ORIGINAL ARTICLE

UDC: 535.8:611.087.1]:616.31
DOI: 10.2298/VSP1104336T

Optical metrology analysis of the lower jaw deformations

Analiza deformacija donje vilice optičkom metrologijom

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Abstract

Background/Aim. New optical stereometric methods based on both contact and noncontact mechanisms for displacement measurement have become common methods in biomechanical behavior research of biomaterials, bone and soft tissue. The aim of this study was to register and measure possible deformations of the lower jaw (mandible) with the intact dental arch using optical metrology method. **Methods.** The system for full field measurement of deformations (strains) comprised of two digital cameras for a synchronized stereoview of the specimen, and the Aramis software. **Results.** The maximum mandibular bone strains were measured in the regions of the lower first premolar and the lower second molar. In the action force of 500 N simulated in the region of the first lower premolar the intensity of deformation was 86 μm. The value of maximum strain in the bone around the molars was 24 μm for the force of 500 N acting on the second lower molar. When it comes to premolars, 3–5 times stronger deformation was observed in the region of the first lower premolar, compared to the deformation values of the second lower premolar area. **Conclusion.** Under loading of the applied forces the measured strains were in the elastic deformation area, meanning that the dependence of force and deformity is linear. The highest values of strain measurements obtained by the optical method were found in the jaw bone tissue around the loading teeth, and the bony regions of the triangle and mental region. According to the obtained results from the Aramis processing software it can be concluded that this method is applicable in a variety of biomedical research.

Key words:
mandible; numerical analysis, computer-assisted; optical devices; orthodontics.

Apstrakt

Uvod/Cilj. Nove optičke stereometrijske metode koje se zasnivaju na kontaktnim i nekontaktnim mehanizmima za merenje zapremine postaju uobičajene metode u istraživanju biomehaničkog ponašanja biomaterijala, koštanog i mekog tkiva. Cilj ove studije bio je da se optičkom metodom merenja registruju i izmere eventualne deformacije koštanog fundamenta donje vilice sa intaktnim zubnim nizom i da se, ujedno, prikažu mogućnosti primene optičke metrologije u istraživanjima u stomatologiji. **Metode.** Sistem za merenje deformacija ispitivane donje vilice sa intaktnim zubnim lukom obuhvatio je dve digitalne kamere koje obezbeđuju stereosinhronizovani prikaz primerka, i softver Aramis. **Rezultati.** Najveće deformacije koštanog tkiva donje vilice izmerene su u regionu donjeg prvog premolara i donjeg drugog molara. Pri delovanju sila od 500 N za region prvog donjeg premolara veličina deformacije bila je 86 μm. Vrednost maksimalne srednje deformacije u koštanom sistemu oko molara iznosila je 24 μm pri delovanju sile od 500 N na drugi donji molar. Kada su u pitanju premolari, 3–5 puta jače deformacije uočene su u regionu prvog donjeg premolara, nego u predelu drugog donjeg premolara. **Zaključak.** Prilikom delovanja primenjenih sila deformacije se nalaze u elastičnom deformacionom polju, a međusobna zavisnost sile i deformacije ima linearan karakter. Najveće vrednosti deformacija dobijene optičkom metodom merenja registruju se u koštanom tkivu donje vilice koja je u neposrednom kontaktu sa zubima koji se opterećuju, kao i u koštanim regionima zakutnjačkog trougla i bradnog (mentalnog) otvora. Na osnovu analize rezultata dobijenih primenom softvera Aramis može se reći da postoje mogućnosti primene ove metode u različitim biomedicinskim istraživanjima.

Ključne reči:
mandibula; numerička analiza, kompjuterski asistirana; pribor, optički; ortodoncija.

Introduction

Biomechanical simulation of mastication force analysis on dried human skull has a wide application in planning and manufacture of prosthetic restorations, maxillofacial-skull surgery and orthopedics, analysing the manner of healing process, estimating the bone-implant interaction and reconstruction of bone segments after tumor elimination [1]. The said analysis can help in understanding the mechanism of the response of human tissues and its functional adaptation. The works of Wolf's (1892) and Frost (1990) describe functional adaptation of bone tissue and the relationship between the

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amount of bone microenvironment stress and consequent biological responses [2]. From the biomechanical view, stress is generated during occlusal function, and in the case of existence of dental-oseal connection (junction) transmittes over the teeth through periodontium, mandibular bone, maxilla and skull. Stresses and strains are induced as a consequence of occlusal thrill (pulsation) in all of the above mentioned structures of the orofacial system. The newly created stresses and strains will cause an adequate response in terms of functional adaptation and morphology adjustment [3]. Methods used so far for analyzing and measuring stress and strain involve application of computer-simulated force on virtual models of the skull. Finite element method (FEM) and photoelastic analysis (PA) are indirect methods for measuring stress and deformation of bone tissue. In recent years a number of optical methods based on direct strain measurement of the tested object have appeared and been widely used for verification of the virtual models and results. Non-invasive optical methods for direct measurement of stereometric strain biomaterials, bone and soft tissue are binocular stereovision, laser-speckle interferometry, photorefractive holographic interferometry technique and optical metrology. The above methods register deformations with extremel occurance and find a broad application in biomedical sciences [4–6].

The aim of this study was to register and mesure any deformation of the lower jaw bone fundament with intact dental arch (complete dentate), and also to show the possibilities of optical metrology in dentistry research by the use of selection (defining) the lower jaw model with intact dental arch; positioning of experimental models in the standard press and occlusal loading simulation; deformation measuring with digital cameras, and analysis of the results.

Methods

A model of the lower jaw with intact dental arch was used in the experiment. The lower jaw with intact dental arch was borrowed from the Laboratory for Anthropology, Institute of Anatomy, School of Medicine, University of Belgrade. According to the data from the laboratory archive, a mandible donor was a man, in late fourties from Serbian population. The lower jaw was inspected visually and evaluated, because it was necessary for experimental model to be without evident traumatic and pathological damages and to have all teeth present. Afterwards, the lower jaw was immersed and left in the physiological (saline) solution (0.9% NaCl) for 48 h in order to reach the volume and elasticity as *in vivo* studies [7].

After drying at 27°C in a drying chamber, the lower jaw with teeth was lacquered with a fast-setting acrylic lacquer white spray of high density (manufactured by Motip). The prepared model was placed in a tensile testing machine (standard press system) to measure deformation. The lower jaw was positioned on a horizontal plate of the tensile testing machine, fixed in specially constructed grooves. The forces applied in the experiment were within the range from 100 N to 500 N (1 N = 0.10 kg). Literature data suggest that maximal force in humans measured in the molar region is 500–700 N, and in the region of incisors 100–200 N [8]. According to Martinović [9], the value of masticatory force in patients with intact dental arch is 200 N. The study adopted intensity of the applied force up to 500 N, since forces greater than 500 N caused fractures of the loaded teeth and the system was unable to register further deformation.

Precise and controlled loading was measured using a gnathodynamometer (Siemens, Germany) horizontal extension. Direction of the applied load was axial to second premolar and first molar with maximal distribution in centric supporting contacts. In such a way, actual loading was simulated in places where it normally receives dental contacts in the position of central occlusion. The position of central occlusion in the human dentition is very common and only during swallowing is repeated 800 times per day [10]. The largest masticatory forces in natural and artificial teeth were observed in the second premolar and first molar area, which is the area of the tooth called "stable area" or "mastication center" (key of occlusion).

Precise measurment of strain in this research was conducted using the equimpment manufactured by GOM. The system consists of two digital cameras and software Aramis. Mobile cameras at a specific time interval make a photo of the distance between the reference points before the load in the calibration phase and later, during the action force.

Before experimental deformation measuring of the experimental models, 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. By choosing the measuring volume the distance between the sensor and the measuring object is determined. The basic elements of the camera system and the measuring volume are shown in Figure 1.

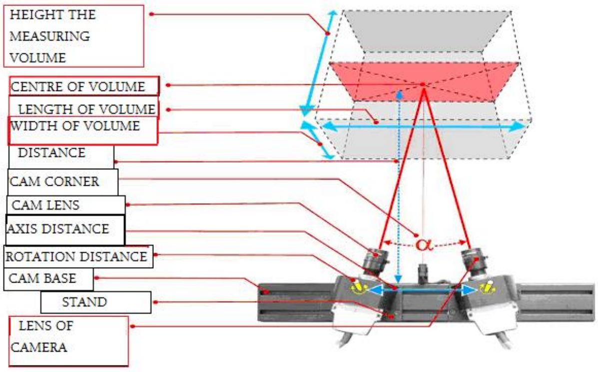

Fig. 1 – The basic elements of a camera system and measuring volume

Calibration objects may be calibration panels or calibration crosses of different dimensions. The project was defined in each new measuring and images were shown in various 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 (digital image correlation – DIC) can measure the parts and constructions of different dimensions (from 1 mm to 2 000 mm) by the same sensor and display deformation with 0.01%–100% preciseness [11].

The 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 and contactlessly, 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 [12]. Unlike tensiometer or extensometer that give only separate measuring values and measure deformities by elastic strips at the places where deformities are expected, Aramis defines deformity distribution over the whole analyzed area enabling better understanding of the material behaviour, constructions and the real measuring objects used in medicine and dentistry. In this study, Aramis separated the superficial layer of the tested bone 2 mm thick and showed distorted fields over the whole surface of the filmed bone, which meant that only the part of the bone spoted by the camera was analyzed by Aramis.

Aramis analyses, estimates and presents the report of material deformation. Also, the graphic presentation of the measured results gives an optimal understanding of the tested object behaviour, especially suitable for three-dimensional deformation measuring under statical and dynamical forces, in order to analyze deformations of real components. The surface of mandible with intact dental arch had to be prepared by putting a fine layer of the dispersive color with expressive contrast (Figure 2). The fine reference points of this spray occupied certain mutual distances that were changed under the loading and registered by the cameras.

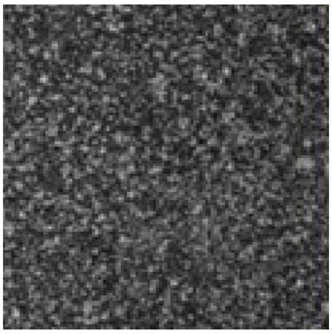

Fig. 2 – The layer with finely dispersive color over the experimental model

Results

Figure 3 shows a deformation field (major strain field) when the load is directed on the central fissure of the lower first premolar with the force intensity, F1 = 500 N. The strain values within the section line are shown in Figure 3. This line connects the points of reference applied to the observed object, the lower jaw bone foundation, and changes its length with the changing in the intensity and the force attack point. Vertical line is placed by the software under the force attack point acting on the lower first premolar. The scale next to Figure 3 allows registration of quantitative changes of the lower jaw, and is expressed in percents. According to the formula for deformation $\varepsilon = (L_0\text{-}L_1) / L_0 \times 100$, where L_0 and L_1 are the length before and after the load force respectively, the intensity of deformation expressed in the percents for the case of the lower first premolars loading, is visible in the scale next to Figure 3 presented in different colors.

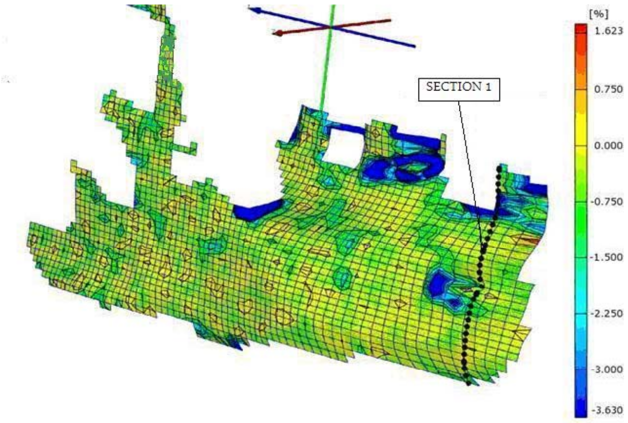

Fig. 3 – Percentage size of the lower jaw deformations at the load of the lower first premolar

In the second part of the experiment, the force was directed to a second premolar. Intensities of the forces that were applied were in the range of 100 to 500 N in the crop of 100 N. Deformation field is illustrated in Figure 4 and is located in the region of elasticity field. The intensity of deformation and strain field within the display was monitored by the scale on the right side next to Figure 4. Software set-section line (section 2) below the precipitating force whose attack (offensive) point is on the central fissure of the lower second premolar.

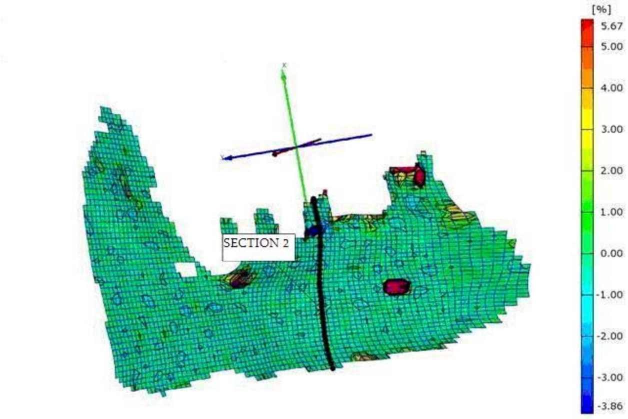

Fig. 4 – Percentage size of the lower jaw deformations at the load of the lower second premolar

The force attack point in the third part of the experiment was localized to the part of realization of the central contacts on the lower first molar so that the sagittal line section (section 3) was below the lower first molar. The acting forces were vertical and the intensity of forces was 100 to 500 N as in the first and second part of the experiment. The most intensive changes were present in the part of strain fields just below the force attack point. When the force intensity was 500 N, the percentage value of deformation and shortening of the length of the line section (Δ L) had the maximum value as shown in Figure 5.

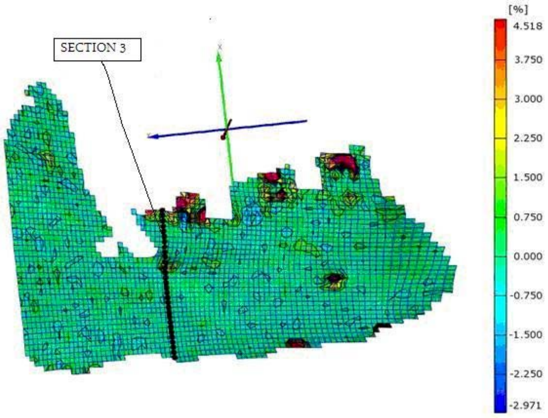

Fig. 5 – Percentage size of the lower jaw deformations at the load of the lower first molar

The force attack point in the last fourth part of the experiment was localized in the central fissure of the lower second molar. Elastic deformation field shows the most intensive deformation in the region of the retromolar triangle, as well as in the bone tissue that is in direct contact with the tooth. Figure 6 shows the distribution of deformation changes in the elastic strain field (major strain field), and the scale beside the figure describes intensity of deformation in the percentage.

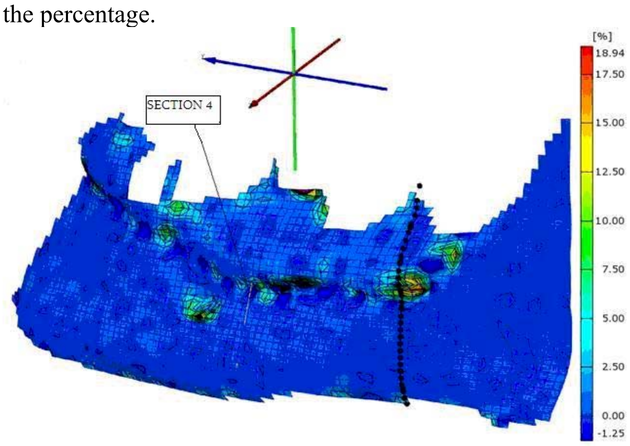

Fig. 6 Percentage size of the lower jaw deformations at the load of the lower second molar

Discussion

The results of previous studies showed a good correlation between the mathematical modeling finite element analysis (FEA) and *in vitro* measurements [12, 13]. In this study, distribution and intensity of deformation of the lower jaw bone with intact dental arch was conducted using the method of optical strain measurement. Reproducibility of optical measurements is very high, with a coefficient of variation of 0.5% [14]. The above fact enables high accuracy verification of virtual models that measure volume changes of bone tissue in the function of the load. The advantage of 3D optical measurement is registration of bone lamellas microdisplacements in direct access to the monitored segments within shortened intervals for obtaining accurate results, without scanning. Disadvantages of this method are that the process of measuring requires a slightly longer time period for registering movement of reference points. The negative side of the optical strain measurement is neutralized by fixing the body of mandible on the horizontal plate of standard presses (tensile testing machine) allowing unlimited time for makin photo of the loaded lower jaw (mandible). This paper presents only one possible application of optical method in dentistry. The study was not performed by modeling of soft tissue and periodontal tissues, but knowing the thickness and quality of these tissues, it is considered that it could affect only the intensity of deformation, that would be slightly lower, but not to the direction of strain distribution [15]. Within the obtained experimental results it can be noticed that under the same force action, deformations in the region of the first and second lower premolars are more expressed than deformations in the region of the molars. The reason for this strain distribution lies in the presence of the fewer number and lesser volume of the roots of lower premolars in relation to the massive and two-roots molars. The maximum mean strain that occurs in bone tissue around the lower premolars is 86 micrometers for the force of 500 N, compared with the maximal mean strain of 24 μm in the bone tissue around the molars (periodontium) at the action force of 500 N on the second lower molar. As for the premolars, stronger deformations are observed in the region of the first lower premolar, than in the region of the second lower premolars (3–5 times higher intensity of deformation) and that is explained by the presence of bone aperture (mental foramen) and poor bone density. Deformations in the region of the first lower molar are less expressed compared with the deformations obtained below the lower second molar. This data is consistent with the anatomical structure (morphology) of the lower jaw that possesses arms in the distal segments (medial crus and lateral crus of the retromolar triangle) that concentrates deformations more than the alveolar bone below the lower first molar. Regularity in the concentration of deformation is expressed as high deformation accumulation in the bone lamellas of alveolar the bone around tooth exposed to the masticatory forces, and in the region of mental foramen. The findings are consistent with other research data where maximum compressive strain was observed in the region of root apexis and bifurcations, therefore in the vicinity of the dental roots showed in the lower jaw of pigs [16, 17]. In all four experimental parts where occlusal loading of premolars and molars teeth was performed, Aramis software registered a marked accumulation of deformation in the region of the mental foramen. Also, a significant strain concentration was present in bone tissue of the lower jaw angle (*angulus mandibulae*) and in the anatomical structure of the retromolar triangle. The results of the research confirmed the findings of strain distributions obtained by as FEA on the scanned model of the lower jaw, where no presence of specific bone paths (trajectories) in the region of the lower jaw body and branches (*corpus* and *ramus mandibulae*) was registered [18].

Analyzing the results of the research, it may be speculated that the biomedical aspects of optical strain measurement method may find a broad application in dental science. It is particularly important in: simulation or reproduction of clinical situations that exist in the oral cavity and more frequent application of biomechanics in clinical practice; better understanding of the distribution of masticatory forces (vertical and inclined) through the bony foundation; monitoring the deformation of the jaw, which was subjected to the action of forces and predicting the intensity and direction of subsequent resorption and remodeling; verification of indirect methods (FEM, PA), thanks to precise data obtained by Aramis software analysis.

Conclusion

Skeletal deformities of the lower jaw with intact dental arch using the optical method of measurement were recorded and analyzed. After evaluating the obtained results the following conclusions may be drawn: when loading the lower jaw with intact dental arch, the distribution of strain through the lower jaw bone system is uniform; the highest values of strain measurements are found in the jaw bone around the loading teeth, and the bony regions of the retromolar triangle and mental region; higher values of strain were observed with the anterior load shifting; the applied force and deformation are mutually linearly dependent, and deformations are in the elastic deformation field; based on the evaluation results it may also be noted that further research using optical methods of strain measurement should focus on monitoring the deformation of bone under the loaded dental restorations, as well as testing qualitative and quantitative characteristics of dental materials.

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Received on July 21, 2010.
Revised on November 26, 2010.
Accepted on December 1, 2010.