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Optical Aspect of Deformation Analysis in the Bone-Denture Complex

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A B S T R A C T

The aim of this study was to register and measure any deformation of mandible models under load. The method for full field measurement of strain is done by using the ARAMIS three-dimensional image correlation system. The system uses two digital cameras that provide a synchronized stereo view of the specimen and the results show the complete strain field during the tests. The biggest deformation values were just under the working force of the biggest intensity 500 N, and for the region of the lower second premolar the deformation is 625 μm. The following study is presented that highlight the use of stereometric measuring system for modern research. It is shown that this measuring methodology can capture the trends of the experiments.

Key words: *optical measurement, strain distribution, human mandible, biomechanics, bone*

Introduction

Knowledge of the biomechanical behavior of the human mandible is very important and may be useful in various clinical situations. From the biomechanical view the mandible is a specialized structure, where muscles, joints and teeth work in a complex synergy, adapted to function in the highly developed masticatory system[1].

During mastication, stress distribution can cause strain in all structures of the mandible: bone, teeth and periodontium[2–5]. As a result of this functional mechanical stimulation stomatognathic structures are subjected to modeling and remodeling events achieving their mature morphologic and physiologic characteristics. Bone remodeling is also an essential component of a successful therapeutic response to many dental procedures. Following the tooth extraction, the alveolar ridge undergoes continual resorption, whereas in terms of the intensity and direction of reduction process, the alveolar ridge of the lower jaw has more unfavorable course than the upper alveolar ridge. Unlike in dentate mandibles, stress distribution in rehabilitated edentulous mandibles is distributed, from denture through mucosa to alveolar bone and rest of the bone tissue. Dentures likely do not give adequate functional stimulation to the bone as do natural teeth. Moreover, compressive forces have been transmitted via dentures to the denture bearing area[6]. The lack of proprioceptive perception due to lost periodontal receptors cause overloading of denture bearing area during chewing resulting in higher resorption rate[7–9].

The biomechanical and physical behaviour of mandibles have been investigated by different approaches[1–5,10]. The study presented here describes the experimental evaluation of human mandibular deformations under standardized in vitro loading conditions. Biomechanical parameters, strains and displacements, were investigated under simulated loading. It was the objective of this study to present non-contact Digital Image Correlation Method (DIC) as an optical method for investigating complex biomechanical reactions of mandibles under mechanical loading. The closer aim was to analyze, register and measure deformation of bone fundament in mandible with intact dental arch and denture rehabilitated edentulous mandible during simulated occlusal loading.

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Method and Material

Two dry human mandibles were used in order to assess the biomechanical behavior of the jaw during various masticatory conditions. The mandible with intact dental arch was first analyzed and the second was edentulous mandible with acrylic denture manufactured and placed over residual ridge. Both mandibles were borrowed from the Laboratory for Anthropology, Institute of Anatomy, School of Medicine, University of Belgrade. According to data from Laboratory archive donors for both mandibles were men, in late fourties from Serbia population. Mandibles were inspected visually and evaluated, because it was necessary for experimental models to be without evident traumatic and pathological damages. Complete denture was fabricated for the edentulous mandible according to accepted dental procedures for manufacturing complete denture. Afterwards, mandibles were immersed and left in the physiological (saline) solution (0,9% NaCl) for 24 hour in order to reach the volume and elasticity as *in vivo* studies[11].

After drying at the temperature of 27°C, both jaws and lower complete denture were lacquered with a white spray of great density. Prepared models were placed in the tensile testing machine. First step was measuring the bone deformation of the full dentate lower jaw. Afterwards, the second experimental model of edentulous lower jaw with complete denture was tested (Figure 1). Applied forces in the experiment were in the range of 100 to 500 N. Precise and controlled loading was measured using gnathodynamometer (Siemens) horizontal extension. Direction of applied load was axial to second premolar and first molar with maximal distribution in centric supporting contacts.

Precise measurement of strain in this research was conducted using the equipment of manufacturer GOM. System consists of two digital cameras and software ARAMIS. Mobile cameras in specific time interval photograph distance between reference points before the load in the calibration phase and later, during the action force.

Before the experimental deformation measuring of the experimental models, the calibration had to be performed. Calibration procedure was necessary for calibrating system and setting measuring parameters, ensuring dimensional consistence and obtaining precise results. For three-dimensional (3D) strain measuring, two cameras were positioned manually and adjusted in accordance with the measuring volume of the calibration object. The choice of the measuring volume dimensions directly depends on the measuring object dimensions. The basic elements of the camera system and the measuring volume are shown in Figure 2. The calibration objects may be the calibration panels or the calibration crosses of different dimensions. The project was defined in each new measuring and the pictures are shown in the different phases of applying the force. The software processing of the successfully measured data enables 3D presentation, presentation of the results, statistic data, diagrams, reports. The optical measuring system (DIC) can measure the parts and constructions of different dimensions (from 1mm to 2000 mm) by the same sensor and display deformation with 0.01–100% preciseness[12].

ARAMIS software used in the study is based on the principle of objective raster (fine-ground) procedure. It serves for measuring 3D changes of shape and distribution of deformation on the surface of statically and dynamically loaded objects. With high accuracy ARAMIS determines the shape of the filmed object, its dimensions, field of three-dimensional movements, vector of distorted field and the features of the biomaterial. In this study, ARAMIS separates the superficial layer of the tested bone 2 mm thick and shows distorted fields over the whole surface of the filmed bone, which means that only the part of the bone the camera spots is analyzed by ARAMIS.

ARAMIS analyses, estimates and presents the report of material deformation. The surface of mandible with intact dental arch and the surface of the bone tissue under the denture base and the denture itself had to be prepared by putting the fine layer of the dispersive color

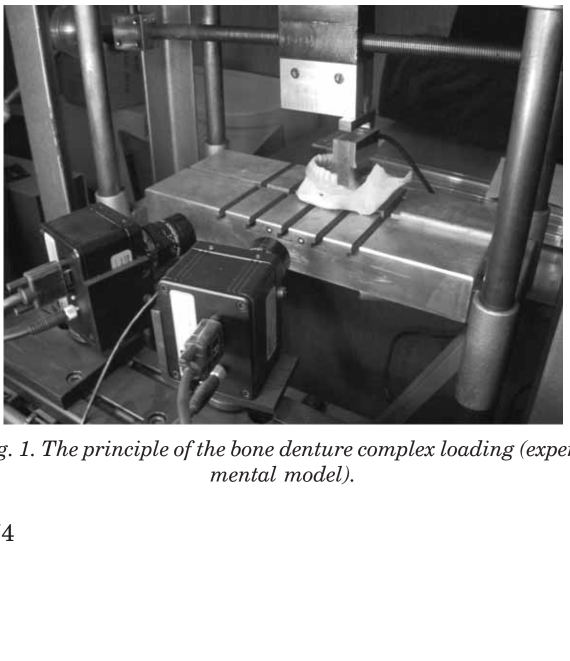

Fig. 1. The principle of the bone denture complex loading (experimental model).

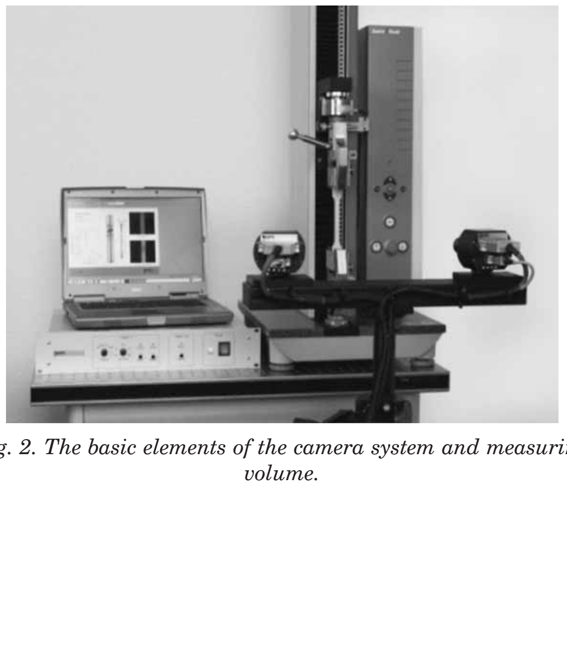

Fig. 2. The basic elements of the camera system and measuring volume.

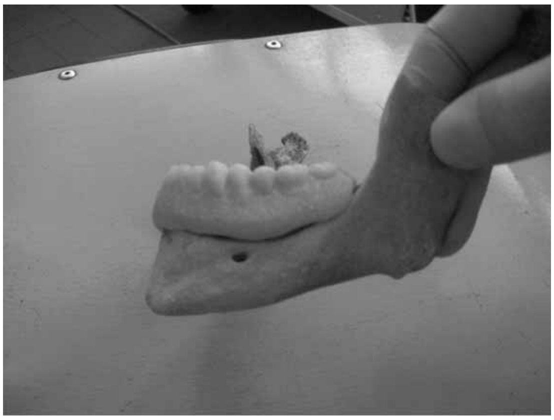

Fig. 3. The layer with finely dispersive color over the experimental model.

with expressive contrast (Figure 3). The fine reference points of this spray occupy certain mutual distances that are changed under the loading and are registered by cameras.

Results

Differences were determined for the stress distribution between two models under different loading conditions. The strain values obtained for fully dentate mandible were lower than obtained strain values for edentulous mandible. According to deformation formula $e = (Lo–L_1)/Lo \times 100$ where Lo and L_1 were the lengths before and after loading respectively, the deformation values were expressed in percents, and presented on the scale by different colors (Figures 4–7). Also, further individual strain values were analyzed with ARAMIS software and are shown in Table 1.

Model of lower jaw with full dental arch

Deformations were measured in function of load from 100 to 500 N at intervals of 100 N within the elastic field. The vertical (sagittal) lines shown in Figures 4 and 5, were set by software under the slams point force acting on the left second lower premolar and left first lower molar. This line changes its length with the change of intensity and the slams point force. Intensity of deformation is presented in the scale on the right side of the figures. Exact values of strain for each applied force intensity are shown in Table 1.

TABLE 1
REVIEW OF SEPARATE DISPLACEMENTS UNDER LOADING BY FORCES OF 100, 200, 300, 400 AND 500 N

	Values of strains in micrometres [μm]			
Forces [N]	LSLP	LFLM	ALSLP	ALFLM
100	8	0	390	104
200	4	3	483	158
300	15	12	546	214
400	16	8	582	263
500	17	19	625	311

LSLP – left second lower premolar, LFLM – left first lower molar, ALSLP – acrylic left second lower premolar, ALFLM – acrylic left first lower molar

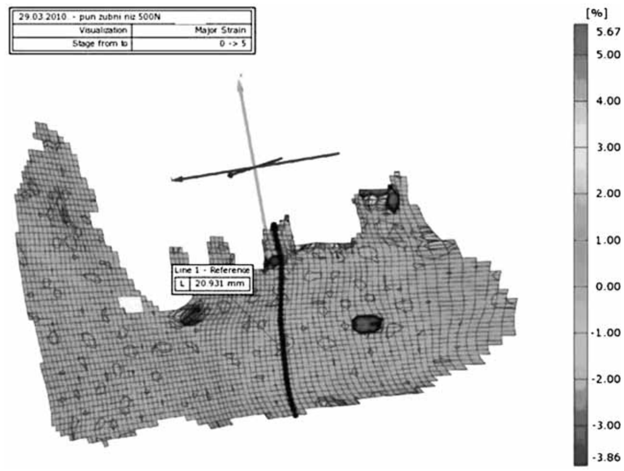

Fig. 4. Major strain field under force loading of 500N intensity onto the second lower premolar.

Model of the edentulous lower jaw with complete denture positioned in situ

The major strain field is shown in Figures 6 and 7 and is obtained during the central fissure loading of 500 N on the adjacent acrylic left lower premolar and molar in the lower total denture. For the vertical (sagittal) line shown in the figures, the values of the denture displacements against the jaw are given in Table 1 with applied forces from 100 to 500 N, increasing gradually by 100 N. This line joins the points of reference placed on the observed object, the denture-jaw complex, and it changes its length with the change of intensity and the slams point

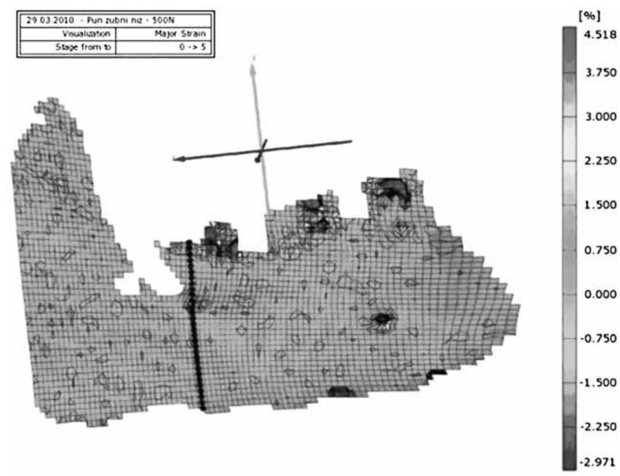

Fig. 5. Major strain field under force loading of 500N intensity onto the first lower molar.

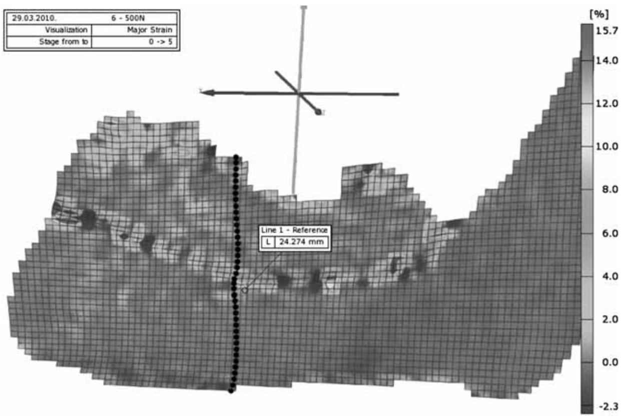

Fig. 6. Major strain field under working force of 500 N onto the acrylic second lower premolar.

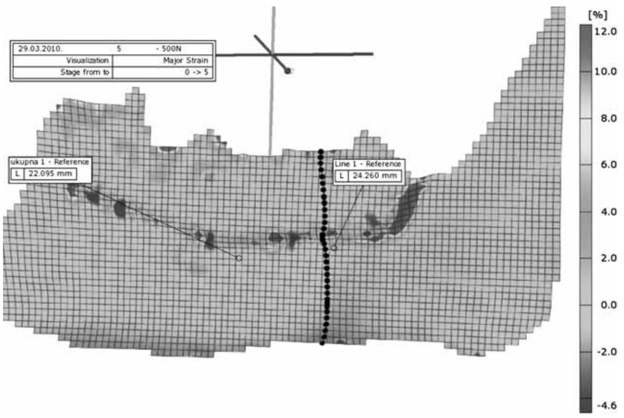

Fig. 7. Major strain field of the lower total denture and the lower jaw under working force of 500 N onto the acrylic first lower molar.

force. The scale in Figures 5 and 6, enables registering of quantative changes in the mandible-lower total denture complex, and it is presented in percents.

Discussion

Digital image correlation method have not been widely used in dental research so far, although it has several advantages over measurements by others digital methods. It is much less sensitive to ambient vibrations, can detect rigid body motion and simultaneously measure 3D displacements in a high dynamic range (microns to millimeters) of measuring capacity. The repeatability of the optical measuring is very good with the variation coefficient of 0.5%[13]. This fact enables verification of the virtual models measuring the volume of the bone tissue changes in the loading function with large precision. The advantage of 3D optical measuring is registering bone lamellas micro displacements by direct procedure on the observed segments with the shortened interval of obtaining the exact results, without scanning.

Its main disadvantage compared to other methods is its lower sensitivity determined by the field of view that does not exceed 0.3 microns. Also this method is limited with the fact that only one side of specimen cameras could catch. This implies that the curves, crevices, crosses parts of the observed mandible models, and also parts under denture base in this case, can not be analyzed. These factors may reduce the resolution and maximum accuracy of the images. The cameras catch only the flat surfaces of specimen in the view field so strain in the structure can only be detected within the view of the camera. The study included only the left part of the mandible models viewed from sagittal (lateral) aspect where right side of the lower jaws was excluded. As all other cadaveric analyzes the experiment may suffer from the donor-related variability of the investigated bone properties, the absence of soft tissue in the anatomic part investigated and impossibility of positioning mandible as in real situation. Nevertheless, this type of study, analyzed with optical method (digital image correlation method), could help us to understand the nature of stress and strain distribution through the hierarchical structure of bone[14].

The modeling of soft tissue has not been done in this research, and also viscoelastic properties of the periodontal ligament (PDL) and mucosa layer were not included when obtaining results. Knowing their dimensions and physical characteristics it was considered that their biomechanical behavior might influence only the intensity of deformation, but not change the direction of deformation distribution[10,15–18]. Nevertheless, it was the intention of this study to analyze and present the digital image correlation as a possible method for strain distribution analyze in the field of dental biomechanics. That is the reasons why displacement values were presented qualitatively as gradient of different colors and analyzed in percents and micrometers, in order to give full insight into the biomechanical behavior of the analyzed structures.

Dominant strain of the model of dentate mandible was in the area of applied load, and with moving the point of loading the size of the deformation is changing. In case of loading molar the deformation is most prominent in the region below the mandibular molar and angle of the mandible (*angulus mandibule*). With the loading anterior shifting, the size of the deformation reaches a maximum value in the area below the premolar and the anatomical details of the *foramen mentale*. Similar direction of the strains propagation is obtained in the case of loading the second experimental model. Except the fact that during loading of acrylic lower premolar certain deformations are observed in the area of the mandible angle, beside their primary detection (Figure 6). Similarities between the stress pattern distribution in both experimental models exist in the localization of the maximum strain within the bone structure of mandible but not in the intensity of the deformation and in the depth of strain alteration which are deeper in the first experimental model. This is explained by the existence of teeth roots and thus different transmission power.

According to the analyzed results, the strain values obtained for second model are much higher as presented in Table 1. Although the values of bone-denture complex deformation are higher comparing to the deformation results of the dentate mandible model, the average value of the deformation in bone tissue is smaller as scales next to the figures are showing. The reason of these findings may be attributed to viscoelasic acrylic component used for making complete dentures. During the influence of masticatory and non-masticatory forces on the acrylic teeth of the lower complete denture, some part of their intensity is amortized thanks to highly elastic component of polymer materials and non-networked polymers of the false teeth[19].

It is noteworthy to say according to the obtained results (Table 1) that deformation under loading of the denture rehabilitated lower jaw are more expressive in the premolar region compared to the molar region. These deformations are the biggest in the region under the acrylic second lower premolar and for the force of 300 N they are 546 μm. The large values of deformation in fact is a proof that the tested lower complete denture does not have a real, stable support and under the influence of external forces the lower complete denture displaces on the bone fundament. According to the obtained results (Table 1), it can also be noticed that deformation values increase is linear, largest deformation values are just under the applied force of the biggest intensity 500 N, and for the region of the lower second premolar deformation is 625 μm. Simulated loading of 500 N induces major strain fields and strain segments onto the denture-bone complex and second premolar and first molar of the first model as seen Figures 6 and 7. However, it should be pointed out that the forces of 500 N are the extreme forces for the case of edentulous patient. It is well known that maximal willing force in humans measured in the molar region is 500–700 N, and in the region of incisives is 100–200 N[20,21]. It depends on the total muscular strength. The functional force is similar with those persons who have the fixed tooth annexes and those who have the preserved dentition, while it is reduced with the total denture persons, according to the mentioned authors, to the quarter or the fifth of the force measured with persons who have natural teeth[20,21]. The weaker intensity forces induce the weaker changes of the deformation values. By interpreting of the major strain fields (Figure 6 and 7), it is registered that the deformation of the mandible bone fundament in the elastic major strain field are the result of vertical displacements of the lower total denture acrylic base.

It is apparent that occlusal forces have a significant impact on both alveolar and basal strains for both models although loading environment was simulated far different from existing loading in the *in vivo* conditions. The analyzed models were supported along the inferior border and accordingly greater stress values are found in the lower part of the lower jaw. These findings are possible partly the result of the used methodology where upper part of the lower jaw cannot be detected due to restrictions of the camera view and the position of the complete denture as in second model. However, limited-field approach of the experiments eventually may give the insight that basal mandibular bone is also influenced by occlusal loads, despite its having no apparent functional role in tooth support[22].

Conclusion

This study presents possible application of the optical method for analyzing distribution of mechanical strain inside the mandible models. The implemented method using cameras for capturing coordinates and respectively position and displacement measuring gives some advantage to traditional measuring techniques. The fast adaptation to new measurement setups and the multitude of easy to apply 3D measurement points allow a precise and efficient strain analysis. Furthermore, optical measurement methods enable a visual presentation of measurement results, which makes a result interpretation easy and intuitive. On the other hand, as in-vitro study even if the simulations results are correct, they need to be confirmed in in-vivo tests and verified accordingly.

The optical method used in this study visualized strain distribution in the mandible models during occlusal loading. Under applied forces appear it may be concluded that deformations within bone and the bone-denture contact area are mostly influenced by the teeth and denture vertical displacement.

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OPTIČKI ASPEKT ANALIZE DEFORMACIJA UNUTAR KOŠTANO-PROTEZNOG KOMPLEKSA

S A Ž E T A K

Cilj ove studije je bio registrirati i izmjeriti deformacije mandibularnih modela u funkciji opterećenja. Metoda za mjerenje cjelokupnog polja deformacije je postignuta korištenjem ARAMIS trodimenzionalnog sustava korelacije slika. Sustav koristi dvije digitalne kamere koje osiguravaju istovremeno simultano snimanje uzorka i rezultati pokazuju kompletno polje deformacija tijekom vršenja testova. Najveće vrijednosti deformacija su neposredno ispod djelujuće sile najvećeg intenziteta od 500 N, i za regiju donjeg drugog pretkutnjaka deformacija je 625 mikrometara. Naredna studija predstavlja prednosti stereometrijskih mjernih sustava za moderna istraživanja. Pokazano je da ova metoda mjerenja može pratiti trendove u eksperimentima.