Finite element method analysis of occlusal splint therapy in patients with bruxism

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Research article

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Abstract

Background: Bruxism is the most important risk factor for temporomandibular joint (TMJ) disorders.

Methods: Three-dimensional models of maxilla and mandible and teeth of 37 patients and 36 normal subjects were made using in-vivo image data. The maximum values of stress and deformation were calculated in 21 patients six months after using splint and compared with the initial conditions.

Results: The maximum stresses in jaw bone and head of mandible in patients were 4.4 and 4.1 times higher than those in normal subjects, respectively. Similar values for deformation were 5.8 and 4.9, respectively. Six months after splint application, the maximum stress in the jaw bone and head of mandible decreased by up to 71.0% and 72.8%, respectively. Similar values for the maximum deformation were 80.7% and 78.7%, respectively. With occlusal splint therapy, the approximation of the maximum deformation to the relevant values in normal subjects was about 2.6 times the approximation of maximum stress to the relevant values in normal subjects. The maximum stress and maximum deformation occurred in all cases in the head of the mandible and the splint had the highest effectiveness in jaw bone adjacent to the molar teeth.

Conclusions: Splint acts as a stress relaxer and dissipates the extra generated stresses and especially the deformation and deviations of TMJ due to bruxism. The splint also makes the bilateral and simultaneous loading possible and helps with the treatment of this disorder through regulation of bruxism by creating a biomechanical equilibrium between the physiological loading and the generated stress.

Background

The prevalence of temporomandibular disorders is 25-50% in adults and, in particular, the prevalence of bruxism is 8-31.4% in adults [1,2]. In general, habits such as bruxism belong the effective factors in temporomandibular joint (TMJ) disorders. From a biomechanical point of view, TMJ is the most complex joint in the human body. More than 2000 neuromuscular control signals are registered daily for normal performance of this joint [3]. The consequences of bruxism are mostly in form of wear and damage and are more prevalent in men than women [4]. Bruxism not only leads to wear, grinding, crushing, fracture and ultimately serious damage to teeth but also may cause hearing loss, maxillofacial problems and even facial deformation. If bruxism is not treated, the teeth, bones and gum may be worn or fractured due to wear pressure [5]. Since bruxism is the most important risk factor for TMJ [6], the study of suitable strategies for treating this disorder is of great importance.

Previous studies related to the subject of this research can be divided into two main groups. The first group of studies has merely examined the changes in the biomechanical parameters in TMJ and mandible. Tanaka et al. examined in their study the effect of age on the manner of changes in the parameters affecting the TMJ disc displacement [7]. Hirose et al. investigated the destructive effects of prolonged jaw and teeth pressing on TMJ disc using finite element method (FEM) [8]. Donzelli et al. examined the kinematic and geometric changes in TMJ discs using FEM analysis [9]. Koolstra et al.

showed with the help of FEM that the articular disk has the ability to distribute loads in a wide area [10]. Naeije et al. investigated in a biomechanical study the loads exerted on TMJ during chewing and chopping [11]. Del Palomar et al. examined the effective biomechanical parameters in lateral excursions of the mandible during chewing with the help of the FEM [12]. Commisso et al. examined the effect of pterygoid muscles on movement of the jaw during mastication using the FEM analysis [13]. Nishigawa et al. measured the maximum bite force in patients with sleep associated bruxism experimentally, however, they did not deal with the change of bite force during or after treatment [14]. Some studies focused solely on biomechanical parameters affecting implant insertion and filling teeth and dental pain [15-18].

The second group of studies has focused on the assessment of treatments of TMJ disorders. Ferreira et al. showed how the occlusal splint distributes stress in TMJ disc [19]. Salmi et al. found a new digital process to produce occlusal splints in a study using a laser scanner and evaluated the effectiveness of this new production method [20]. Kobayashi et al. examined the association between asticatory performance and bite force in children with bruxism [21].

The results of previous studies have shown that occlusal splint therapy can be a treatment option for patients suffering from bruxism [21-23]. These studies showed that psychological factors such as stress are associated with bruxism, however the exact contribution of these parameters is still unknown [21]. Therefore, it was tried in this research to perform a study with the aim of quantitative assessment of the effectiveness of occlusal splint for treating bruxism using *in vivo* image data of patients and normal samples for examinating of the manner of changes in parameters affecting this disease after occlusal splint therapy and gain more insight into the detail performance mechanism of this therapy.

Methods

The study population included 19 women and 18 men aged between 21-49 years old and with a body mass index between 18.2-21.9 $Kg.m^{-2}$. It should be noted that these patients had no other complications besides bruxism in the region of head, jaw and teeth. Normal samples included 18 women and 18 men aged between 26-52 years old and with a body mass index between 19.6-22.3 $Kg.m^{-2}$. Using the images obtained from the CT scan of the jaw and teeth of samples and importing these images into Mimics software version 13.1 (Materialise, Leuven, Belgium), the point cloud of the maxilla, mandible and teeth of each sample were produced as separate parts (Fig 1, a). In Mimics, the bony parts of the maxilla, mandible and teeth in image file were kept. After modifying the areas containing soft tissue in all image slices and repeating these modifications layer by layer, the spaces between layers were finally modified and differentiated and the point clouds of the teeth and jaw bone were extracted as the software output. Subsequently, the point clouds were transferred to the CATIA software version 5R21 (Dassault Systemes, Waltham, Mass., USA), and a three-dimensional model of the maxilla, mandible and teeth were built (Fig 1, b).

Three-dimensional models of the maxilla, mandible and teeth of all 37 patients and 36 normal samples were assembled in conditions of no contact pressure respect to each other. Six months after insertion of the occlusal splint, the process of preparing CT scan images, creating the point cloud, and building the three-dimensional models of jaws and teeth were repeated for patients. At this stage, the 3D models of used splints of the same patients were constructed from their CT scan images and the 3D splint models were inserted between the upper and lower teeth of patients. It is worth noting that due to limitations, there was only possible to create the 3D model of jaw, teeth and splint of 10 women and 11 men after 6 months of using splint. Since the FEM solution is one of the most common methods for orthopedic simulation [24-26], the assembled models were transferred finally to ABAQUS software version 6.14 (Dassault Systemes) for FE analysis. Table 1 shows the material properties considered for jaw bones, teeth, and splints [19, 27]. One of the most important points in FE analysis is how different parts of the model interact with each other. In this study, these interactions and constraints were defined based on the actual anatomical function of these components in human body. The constraint considered for the contact between the inserted teeth on the upper and lower jaws with splint was a surface-to-surface constraint with a friction coefficient of 0.5 [19]. The degree of freedom of the upper surface of maxilla was considered to be zero at all three directions of x, y and z, i.e., the surface was considered to be fixed. Other degrees of freedom were considered in accordance with the real performance of TMJ, so that the necessary degrees of freedom for opening and closing movements of jaw (rotational degree of freedom) as well as the translation and lateral displacement of jaws over each other (translational degree of freedom) were considered (Fig 2, a). According to previous study a first order Ogden hyperelastic model was used for defining the periodontal ligament with poisson's ratio of 0.45 and material parameter MPa [28]. The average amount of force exerted by the medial pterigoid muscle and masseter muscle for both left and right muscles was assumed to be 50 N [19, 27]. It should be noted that, according to previous studies, the force of this muscles should be applied under a particular angle to the model, as shown in Fig 2, a. One of the most important issues in numerical computer simulations is to ensure the mesh independence of responses [29-33], The tetrahedral element was used for meshing the models (Fig 1, c). The results showed that the maximum difference between the stress values in the medium and fine meshes in all three groups of patients, normal samples and patients after 6 months of using the occlusal splint was less than 1.8%. Therefore, the convergence of responses from the grid and time step was ensured (Fig 2, b).

Statistical analyses

The mean value, standard deviation (SD) and coefficient of variation (CV) for maximum stress and maximum deformity were calculated in all three groups of patients, normal samples and patients after 6 months of using the occlusal splint using SPSS version 22 (IBM Corp., Armonk , New York, USA).

Results

Data validation is one of the most important concerns in computer simulations. Therefore, it was necessary to verify the correctness of the simulation results in order to assure the accuracy of the assumptions and the modeling and analysis processes. For data validation, the maximum bite force was measured experimentally in normal samples and patients (before using the splint) and was compared with the similar results calculated in the simulation process. For this goal, a miniature strain-gauge transducer (LM-50- KAM186, Kyowa Electronic Instruments Co., Tokyo, Japan) was mounted in the right and left first molar regions in all samples and the average value of maximum bite forces was recorded after 30 records for each sample and was compared with the similar parameter calculated by FEM simulation. Fig 3 shows that the maximum difference between the computer simulation and experimental results of the maximum bite forces in all patients and normal samples was less than 3.9%. Therefore, the validity of the simulation process is confirmed. Then, the correctness of the statistical analysis of the main results of this study, i.e. the maximum stress and maximum deformation, should be assured for each of the three groups of patients, normal samples and patients after 6 months of using splint. The results of the statistical analysis showed that the highest amount of CV in all three groups of samples was less than 3.1% for both maximum stress and maximum deformation (Table 2). The results in Table 2 showed that SD and CV values were acceptable for all parameters in all three groups of samples. It should be noted that the reported values for maximum stress and maximum deformation in the rest of the paper are the average values of these parameters for each of the three groups of patients, normal samples and patients after 6 months of using splint.

According to Fig 4, a and Table 2, the maximum stress in the jaw bone of normal samples and patients was 4.82 and 21.10 MPa, respectively. Results of analysis of patients 6 months after using splint showed that the maximum stress was 6.12 MPa. The maximum stress produced in the head of mandible of normal samples and patients was 6.91 and 28.26 MPa, respectively. The respective value of this parameter in patients 6 months after using splint was 7.68 MPa.

Fig 4, b showed the manner of changes in deformation values. The results showed that the maximum deformation in jaw bone of normal samples and patients was 63.91×10^{-4} and 368.10×10^{-4} mm (Fig 4, c and Table 2). Similar parameter for patients six months after using the splint was also 71.10×10^{-4} mm. The maximum deformation in the head of mandible of normal samples and patients was 9.40×10^{-4} mm and 437.20×10^{-4} mm, respectively. This value decreased in patients 6 months after using splint up to 93.11×10^{-4} mm (Table 2).

Discussion

The main objectives of this study were the numerical examination of the manner of changes in effective parameters in occlusal splint therapy during bruxism treatment as well as the assessment of the effectiveness of using occlusal splint for treating this disease. Stress and deformation are the most important biomechanical indices for assessing TMJ disorders and are usually used for quantitative examination of these disorders [13, 34]. However, the bite force, as mentioned earlier, was used for data validation in the present study due to the fact that the experimental measurement of stress and deformation is very difficult [13] and experimental measurement of the distribution of these parameters in jaw bone is impossible. Therefore, the bite force parameter, which can be obtained both experimentally and using FEM simulation, was used in this study for data validation. The values of von Mises stress and deformation in jaw bone were also calculated using FE method for patients, normal samples and patients after 6 months of using splint in order to assess the disease. The results showed that the maximum stress in jaw bone of patients was 4.4 times the maximum stress in normal samples. After using the splint, the maximum stress decreased by 71.0% (Table 2). However, based on the results, the maximum stress in patients after using splint did not return exactly to the range of maximum stress in normal samples and there was a difference of 26.9% between the values of maximum stress in normal samples and patients after splint treatment. The contact surfaces opposite to the jaw bone are not exactly parallel to it and there are various geometric complexities in this area. Also, with regard to the jaw anatomy, the muscular forces exerted to it are not exactly perpendicular to the surface and are exerted in a particular orientation. Therefore, the von Mises stress calculated by computer simulation presented shear stress, in addition to compressive stress. Consequently, all areas undergoing deformation are not in the same direction and this can also lead to local shear stress. Hence, the lateral walls of splint can play an effective role in confrontation with these shear stresses and this is an important issue in designing the splint. Regarding the large difference between the elastic modules of splint material and jawbone and teeth materials (Table 1), a large contribution to load absorbing and damping can be attributed to the splint due to the softness and flexibility of its material. Therefore, the splint acts as an absorber and dissipater of the generated stress and can help reduce stress and somehow relax stress. If this additional loading due to the bruxism is not damped by splint, a reaction force and consequently an additional reaction stress will be generated in TMJ, which will damage the joints, muscles and ligaments associated with TMJ. Therefore, splint creates a biomechanical equilibrium between the physiological loading and the generated stress through stress relaxation. The imbalance between the input physiological loading and the generated stress can be one of the biomechanical causes of bruxism and the splint can contribute to the neuromuscular reflex and to reduce the stresses on ligaments and joints associated with the TMJ by helping to achieve this balance. As shown in Fig 4, d, the maximum stress in the total jaw bone is generated in the TMJ and, in particular, in the head of mandible. Its biomechanical cause can be the stress concentration, since the head of mandible, considering the jaw bone anatomy, has the most complex and limited cross sections in the entire mandible. The maximum stress in the head of the mandible in patients was 4.1 times that of normal subjects but reduced by 72.8% after using the splint. The difference between this stress and the similar parameter in normal samples was 11.1%. The important point is that 6 months after using splint, the difference between the maximum stress in the head of the mandible and the other parts of the jaw bone was closer to the similar parameter in normal samples. This means that the effectiveness of the occlusal splint in patients suffering from bruxism in reducing the stress in the head of mandible is more than other locations of mandible. It should be noted that the location of generation of the maximum stress after using the splint did not change and maximum stress occurred in the head of mandible. The results showed that the location of occurring the highest deformation was, like the maximum stress in the head of mandible. According to Table 2, the maximum deformation in jaw bone and head of mandible of patients was, respectively, 5.8 and 4.9 times that in normal samples and decreased by 80.7% and 78.7%, six months after using splint. The difference between the maximum deformation in jaw bone and head of mandible of patients who used splint for six months and normal samples was 11.3% and 4.1%, respectively. The results in Table 3 showed that the maximum stress and deformation in all samples were in the upper jaw greater than the lower jaw. Similar to the reported results for patient No. 1, the greatest effectiveness of splint in the jaw bone was related to the areas adjacent to the first, second and third molar teeth in all patients (Table 3). The results also showed that the stresses in the left and right mandible of patients are not necessarily balanced and uniform. However, due to the flexibility of the splint material, the bilateral and simultaneous loading becomes possible, which can also be useful in the treatment of bruxism. It should be noted that the splint's effectiveness is much less canine teeth. The results showed that occlusal splint therapy was effective in reducing stress and deformation, especially in the head of mandible. It should be noted that following occlusal splint therapy, the maximum deformation approached almost 2.6 times the maximum stress to the respective values in normal samples. Thus, the effectiveness of splint was higher in reducing deformation than stress. In fact, the design of the occlusal splint therapy is not based on the prevention of bruxism, but the results of this study show that the occlusal splint can help treat this disease, by reducing stress and correcting deformations and deviations, especially in the head of mandible, and eventually reducing the additional support reaction due to bruxism in TMJ. It is suggested that the future studies record and compare the stimulation of TMJ-related muscles affecting bruxism before and after using splint by patients, so that the effect of splint on muscle stimulation and bruxism frequency is also examined as the main focus of the present study was on intensity not frequency.

Conclusions

The results showed that the occlusal splint creates a biomechanical equilibrium between the physiological loading and the generated stress by stress relaxation. The splint also provides the possibility for making the asymmetric and non-uniform loading due to bruxism bilateral and simultaneous. Thus, the occlusal splint can lead to regulation of bruxism by reducing stresses, and in particular, by reducing deformations and deviations in TMJ and consequently can help treat this disease. The results of this study can be useful in quantitative evaluation of the changes in stress and deformation before and after treatment of bruxism as well as in development of a biomechanical approach for assessing the effectiveness of occlusal splint therapy.

Abbreviations

SD: standard deviation; CV: coefficient of variation; TMJ: temporomandibular joint; FEM: finite element method.

Declarations

Ethics approval and consent to participate:

All procedures performed in studies involving human participants were in accordance with the ethical standards of North Tehran Branch, Islamic Azad University, Tehran, Iran, (Ethics committee of biomedical research center) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Furthermore, this article does not contain any studies with animals performed by any of the authors. It is noteworthy that according to ethical standards of North Tehran Branch, Islamic Azad University, Tehran, Iran, (Ethics committee of biomedical research center), all patients and normal subjects provided verbal informed consent before undergoing any study-specific procedures.

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Tables

Table 1. Material properties of jaw bone, teeth and occlusal splint [19, 27].

Parameters	Elastic modules (MPa)	Poison ratio
Jaw bone	1370	0.3
Teeth	18000	0.31
Occlusal splint	0.027	0.35

Table 2. Stress and deformation values in jaw bone and head of mandible.

SD: standard deviation; CV: coefficient of variation.

Cases	Values	Jaw bone			Head of mandible		
		Maximum	SD	CV	Maximum	SD	CV
Normal samples	**Stress (MPa)**	4.82	0.14	3.01	6.91	0.18	2.82
	Deformation ($\times10^{-4}$ mm)	63.91	1.61	2.70	9.4	0.23	2.68
Patients	**Stress (MPa)**	21.10	0.63	3.10	28.26	0.81	3.07
	Deformation ($\times10^{-4}$ mm)	368.10	10.31	3.06	437.2	13.64	3.10
Patients 6 months after using splint	**Stress (MPa)**	6.12	0.16	2.82	7.68	0.18	2.56
	Deformation ($\times10^{-4}$ mm)	71.10	1.97	2.91	93.11	2.65	3.05

Table 3. Stress and deformation values in upper and lower teeth of patient No. 1 and patient No. 1 after using splint.

Tooth number		Maximum stress in upper teeth (kPa)		Maximum stress in lower teeth (kPa)		Maximum deformation in upper teeth ($\times 10^{-5}$ mm)		Maximum deformation in lower teeth ($\times 10^{-5}$ mm)	
		Patient	Patient after using splint	Patient	Patient after using splint	Patient	Patient after using splint	Patient	Patient after using splint
Left side	Third molar	0.56	0.17	1121.3	63.1	0.023	0.004	25.4	5.6
	Second molar	0.34	0.09	923.6	58.2	0.023	0.004	23.8	5.4
	First molar	0.26	0.09	854.7	55.6	0.021	0.003	21.9	5.4
	Second premolar	0.11	0.08	487.6	54.3	0.016	0.002	14.7	4.8
	First premolar	0.08	0.07	364.8	54.1	0.011	0.002	13.6	4.8
	Canine	0.21	0.18	784.6	754.5	0.016	0.014	21.8	21.4
	Lateral incisor	0.18	0.08	728.4	54.5	0.016	0.003	21.8	5.1
	Central incisor	0.17	0.07	526.8	54.3	0.015	0.003	15.9	5.1
	Third molar	0.62	0.19	1264.3	68.9	0.028	0.004	24.9	5.5
	Second molar	0.61	0.17	1026.7	62.8	0.025	0.003	24.1	5.5
	First molar	0.49	0.11	830.2	59.4	0.025	0.003	20.8	5.2

Right side	Second premolar	0.28	0.08	377.6	53.4	0.016	0.002	15.2	4.9
	First premolar	0.08	0.06	362.9	52.1	0.015	0.001	12.5	4.7
	Canine	0.36	0.32	810.6	794.2	0.025	0.024	19.7	19.5
	Lateral incisor	0.23	0.08	710.8	58.8	0.023	0.003	19.4	5.1
	Central incisor	0.19	0.08	649.7	55.4	0.022	0.001	15.5	5.0

Figures

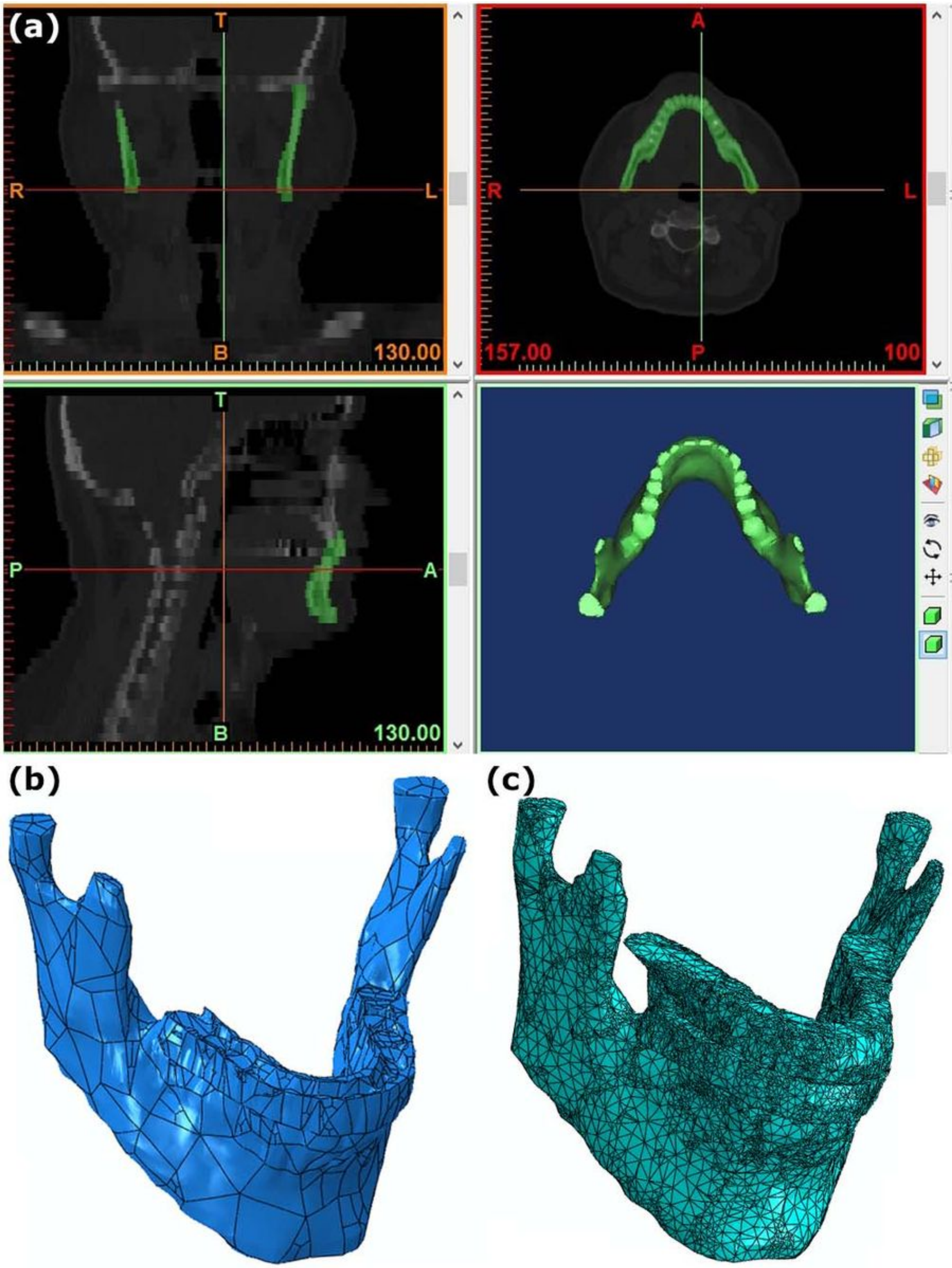


Figure 1

a) The point clouds of the maxilla, mandible and teeth. (b) 3D model. (c) Meshed model.

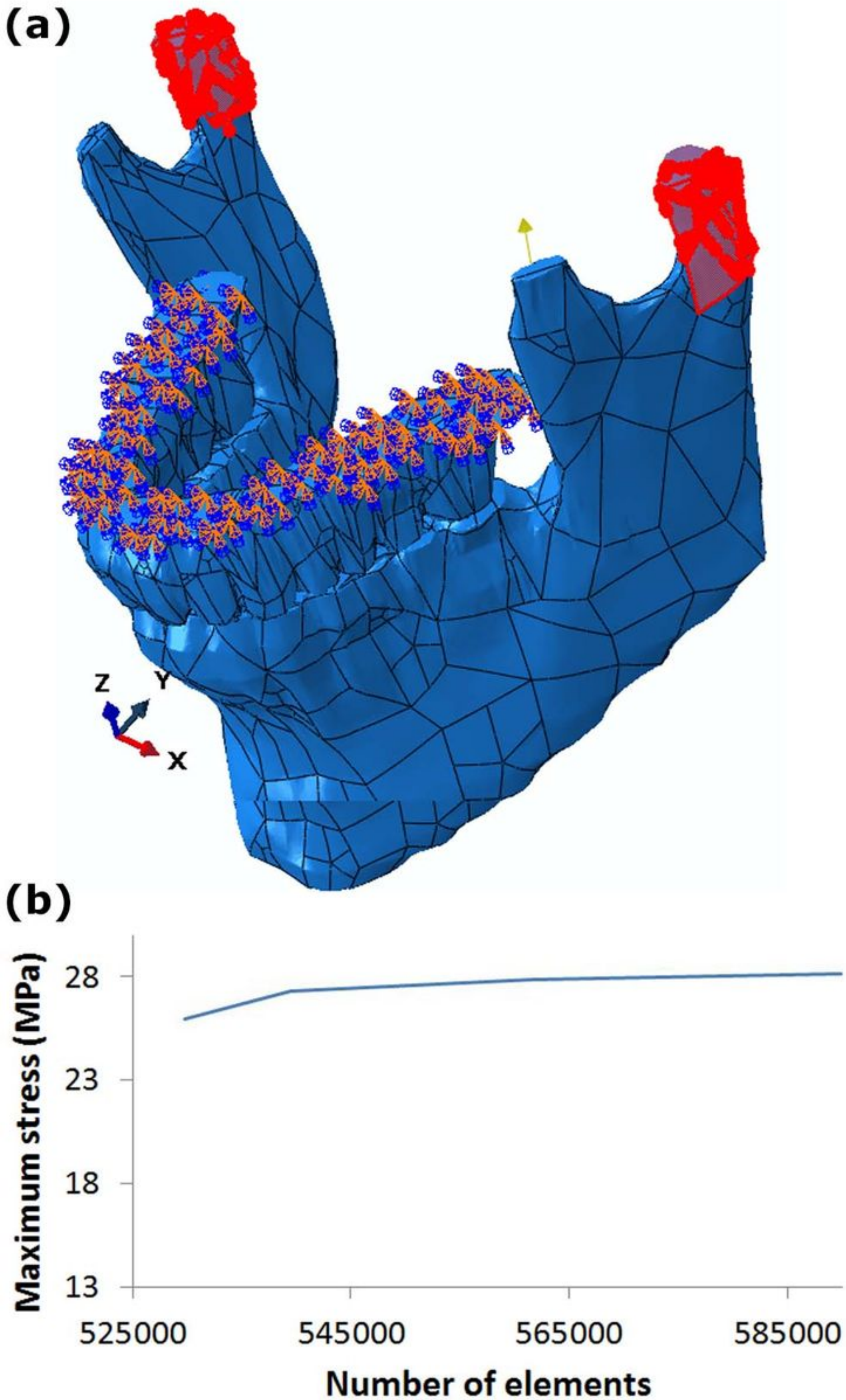
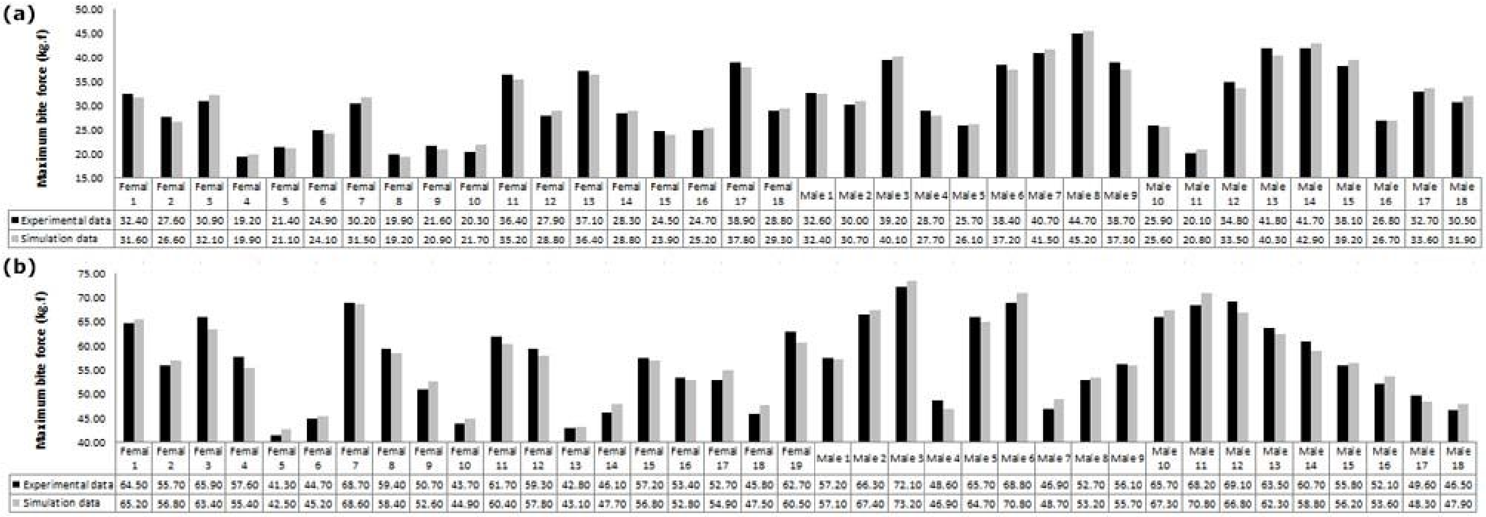


Figure 2

(a) Degree of freedom, interactions and constraints between parts. (b) Diagram of maximum stress in head of mandible-number of elements for grid independence study.



(a)

	Femal 1	Femal 2	Femal 3	Femal 4	Femal 5	Femal 6	Femal 7	Femal 8	Femal 9	Femal 10	Femal 11	Femal 12	Femal 13	Femal 14	Femal 15	Femal 16	Femal 17	Femal 18
Experimental data	32.40	27.60	30.90	19.20	21.40	24.90	30.20	19.90	21.60	20.30	36.40	27.90	37.10	28.30	24.50	24.70	38.90	28.80
Simulation data	31.60	26.60	32.10	19.90	21.10	24.10	31.50	19.20	20.90	21.70	35.20	28.80	36.40	28.80	23.90	25.20	37.80	29.30

	Male 1	Male 2	Male 3	Male 4	Male 5	Male 6	Male 7	Male 8	Male 9	Male 10	Male 11	Male 12	Male 13	Male 14	Male 15	Male 16	Male 17	Male 18
Experimental data	32.60	30.00	39.20	28.70	25.70	38.40	40.70	44.70	38.70	25.90	20.10	34.80	41.80	41.70	38.10	26.80	32.70	30.50
Simulation data	32.40	30.70	40.10	27.70	26.10	37.20	41.50	45.20	37.30	25.60	20.80	33.50	40.30	42.90	39.20	26.70	33.60	31.90

(b)

	Femal 1	Femal 2	Femal 3	Femal 4	Femal 5	Femal 6	Femal 7	Femal 8	Femal 9	Femal 10	Femal 11	Femal 12	Femal 13	Femal 14	Femal 15	Femal 16	Femal 17	Femal 18	Femal 19
Experimental data	64.50	55.70	65.90	57.60	41.30	44.70	68.70	59.40	50.70	43.70	61.70	59.30	42.80	46.10	57.20	53.40	52.70	45.80	62.70
Simulation data	65.20	56.80	63.40	55.40	42.50	45.20	68.60	58.40	52.60	44.90	60.40	57.80	43.10	47.70	56.80	52.80	54.90	47.50	60.50

	Male 1	Male 2	Male 3	Male 4	Male 5	Male 6	Male 7	Male 8	Male 9	Male 10	Male 11	Male 12	Male 13	Male 14	Male 15	Male 16	Male 17	Male 18
Experimental data	57.20	66.30	72.10	48.60	65.70	68.80	46.90	52.70	56.10	65.70	68.20	69.10	63.50	60.70	55.80	52.10	49.60	46.50
Simulation data	57.10	67.40	73.20	46.90	64.70	70.80	48.70	53.20	55.70	67.30	70.80	66.80	62.30	58.80	56.20	53.60	48.30	47.90

Figure 3

The maximum difference between the computer simulation and experimental results of the maximum bite forces in normal samples (a) and patients (b).

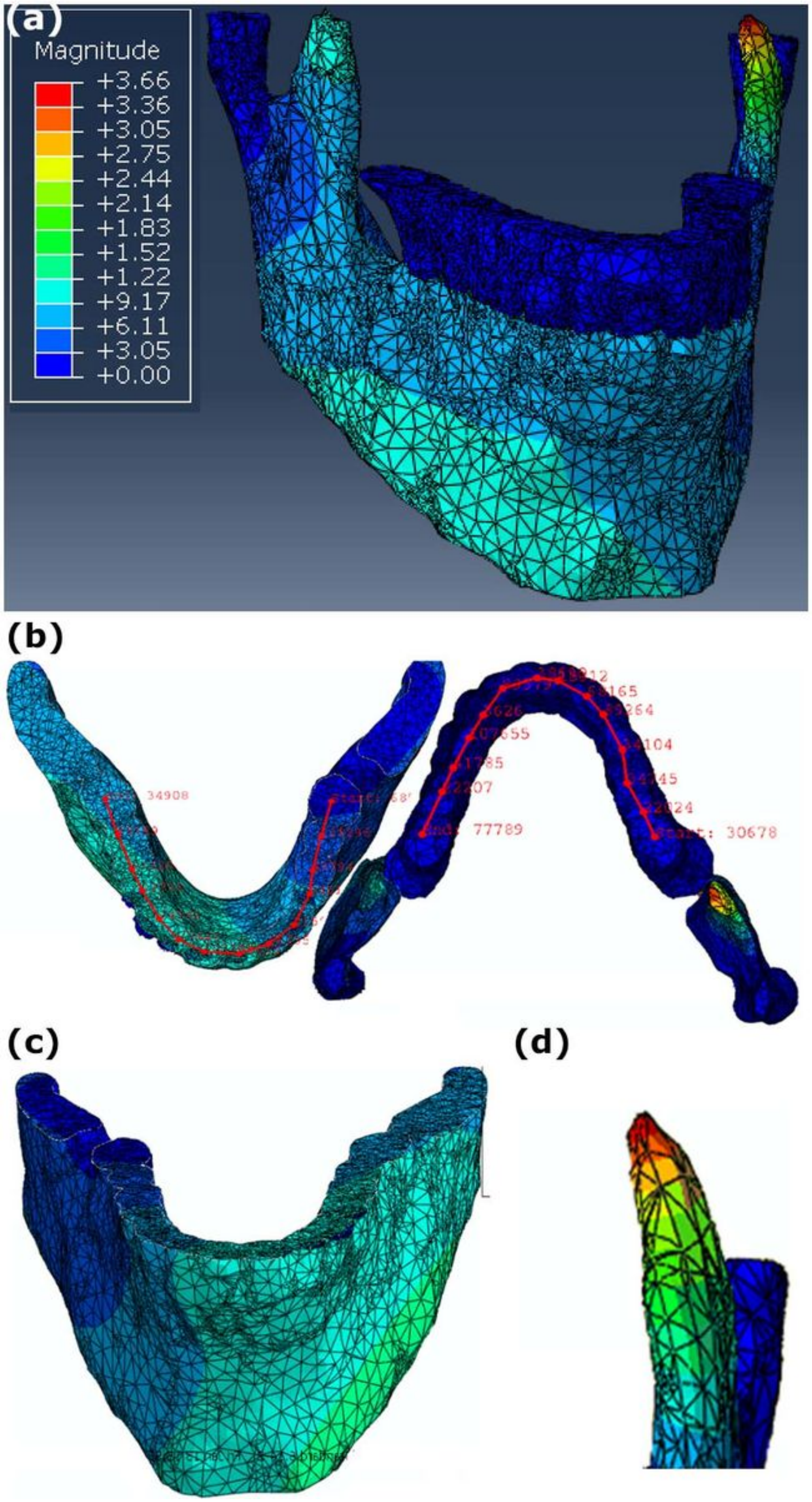


Figure 4

(a) Stress distribution of the jaw bone for normal sample (b) the manner of changes in deformation values in the upper and lower jaws. (c) deformation distribution of the jaw bone for normal sample. (d) The location of maximum stress.