in accordance with anatomical properties of the mandible. Polygonal model was created over the input data (anatomical landmarks of the mandible) acquired from computed tomography scans. For the creation of computer-aided design (CAD) models in CATIA software, referential geometrical entities were defined according to the bone geometry and morphology features. **Results.** Definition of B-spline curves was performed on the body and on the ramus of the mandible. In this way, it was possible to create the geometrically accurate and anatomically correct three-dimensional geometric (surface and solid) models. The accuracy of the obtained surface model was tested through comparison with the geometry of the original bone model. **Conclusion.** Compared to the previously applied methods for creating geometric models, MAF provides more satisfactory results, and in some cases even better.

Key words:
mandible; methods; models, anatomic; printing, three-dimensional; technology, medical; tomography, x-ray computed.

Apstrakt

Uvod/Cilj. Geometrija svake kosti skeletnog sistema čoveka je jedinstvena. Cilj ovog istraživanja bio je da se prezentuje primena nove metode, metode anatomsikih entiteta (MAF) za kreiranje geometrijskog modela (površinskog i zapreminskog) ljudske donje vilice. **Metode**. Metod je baziran na referentnim geometrijskim entitetima (RGEs) koji se definišu na poligonalnom modelu mandibule, u skladu sa anatomskim osobinama mandibule. Poligonalni model je kreiran preko ulaznih podataka (anatomskih orjentira donje vilice) dobijenih na osnovu podataka sa snimaka kompjuterizovanom tomografijom. Za kreiranje kompjuterski podržanim dizajnom (CAD) modela u programu CATIA, referentni geometrijski entiteti su bili definisani u skladu sa geometrijskim i morfološkim odlikama mandibule. **Rezultati**. Definisanje B-*spline* krivih vršeno je na telu i granama mandibule. Na taj način je bilo moguće kreirati geometrijski tačan i anatomski korektan trodimenzioni geometrijski (površinski i zapreminski) model. Tačnost dobijenih površinskih modela je testirana upoređivanjem sa geometrijom originalnog modela kosti. **Zaključak.** U odnosu na ranije primenjene metode za kreiranje geometrijskih modela, MAF daje zadovoljavajuće rezultate, u nekim slučajevima čak i bolje.

Ključne reči:
mandibula; metodi; modeli, anatomski; štampanje, trodimenzionalno; tehnologija, medicinska; tomografija, kompjuterizovana, rendgenska.

Introduction

The development of computed tomography (CT) and three-dimensional (3D) reconstruction brought a revolution in diagnostic radiology. 3D reconstruction algorithms were more optimized and three-dimensional image reformatting of standard two-dimensional (2D) CT data became an often used tool to provide the radiologist and surgeon with readily recognizable images of the complex anatomic structures [1].

The creation of the 3D digital models with the help of reverse engineering and geometric morphometric methods (GMM) create the fundamental part of a new field of the "virtual anthropology" (VA) [2]. VA, or "virtual morphology" enables working with virtual copies of specimens and analyzes of shape and size based on a comprehensive quantitative basis that can capture the complete geometry. In VA, advance statistical methods, computer graphics, informational technologies are used, which enables us to

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obtain geometrical, topological and morphological data on the observed object [2].

An anatomically correct and geometrically accurate model of a human bone (in this case the human mandible) is necessary in the computer-based preoperative planning especially in orthodontics, prosthetics, and maxillofacial surgery. Such model allows the creation of the patient-adapted bony implants, and different devices such as the fixators improving the preparation and simulation of surgical interventions [3].

“The mandible is more susceptible to trauma compared to other body parts due to its localization and anatomy” [4]. A surgical reconstruction of some mandibular congenital deformities is a very complex procedure, difficult for patients. Sometimes it is accompanied with distinct craniofacial deformities or missing bony structures. The main reasons for such pathological bony features are: bony fractures, malformations, tumors and another injuries. Creation the 3D geometrical model of the human mandible is a challenge, because the mandible has a very complex shape, structure and geometry [5].

There are two general approaches to the generation of 3D geometrical models of human bones [6].

The first method for creating a geometric model is based on the use of volumetric scanning methods. Volumetric scanning methods (CT or magnetic resonance imaging – MRI) allow the creation of 3D data sets that can be transformed into an adequate model (e.g. polygonal) suitable for further processing. Data processing is usually performed in specialized software solutions [7, 8], such as, for example, Mimics [9], 3D Doctor [10] which at the same time enable the conversion between various formats of geometrical models.

The second method for creating a geometric model of the bone is based on the bone shape prediction. Predictive models are models whose geometry and topology can be adjusted to a specific patient, based on specific parameters [6]. Morphometric parameters are measurable dimensions, and can be obtained based on 2D images (X-ray) or volumetric models obtained by a volumetric scanning method (CT, MRI). Models obtained by this method are very accurate if the number of parameters are adequate and model structure itself is well-chosen. Benazzi et al. [11] and Higgins et al. [12] propose the mathematical-statistical GMM to create predictive (statistical) model.

The mandible, because of its characteristic shape, structure and geometry represents a real challenge for geometric modeling. The accuracy of the model geometry plays a crucial role in a variety of research and analysis. Stavness et al. [13] developed a biomechanical model of the human jaw and laryngeal structures. The process of creating the model geometry is realized on high resolution CT scans. Software application Rhino [14] is used to fit nurbs surfaces to the segmented data. Biomechanical models provide information on the model geometry and provide an important platform during the appliance and efficiency of the simulation of the human system. Therefore, correct and precise geometry of a model is necessary. Model of the human masticatory system which can be used to simulate the action of simple bites, is presented by Essen et al. [15]. The geometry of the skull and jaw model was created using high order cubic Hermite elements. The authors have chosen these items because such model: preserves continuity between the derivative element boundaries allowing for a mesh that accurately represents the geometry using a far smaller number of elements. The accuracy of the model geometry plays a crucial role, because of analyzes carried out on the model.

Mandible shape modeling using the second eigenfunction of the Laplace-Beltrami operator is presented by Seo et al. [16]. The method described in the previously mentioned paper is based on the centreline, anatomical landmarks to quantify mandibular shape. The centreline (passing through the middle of mandible), provides a framework for modeling and assessment of the development of the mandible jaw between the ages from birth to 20 years. This approach provides additional information about the anatomical marks and morphometric measurements, model or poor geometric accuracy.

Application of method of anatomical features (MAF) is initially used for the creation of geometrical models of the human long bones (polygonal, surface and solid) [6]. The main challenge for the author of this study was to change the MAF for creating geometric models and other types of bones.

MAF is based on referential geometrical entities (RGEs). RGEs (lines, planes, curves, points, axes) are defined on polygonal model. The process of creating RGEs for the creation of an appropriate geometric model of the bone is based on the anatomical and morphological characteristics of the bone. In this way, the estimated models maximally suits the real bone of the patient. A quality of the created geometric model allows to an easier and more precise preoperative preparation in the surgery, implementation of the implants, placement of the fixators etc.

The main aim of MAF application is to generate the 3D geometrical models of the bones (polygonal, surface and solid) and parametric models [17] (predictive bone models), with high geometrical accuracy and anatomical precision. Geometrically accurate and anatomically correct 3D model of the bones, created by using application of MAF, also allows the creation of the patient-adapted (personalized) bone fixators [18] and implants [19].

In this paper application of MAF for the creation of 3D surface model of human mandible is presented. The accuracy of obtained 3D surface was tested by two analysis: one for the surface deviations and the second one for the analysis of morphometric parameters. The results of analyses were satisfactory.

Methods

In this research, geometrical analysis of the human mandible was based on input data by using CT scans. 64-slice – multislice CT (MSCT) scanner was used (Aquillion 64, Toshiba, Japan), and standard protocol for recording was applied: voltage of 120 kVp, tube current of 150 mA, rotation time of 0.5 s, and thickness of 0.5 mm. The mandible samples came from Serbian adults males aged from 50–70 years. The raw data, coordinates of points of scanned tissue, were imported into the appropriate computer-aided design (CAD) software for reverse modeling. Reverse modeling of the human bone's geometry using CAD software to create 3D digital model of human bones was primarily based on radiological images (X-ray, CT, MRI). In this research, CATIA V5 R21 [20], CAD software were used.

The steps that used to create surface model of the mandible were described by Vitković et al. [7] and they were: creation of the anatomical model; preparatory processes (importing and sorting out the cloud of points, creating a polygonal model); definition of the RGE of the human mandible; definition of the anatomical points and creation of the spline curves; creation of the surface model of human mandible.

Creation of the anatomical model

The anatomical model was based on anatomical landmarks of the certain human bones. Anatomical landmarks were presented on anatomical pictures in anatomical atlases, but according to the complex morphology of the human bones, their best definition had to do experts, anatomists or anthropologists. Anatomical model of the bone "described" the relations between anatomical landmarks and their position on the polygonal model.

The mandible (lower jaw, lat. *mandibula*) [21–24], is the biggest and most massive face bone of the viscerocranium, connected with skull by temporomandibular joint. It participates in the construction of the temporomandibular joint by its condilar process. The temporomandibular joint is only movable joint of the head. The main parts of the mandible are the body and the ramus. Between these parts is a mandibular angle.

The body of the mandible (lat. *corpus mandibulae*) has a horseshoe shape and represents its horizontal part. Its upper part called alveolar part, made inferior dental arch. The body of the mandible has two sides (external and internal) and two margins, the upper one which matches the dental arc (lat. *arcus alveolaris*) and a lower edge or the basis of the mandible (lat. *basis mandibulae*).

The ramus of the mandible has approximately rectangular shape. It is located upward and backward in relation to the mandibular body forming an angle of 90°–140°, most commonly 120°–130°. It has two sides: external and internal, and four edges: upper, lower, anterior and posterior. The upper edge has two processes: anterior or coronoid (lat. *processus coronoideus*) and posterior or condilar (lat. *processus condylaris*). The latest one is composed of two parts: the upper one or head (lat. *caput mandible*) and the lower one or neck (lat. *collum mandible*). The head of the mandible is triangular in shape, flattened in the anteroposterior direction. The neck of the mandible represents the lower, narrow part of the condylar process. Anatomy of human mandible is presented in Figure 1.

Preparatory processes

Preparatory processes included: importing and sorting out the cloud of points and creating a polygonal model. After defining the anatomical model, creation of the basic model geometry was introduced. Preparatory processes were presented in the paper Vitković et al. [7] and included the following steps: CT scanning of the part human body (in this case the human mandible), preprocessing of raw data (scans), their transformation into STereoLithography (STL) format, importing the scanned models in STL format into CATIA application. At the end of the preparatory processes [6], the polygonal geometrical bone model was created.

Definition of the RGE of human mandible

The coordinate system was created on the polygonal model. Origin of the coordinate system was defined as the middle of the distance between the most lateral points on the right and left condyles. The constructed planes of the object coordinate system (OBC) of mandible were presented on Figure 2 and they were: medio-sagittal plane (MSP), horizontal plane (HP) and coronal plane (CP). MSP was constructed as the plane which contains the Origin of the OBC normal to bicondylar breadth (Con-ConD).

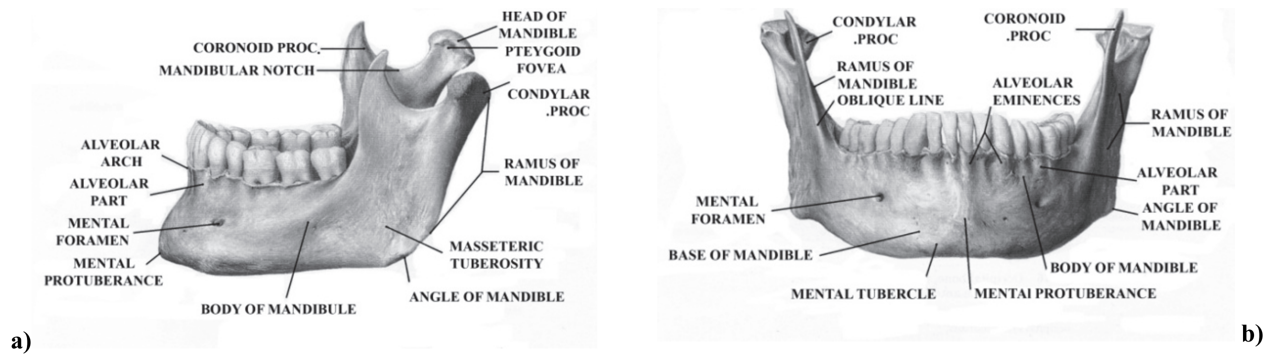

Fig. 1 –The mandible: a) lateral aspect; b) anterior aspect [1].

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[1] Figure 1 was taken and modified from Atlas of Human Anatomy, Head, Neck, Upper-Limb, Sobbota, 1993.

Table 1

Anatomical landmarks (points)

Anatomical landmarks	Definition
Mental foramen	One of two foramens located on the anterior surface of the mandibular body
Gnathion	The most inferior midline point on the inferior margin of the mandibular body
Gonion	The most inferior point on the mandibular angle (bilateral)
Condylion	The most prominent point on the condylar process (bilateral)
Mandibular notch point	The point in the middle part of the mandibular notchs

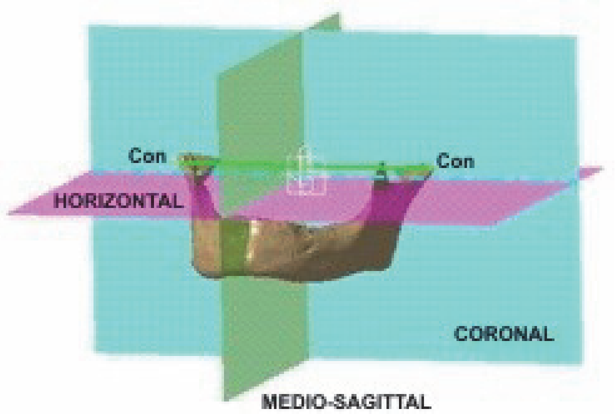

Fig. 2 – Coordinate system defined on a human mandible polygonal model.

MSP was a plane which separates human mandible on two halves – left and right. MS contained the gnathion (Gn) anatomical point (the most inferior midline point on the inferior margin of the mandibular body). HP was the plane normal to the MSP and it contained the gonion (the most inferior point on the mandibular angle) anatomical point. To be used as a plane of OBC, this plane was translated to the origin of OBC. CP was a plane which was normal to the HP and divided the mandible on two anatomical sections – anterior and posterior. It was placed at the Origin of OBC. X axis of the OBC was defined as normal to MSP. Y axis was defined as normal to AP plane. Z axis was normal to HP.

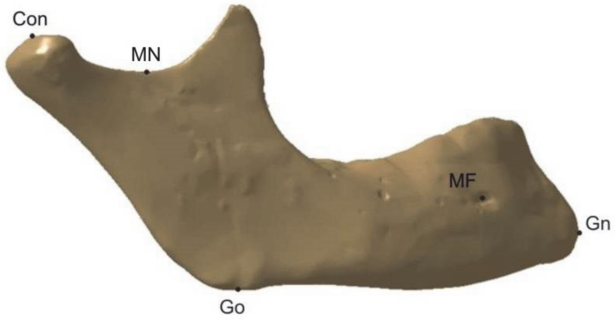

Fig. 3 – Anatomical landmarks points.

Con – condylion; MN – mandibular notch point; MF – mental foramen; Go – fonion; Gn – gnathion.

Characteristic bony landmarks on the human mandible were defined in the previous publication [25], and in this article they are presented in Table 1 and Figure 3. Definition of the mandibular anatomical landmarks was performed on the polygonal model. Points had to be defined separately for each of the human bone in relation to its anatomical and morphological characteristics. The mandibular notch point (MN) was added by the authors of this research, because it was necessary as a support point for the proper definition of coronoid process geometry.

Definition of the anatomical points and spline curves

Definition of the geometric entities was done on the polygonal model of the mandible. Geometrical entities, the B-spline curves, were defined following the bone geometry and its specific morphology, and in accordance to the anatomical bone model of the mandible. B-spline curves were created by the cross section of the adequate planes and polygonal models. The set of B-splines defined over the whole polygonal bone model has been called the skeleton model [7] [*]. Definition of B-spline curves were performed on the body and the ramus of mandible. B-spline curves on a polygonal model of the mandible are shown on the Figure 4. The anatomical points on each B-spline were defined manually. B-spline curves were divided into several parts (each part defines the appropriate points).

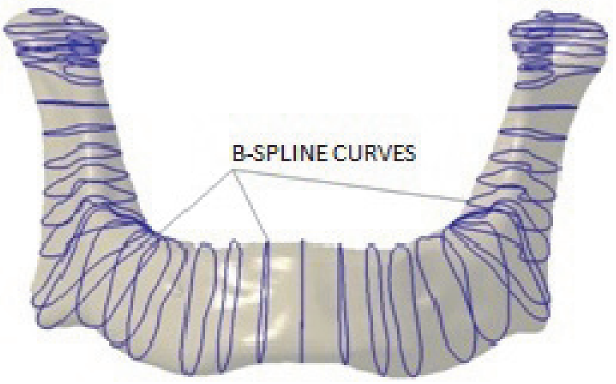

Fig. 4 – B-spline curves on a polygonal model of the human mandible.

Definition of the surface model of human mandible

Based on the axis of rotation (Z axis) and MSP, it is possible to define rotational planes, which are defined to form a certain angle with the basic plane of the intersection, passing through the axis of rotation. Based on the characte-

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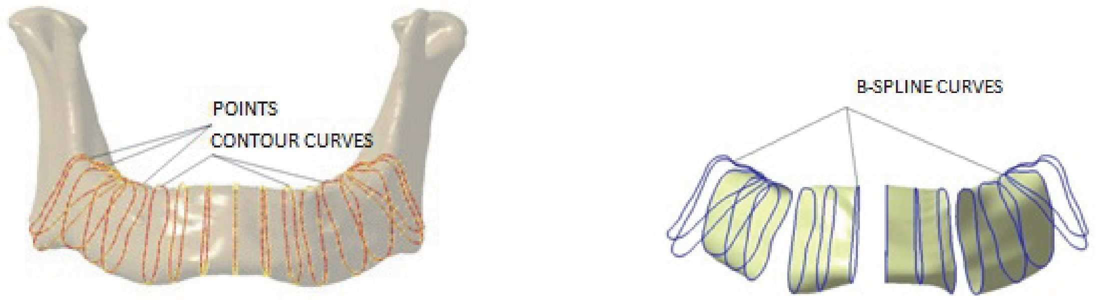
[*] Term *skeleton* has geometrical meaning not anatomical.

ristical anatomical landmarks of the mandible [25] and MSP (rotated to the right angle), sixteen planes were created. Sixteen planes of intersection were defined on the elements of the polygonal model which define some characteristic elements of the bone surface. These planes were used to create cross-sections. At the intersection of these planes with polygonal model, contour curves were generated. These curves were used to create points and spline curves (B-spline) (Figure 5a). Spline curves were used to create surface model of the mandibular body and the ramus (Figure 5b).

A similar procedure, with fourteen planes was used to create a 3D model of the mandibular ramus. Spline curves follow the shape of the ramus, and in that way the morphology (form or shape) of the bone is preserved. B-spline curves created on the ramus polygonal model are presented on the Figure 6a and b, showing that splines follow the external morphology of the bone.

3D surface model of human mandible was created by merging 3D surfaces of the mandible body and ramus. The solid model was obtained by filling the volume of the surface model in CATIA (Figure 7).



a)

b)

Fig. 5 – a) Points and contour curves on the body of mandible; b) Creation of the 3D surface model.

a)

b)

Fig. 6 – a) Points and contour curves on the ramus of the mandible; b) Creation of the 3D .

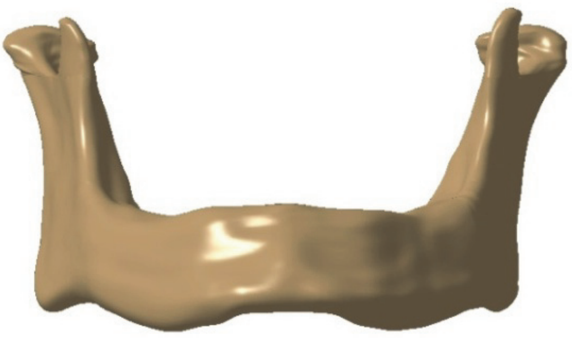


Fig. 7 – 3D solid model of the human mandible.

Results

Geometrical accuracy of the obtained surface model was tested by the application of the deviations analysis in CATIA software. Two analysis were performed, one for the surface deviations and the second one for the analysis of morphometric parameters.

Maximum surface deviations

Maximum surface deviations of the surface model of human mandible created from the input surface models of the original mandible specimens are presented in Figure 8. The surface models were created by using Quick Surface Reconstruction module (QSR) – automatic surface feature in CATIA software.

Deviation values are displayed in different colors. It can be noticed that deviation value was also below the recommended limit. Maximal deviation was 1.66 mm displaying the deviation of common region between two surfaces.

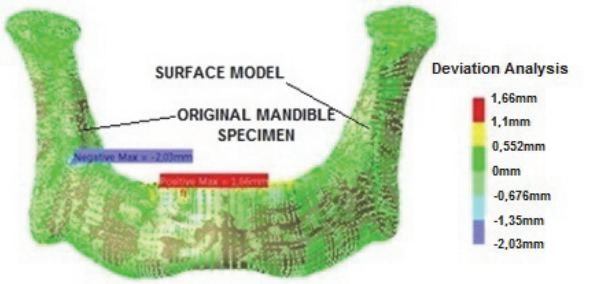


Fig. 8 – Maximum deviations of the calculated surface model of the human mandible from the input human mandible models.

Analysis of morphometric parameters of the human mandible

Data from the literature [25] (Figures 9–11), indicates that the configuration of the mandible can be accurately perceived by means of ten (10) basic central and bilateral morphometric parameters presented in Table 2 and Figure 12.

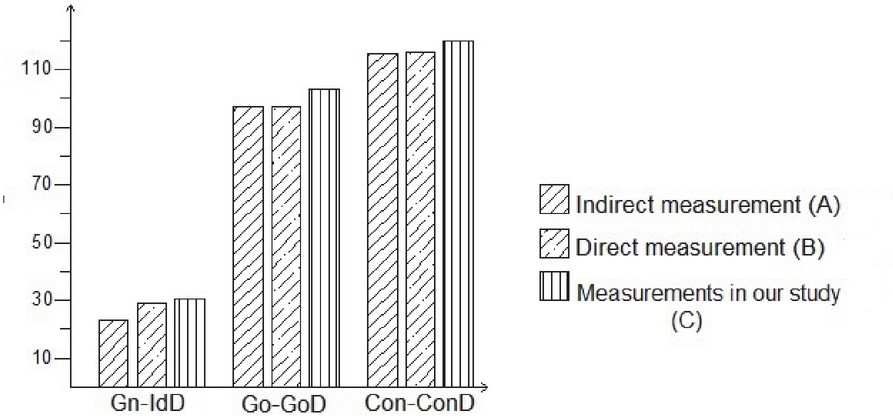


Fig. 9 – Comparison of our results (C) with those from the study of Arsić et al. [25] (A, B). For abbreviations see in Table 2.

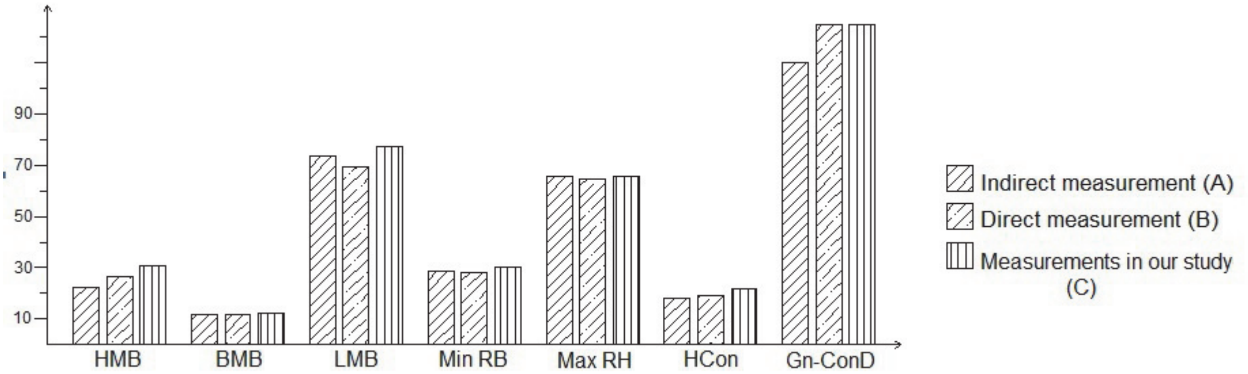


Fig. 10 – Bilateral morphometric parameters measured on the right half of the mandible: comparison of our results (C) with those from the study of Arsić et al. [25] (A, B) For abbreviations see in Table 2.

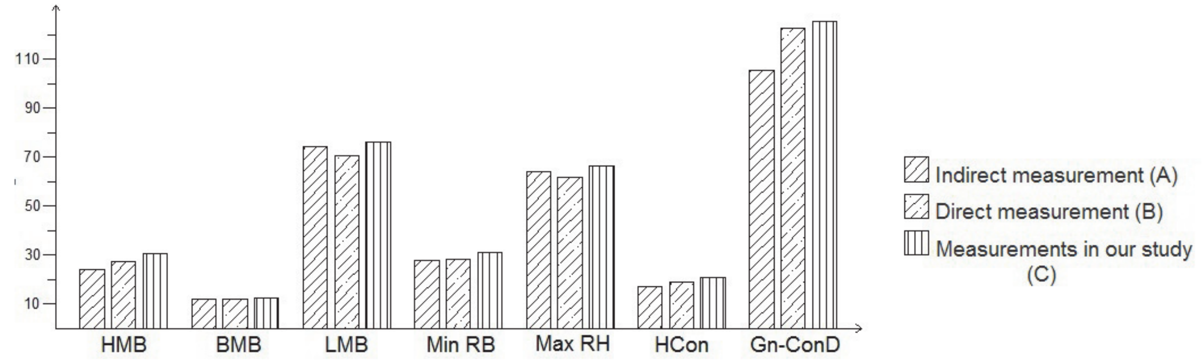


Fig. 11 – Bilateral morphometric parameters measured on left half of the mandible: comparison of our results (C) with those from the study of Arsić et al. [25] (A, B) For abbreviations see in Table 2.

Table 2

Central/midline morphometric parameters (MP)

MP	Definition
Gnathion-interdental distance (Gn-IdD)	Distance from the gnathion (Gn) to the alveolar septum between two incisors
Bigonial width (Go-GoD)	Direct distance between right and left gonion (Go)
Bicondylar distance (Con-ConD)	Direct distance between the most lateral points on the right and left condyles
Height of the mandibular body (HMB)	Distance from the alveolar border to the mandibular base at the level of the mental foramen (MF)
Breadth of the mandibular body (BMB)	Maximum breadth measured at the level of the mental foramen perpendiculary to the long axis of the mandible
Length of the mandibular body (LMB)	Distance between Go to Gn
Minimum ramus breadth (Min RB)	Minimum breadth of the mandibular ramus measured perpendiculary to the plane of the maximal height of the ramus
Maximum ramus height (Max RH)	Distance between the highest point on the mandibular condyle (condylion) (Con) to Go
Height of the condyle (HCon)	Distance between the Condylion (Con) and axis of the most inferior point of mandibular notch perpendiculary to Max RH
Gnathion-condylar distance (Gn-ConD)	Distance between Gnation (Gn) and Condylion (Con)

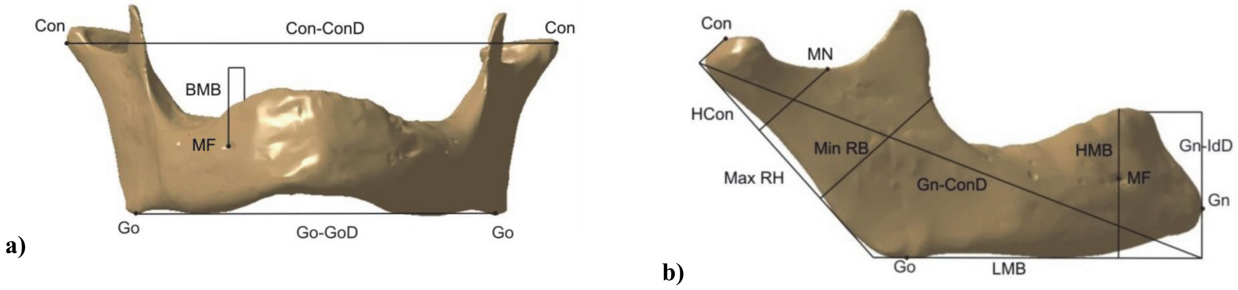


Fig. 12 – Morfometric parameters and anatomical points presented on polygonal model of the human mandible: a) anterior view; b) lateral view. For abbreviations see in Table 2.

Position of anatomical point directly affects on values of morphometric parameters. Results of analysis for morphometric parameters are presented for ten (10) surface models created by MAF.

Table 3 shows the mean values of the central/middline morphometric parameters obtained through indirect measured and standard deviation.

Tables 4 show the average values and standard deviations of bilateral morphometric parameters measured on both sides. There was no statistically significant difference between the analyzed measurement values on the left and right sides.

Table 3

Central/midline morphometric parameters (MP)

MP	Mean (mm)	SD (mm)
Gn-IdD	30.462	0.48
Go-GoD	103.73	0.50
Con-ConD	126.509	0.54

Note: MP are defined in Table 2.
SD-standard deviation.

Table 4

Values of the bilateral morphometric parameters (MP) measured on the left and right half of the mandible

MP	Left	Right
	mean ± SD (mm)	mean ± SD (mm)
HMB	30.579 ± 0.45	30.648 ± 0.52
BMB	11.9 ± 0.17	12.0 ± 0.16
LMB	76.957 ± 0.75	77.028 ± 0.72
Min RB	30.937 ± 0.27	30.478 ± 0.26
MaxRH	66.524 ± 0.78	65.586 ± 0.59
HCon	20.974 ± 0.39	21.65 ± 0.40
Gn-ConD	125.653 ± 0.99	124.936 ± 1.21

Note: MP are defined in Table 2.
SD - standard deviation.

Discussion

In the previous published paper [26] two approaches to obtain 3D geometric surface model of the human mandible were presented. The first one was the classical techniques of reverse engineering and the second one was based on the MAF. Maximal deviation value of the surface model created by MAF is 1.66 mm, 22.3% better than on the surface models created by classical techniques of reverse engineering (2.03 mm). This means that the quality of the resulting geometrical model of the mandible has a direct relationship to the precise identification of RGEs. Definition of RGE of the human mandible allows of the significant progress in reverse modeling and defining the precise geometry of the mandible.

The data from the litrerature [25] show that the configuration of the mandible can be accurately defined by means of the ten (10) basic central and bilateral mandibular parameters (Figure 9). Central and bilateral morphometric parameters were obtained by indirect measurement in this research.

In the previous study of Arsić et al. [25], the morphometric parameters were measured directly (using the callipers with precision of 0.05 mm) and indirectly (2D reconstructions of MSCT recording). Our research clearly shows that the indirect measurement of morphometric parameters on 10 mandible surface model, obtained on the basis of CT scan, gives valid results compared to the correspondent values obtained in the mentioned study. Comparison of the measurement results in our study with those in the study of Arsić et al. [25] is shown in Figures 1–3.

In the study of Čutović et al. [27], a radiographic cephalometry analysis of dimensions of condylar processus in persons with mandibular prognathism was done. Comparing the dimensions of condylar instalment in eugnathic people (people who, according to orthodontic current criteria, have a harmonious appearance of the face), has shown that there is a nonexistent statistical significant difference compared to our mean values for HCon (> 2.2 mm) and Max RH (> 1.574 mm). Three-dimensional analysis of the parameters is essential for: creating a statistical model of the mandible [28] and the analysis of craniofacial morphology [29]. Analyzing mean values of parameters Max RH, Gn-ConD and HCon from the above mentioned study [27], it was shown that they are larger (> 5 mm) than our correspondent mean values. Imprecision in the determination of the characteristic anatomical points, directly affects the values of morphometric parameters. For this reason, errors in the definition of the bone geometry, or measurement errors of the morphometric parameters should be kept to a minimum.

Numerous morphometric studies were performed on human mandible suggest their significant variability in relation to gender and ethnic affiliation of population [30–34]. Population shows many differences in the various details of the facial bone morphology [30]. These differences are easily noticeable when comparing individuals of different ethnic backgrounds. Chinese people have more dental protrusion, shorter midfacial length and steeper mandibular plane, compared to British Caucasian counterparts [31]. Huang et al. [32] compared Americans from Africa and Europe, a descent living in Birmingham, and demonstrated greater bidentoalveolar protrusion in the African American sample. Some studies show that differences also exist among populations of the white race [33, 34]. In the feature investigation we can precisely define morphometric parameters according to the anatomical variations, gender, age, ethnic origin and state of dentition, on the 3D model of the human mandible.

Conclusion

MAF was initially applied for the development of the polygonal, surface and solid model of the human long bones. We presented that it is possible to apply the mention method for creating geometric models and other types of bones (in this case the human mandible). The accuracy of the obtained surface models was tested through the comparison with the original polygonal model geometry, obtained of the CT scans. Two analysis were performed, one for surface deviations and second for the analysis of the morphometric parameters. The created 3D geometrical model of the human mandible obtained by MAF has high geometrical accuracy and anatomical precision.

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