Timing Selection for Loosened Tooth Fixation Based on Degree of Alveolar Bone Resorption – a Finite Element Analysis

Xi Ding (✉ dingxizj@hotmail.com)

Wenzhou Medical University

Zhang-yan Ye

Pingyang Hospital Affiliated to Wenzhou Medical University

Hao Ye

Wenzhou Medical University

Xi-xi Yu

Wenzhou Medical University

Yong Wang

Wenzhou Medical University

Li-jun Wu

Wenzhou Medical University

Research Article

Keywords: periodontitis, three-dimensional finite element, biomechanics, bone resorption, loosened tooth fixation

Posted Date: February 17th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1299833/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Abstract

Objective: To make a three-dimensional finite element biomechanical analysis of mandibular dentition and its bone interface with varying degrees of alveolar bone resorption, and evaluate timing of fixation to prevent tooth loosening.

Methods: Volunteer CT images in combination with periodontitis classification were used to construct a finite element model of mandibles with varying degrees of alveolar bone resorption. By simulating occlusal force loading, biomechanical analysis was made on the periodontal membrane, tooth root and surrounding bone interface of mandibular dentition with varying degrees of alveolar bone resorption.

Results: A finite element model of the mandible with varying degrees of alveolar bone resorption was established. The von Mises stress value of the periodontal cortical bone, cancellous bone, root surface and periodontal membrane of mandibular dentition was positively related with the degree of alveolar bone resorption, and the von Mises stress at the interface between the periodontal membrane and tooth root was increased significantly in moderate to severe periodontitis models. The von Mises stress at the interface between the periodontal cortical bone and cancellous bone was increased significantly in the severe periodontitis model. During oblique loading, the stress value at each interface was significantly higher than during vertical loading.

Conclusion: The model established in this study can effectively realize a biomechanical study of a mandible with varying degrees of alveolar bone resorption. In clinical treatment of teeth with moderate to severe periodontitis, loosened tooth fixation can be used to prevent tooth loosening.

Background

Periodontitis has become an oral disease with very high incidence in China, and has generally, become the leading cause of tooth loss in adults [1]. Clinically, tooth loss caused by chronic periodontitis is often accompanied by severe soft and hard tissue defects, which affects appearance and function, and also brings certain difficulties to denture restoration and implantation [2]. Periodontitis is closely related to systemic diseases, but due to limitations of medical ethics, it is very difficult to directly measure the intraoral biomechanical characteristics of patients with periodontitis. This finite element method can be used to make stress analysis of the oral structure, shape, load and mechanical properties of materials for objective, accurate and true stress distribution [3]. Periodontal disease treatment is mainly synthetic serial treatment, with periodontal drug treatment and surgical treatment to control inflammation, with restoration treatment to adjust occlusion, eliminate tooth trauma and reduce the burden of periodontal supporting tissues. With loosened tooth fixation to disperse occlusal force, control pathological loosening and displacement, and improve chewing efficiency, the affected tooth can get physiological rest, which is beneficial to the control of periodontal inflammation and healing of damaged periodontal tissue. After perfect periodontal treatment, tooth looseness of patients with moderate to severe periodontitis can be significantly improved without obvious looseness. In view of changes in stress distribution caused by varying degrees of alveolar bone absorption in mandibular dentition under stress, in this study, finite element analysis was made on the periodontal membrane, root surface, periodontal cortex and cancellous bone of mandibular dentition, providing a scientific biomechanical basis for the timing of preventive fixation of loosened tooth.

Objectives And Methods

1.1 The experimental volunteer was selected from the 2nd generation of Chinese virtual person (living digital-human) "No.23" volunteer, with complete dentition.

1.2 Biomechanical analysis of the finite element model of mandibles with varying degrees of alveolar bone resorption.

CT image data of mandible of volunteers were imported into the medical three-dimensional image reconstruction software Materialise Mimics 10.0 software (Materialise Company, Belgium) in DICOM format to generate the bone tissue surface profile. The gap between the tooth root and mandible was filled with a 0.2 mm periodontal membrane structure, and in combination with various software tools and

clinical anatomical features, the profile curve of each structure was manually plotted. The mandible containing each anatomical structure was reconstructed (including the separation of cortical bone and cancellous bone, enamel, dentin-cementum complex, periodontal membrane, dental pulp, temporomandibular joint condyle and other structures), then imported into reverse engineering software Geomagic Studio12.0 software (Geomagic Company, USA) in STL format, using polygon editing tools to optimize the mesh of each independent anatomical structure. Alveolar bone resorption in chronic periodontitis is generally described by the ratio of resorption area to the length of tooth root, and usually divided into three degrees. In order to unify bone resorption of each tooth position in the sample models, the critical value of bone resorption in varying degrees of periodontitis was used as the standard for division. The model was trimmed, and the total length of the measured tooth root was subtracted from the distance of enamel-cementum boundary and alveolar ridge to calculate the root length of the inner alveolar bone of each tooth. The height of alveolar bone was reduced to 0, 1/3, 1/2 and 2/3 of the inner length of the root bone. The edge was trimmed to make it smooth and continuous. Four models were established to simulate (a) non-periodontitis (b) mild periodontitis (c) moderate periodontitis and (d) severe periodontitis of the mandible models, and to simulate the stable state of bone resorption after periodontal treatment [4]. The model was imported into the finite element pre-processing software HyperMesh 11.0 (Altair Company, USA) for materialization. After the Boolean operation, finite element models of a mandible with varying degrees of alveolar bone resorption were constructed, and material mechanical parameter attributes and boundary load conditions were set and imported into the finite element analysis software ABAQUS.6.14 (Dassault Company, France) for solution.

1.3 Loading method and loading force.

100N, 50N and 25N were loaded on the occlusal surfaces of molars, premolars, and anterior teeth, respectively. The loading direction was vertical and oblique by 45° to observe stress distribution of the root interface, periodontal membrane, and periodontal cortical bone and cancellous bone of mandible. Under loading conditions, the edge of the mandible was fixed to prevent the jaw from displacement in the X, Y and Z directions.

1.4 Experimental preset conditions.

All the anatomical structures were homogeneous and isotropic linear elastic materials [5], and the material mechanical parameters of all anatomical structures were shown in Table 1 [6-7].

Table 1

Material Mechanical Parameters

Material	Elasticity modulus (Gpa)	Poisson's ratio
Cortical bone	13.700	0.300
Cancellous bone	1.370	0.300
Dentin cementum complex	18.600	0.310
Enamel	41.000	0.300
Root canal pulp	0.020	0.450
Periodontal membrane	0.069	0.450

Results

1. Construction of finite element models of mandible with varying degrees of periodontitis.

The finite element models of mandibles with varying degrees of periodontitis containing cortical bone, cancellous bone, tooth enamel, dentin cementum complex, periodontal membrane, dental pulp, temporomandibular joint condyle and other structures were constructed,

as shown in Figure 1. There were 283886 tetrahedrons in the non-periodontitis model, 274913 tetrahedrons in the mild periodontitis model, 273965 tetrahedrons in the moderate periodontitis model, and 261095 tetrahedrons in the severe periodontitis model.

2. Three-dimensional finite element biomechanical analysis of mandibles

2.1 Biomechanical analysis of tooth root interface

During vertical loading, the von Mises stress distribution on the root surface was concentrated on the root labial side of the lower anterior teeth. The maximum Von Mises stress (MVMS) of mandibular dentition was concentrated on the incisor. The MVMS of the root interface of normal mandible was 13.43MPa; the MVMS of the root interface of mild periodontitis was 15.60MPa; the MVMS of the root interface of moderate periodontitis was 21.79MPa; the MVMS of the root interface of severe periodontitis was 29.97MPa. Stress distribution was shown in Figure 2. During 45° oblique loading, the stress was concentrated on the root surface of mesiolingual posterior teeth, and the MVMS was concentrated on the root surface of the mandibular first molar. The stress was 2-3 times than when vertical loading. Stress distribution was shown in Figure 3. In addition, during both vertical and oblique loading, the MVMS was increased with aggravation of periodontitis, and stress was increased more significantly with moderate to severe periodontitis.

2.2 Biomechanical analysis of periodontal membrane interface

During vertical loading, the von Mises stress distribution of the periodontal membrane was concentrated at the corresponding position of periodontal membrane on the labial side of the lower anterior tooth root close to the neck. The MVMS was concentrated in the incisor. The MVMS of the periodontal membrane of a normal mandibular was 1.35MPa; the MVMS of the periodontal membrane with mild periodontitis was 1.65MPa; the MVMS of the periodontal membrane with moderate periodontitis was 2.33MPa; the MVMS of the periodontal membrane with severe periodontitis was 3.15MPa. Stress distribution is shown in Figure 4. During 45° oblique loading, stress was concentrated at the corresponding position of the periodontal membrane on the lingual side of the lower anterior tooth root close to the neck. The MVMS was concentrated on the mandibular first molar, and the stress was 2- 4 times than during vertical loading. Stress distribution is shown in Figure 5. It was found that during vertical and oblique loading, the MVMS increased with the aggravation of periodontitis, and stress of the periodontal membrane was increased more significantly in moderate to severe periodontitis.

2.3 Biomechanical analysis of the periodontal cortical bone interface

During vertical loading, occlusal force was transmitted to the mandible via the periodontal membrane of the tooth. When the cortical bone of the mandible was stressed, the maximum Von Mises stress was located in the corresponding cortical bone area of the labial neck of the incisor root; the minimum stress was located in the corresponding cortical bone area of the neck of the canine root. Stress distribution is shown in Figure 6. With 45° oblique loading, stress was concentrated in the corresponding cortical bone area of the mesiolingual neck of the posterior tooth. Stress distribution is shown in Figure 7. It was found that during vertical and oblique loading, the MVMS was increased with aggravation of periodontitis. In mild to moderate periodontitis, stress was increased slowly; in severe periodontitis, cortical bone stress was increased more significantly.

2.4 Biomechanical analysis of the periodontal cancellous bone interface

When the cancellous bone of the mandible was stressed, the stress was mainly distributed in the corresponding cancellous area of the root apex. During vertical and oblique loading, the MVMS was increased with aggravation of periodontitis. The maximum Von Mises stress was located in the apical area of the second molar. In mild to moderate periodontitis, stress increased slowly. In severe periodontitis, stress of cancellous bone increased more significantly. Stress distribution of cancellous bone during vertical and oblique loading is shown in Figure 8 and Figure 9.

Table 2-9: Stress Value of Tooth Root Interface, Periodontal Membrane, Cortical Bone and Cancellous Bone During Vertical and Oblique Loading

Table 2

Peak stress of root interface during vertical loading(MPa)

Group	47	46	45	44	43	42	41	31	32	33	34	35	36	37
A	9.24	6.60	5.65	9.88	3.97	8.23	13.04	13.43	7.88	3.82	10.24	5.49	6.56	7.18
B	10.59	7.07	6.94	12.84	4.42	9.12	15.60	15.06	8.794	4.21	11.96	6.28	8.62	8.783
C	13.52	8.21	8.05	14.48	5.44	12.89	20.19	21.79	11.14	5.49	16.66	7.29	10.24	13.83
D	17.39	9.35	9.92	20.30	7.38	18.91	25.55	29.97	16.91	7.09	24.05	9.94	11.73	20.84

Table 3

Peak stress of root interface during 45° oblique loading(MPa)

Group	47	46	45	44	43	42	41	31	32	33	34	35	36	37
A	20.66	25.68	27.19	29.14	9.69	6.08	17.69	18.58	7.693	12.25	30.96	31.06	18.78	14.91
B	23.54	30.03	36.43	34.63	6.85	11.96	21.32	21.87	14.82	7.30	38.07	36.34	25.48	18.86
C	32.30	43.32	47.13	48.65	8.38	18.07	34.02	31.68	19.65	9.72	53.85	50.56	33.25	31.97
D	45.33	76.24	54.70	63.88	12.35	29.71	37.76	42.45	31.86	12.70	73.17	69.41	53.7	57.21

Table 4

Peak stress of periodontal membrane during vertical loading(MPa)

Group	47	46	45	44	43	42	41	31	32	33	34	35	36	37
A	1.12	1.04	0.67	1.16	0.49	1.02	1.21	1.35	1.12	0.46	0.97	0.66	0.92	0.93
B	1.22	1.12	0.77	1.19	0.52	1.17	1.41	1.65	1.29	0.48	1.22	0.78	1.28	1.00
C	1.69	1.40	0.86	1.55	0.60	1.43	1.93	2.33	1.79	0.57	1.52	1.00	1.65	1.31
D	2.59	1.76	1.06	2.13	0.76	2.74	2.74	3.15	2.66	0.71	2.47	1.313	2.13	1.91

Table 5

Peak stress of periodontal membrane during 45° oblique loading(MPa)

Group	47	46	45	44	43	42	41	31	32	33	34	35	36	37
A	2.24	3.31	2.63	2.58	0.88	1.08	1.67	2.11	1.47	0.87	2.91	2.95	2.60	1.66
B	2.49	3.83	3.19	3.00	1.03	1.26	1.89	2.14	1.66	0.87	3.00	3.32	3.91	1.94
C	5.14	3.64	3.87	3.94	1.38	1.69	2.70	2.81	2.14	1.13	4.04	4.63	5.40	2.83
D	6.30	8.93	5.36	5.27	1.53	2.39	2.86	3.70	3.28	1.38	7.77	7.33	8.06	4.34

Table 6

Peak stress of periodontal cortical bone during vertical loading[MPa]

Group	47	46	45	44	43	42	41	31	32	33	34	35	36	37
A	10.71	11.07	8.241	10.63	8.82	9.90	12.74	14.22	10.03	8.23	8.61	10.21	12.43	10.29
B	11.31	9.92	8.822	9.26	9.45	9.55	11.85	9.49	10.62	9.21	8.56	8.71	13.43	9.53
C	9.44	13.99	8.399	13.08	9.35	15.03	21.01	15.32	12.55	10.69	15.37	9.40	12.19	8.57
D	16.12	16.41	10.09	21.15	11.28	18.18	36.1	31.30	20.02	11.11	16.21	13.25	18.78	32.52

Table 7

Peak stress of periodontal cortical bone during 45° oblique loading[MPa]

Group	47	46	45	44	43	42	41	31	32	33	34	35	36	37
A	23.35	26.53	34.96	35.54	25.31	16.09	14.48	16.14	19.03	31.04	39.73	32.86	28.48	24.42
B	26.99	31.82	31.56	35.27	31.56	29.12	13.10	14.90	15.87	34.77	33.07	27.20	25.41	19.42
C	33.02	36.05	36.80	35.67	28.65	13.46	27.35	17.98	17.28	33.40	36.46	36.09	33.44	27.85
D	38.01	57.69	53.92	56.81	37.14	21.46	44.1	38.68	23.41	33.02	58.43	60.99	55.63	77.75

Table 8

Peak stress of periodontal cancellous bone during vertical loading[MPa]

Group	47	46	45	44	43	42	41	31	32	33	34	35	36	37
A	4.16	3.96	2.31	2.27	1.94	2.27	2.65	3.26	1.78	1.99	1.90	2.19	3.79	3.34
B	4.94	4.66	2.63	2.38	2.27	2.06	3.13	2.98	2.63	1.95	2.10	2.08	4.28	4.40
C	5.94	4.96	2.50	2.53	1.95	2.61	4.10	3.80	2.54	1.85	2.70	2.37	5.48	4.33
D	8.24	5.78	2.95	3.13	2.30	3.53	5.17	5.34	3.95	2.16	4.33	3.10	6.21	6.84

Table 9

Peak stress of periodontal cancellous bone during 45° oblique loading[MPa]

Group	47	46	45	44	43	42	41	31	32	33	34	35	36	37
A	6.80	5.53	6.33	6.39	3.64	3.35	2.84	3.46	3.78	3.09	6.81	5.66	5.88	3.36
B	8.37	6.07	6.38	6.88	3.26	2.51	2.76	2.94	3.38	3.18	7.37	6.51	5.84	5.26
C	12.15	7.95	7.64	6.55	3.25	2.91	3.52	4.05	3.22	3.38	6.33	10.22	7.97	8.95
D	18.53	13.54	11.97	12.93	3.36	5.05	4.96	9.24	5.28	3.56	12.53	17.77	11.57	12.41

Discussions

1. According to experimental results and Table 2-9, the stress of each structure of periodontal tissue was increased with the degree of alveolar bone resorption. The change in stress of the periodontal membrane of the mandible was similar to the trend of change in the stress of the root surface. In moderate to severe periodontitis, stress was increased significantly, while the stress distribution of cortical bone and cancellous bone of mandible were similar. In severe periodontitis, stress increased significantly. Although the load was within the limit of the physiological tolerance of each tissue, stress fatigue would occur if a repeated load exceeded a certain limit. This result was consistent with alveolar bone resorption and tooth loosening in advanced periodontitis, and the influence of

oblique force on stress distribution was greater than that of vertical force [8]. Reddy used the finite element method to analyze changes in the stress of the periodontal membrane of single maxillary incisor at different levels of alveolar bone and found that with decrease in the height of alveolar bone, stress concentration of tooth cusp increased significantly [9]. Some scholars found the maximum tensile stress of the periodontal membrane of a maxillary incisor in the lingual neck area increased with decrease in bone height, but stress decreased with the increase in width of the periodontal membrane, and changes in the height of alveolar bone had little effect on the cortical bone [10]. Based on previous studies, the finite element method is not only of great significance for study of periodontal tissue stress and deformation under loads, it also provides medical and biomechanical experts with a basis for their biomechanical behavior in oral treatment [11].

2. With alveolar bone resorption, the clinical crown is lengthened, which increases the axial force of the root surface. According to the results of finite element analysis, stress increase during oblique loading is more obvious than during vertical loading. Lateral force shall be minimized. Many scholars have used loosened tooth fixation to disperse the occlusal force of lower anterior teeth. Nikolaus used the finite element method to make stress analysis on the therapeutic effects of periodontal splints made of different materials [12], and many scholars have also made clinical evaluation on the treatment timing of loosened tooth fixation [13-14]. Factors such as wear of occlusal surface and tooth movement in patients with periodontitis will affect the distribution of occlusal force and occlusal contact [15]. However, many studies have directly observed intraoral periodontal parameters for comparative analysis. In combination with study results, for the root surface and periodontal membrane interface, stress increase is particularly significant in moderate to severe periodontitis. In order to ensure uniform stress distribution and reduce stress concentration, and prevent lower anterior teeth from loosening and falling out, patients with moderate to severe periodontitis may undergo preventive internal fixation of lower anterior teeth to disperse occlusal force.
3. The mandible model of periodontitis in the study simulates bone level through alveolar ridge trimming. The mandibular alveolar ridge at the defect site has no obvious structural change except for loss of height. Under actual situations, alveolar bone resorption in periodontitis is not uniform and continuous horizontal resorption, and the depth of periodontal pockets on different sides of each tooth is not the same. According to literature reports, there are differences in the morphology and characteristics of a normal mandible and alveolar ridge trophic mandible, and bone characteristics and evolution, as well as changes in bone density shall also be taken into account for mandible changes [16-17]. With rapid development of computer medical imaging technology and medical technology, application of the finite element method in the field of stomatology can achieve more accurate biomechanical analysis in vitro for various oral diseases, thereby simulating and guiding clinical practice [18]. The significance of biomechanical analysis of mandibular models with varying degrees of alveolar bone resorption was to conduct mechanical analysis and evaluation of the tooth and periodontal tissues of patients with periodontitis, to avoid stress concentration, and then to prompt clinical optimization treatments, improve long-term success rates and avoid stress fatigue. Later, clinical CT images of patients with periodontitis will still be collected to validate data measurements and finite element biomechanics results.

Declarations

Acknowledgements

We thank Dalian University of Technology for software support

Authors' contributions

Xi Ding and Li-jun Wu conceived the ideas and supervised this work; Zhang-yan Ye and Hao Ye conducted the Experimental design, finite element modeling, made the impressions and led the writing; Xi-xi Yu and Wang Yong performed data analysis and paper writing. All authors read and approved the final manuscript.

Funding

This work was financial supported by Wenzhou Science and Technology

Bureau Projects (No.Y2020594 and No.Y20210398) and National Natural Science Foundation of China(31471146). Funding body did not have any role in the design of the study, collection, analysis and interpretation of the data or in the writing of the manuscript.

Availability of data and materials

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Declarations

Ethics approval and consent to participate

Not applicable. The CT images of the 2nd generation of Chinese virtual person (living digital-human) "No.23" volunteer is from the database, which is the research findings Of National Natural Science Foundation of China(31471146) conducted by co-author(Li-jun Wu). There is no living human beings are involved in this study.

Consent for publication

Not applicable. In this study there was no details, images, or videos relating to an individual person that needed to be agreed to publish.

Competing interests

The authors declared that they have no competing interests.

References

1. Zhao D, Khawaja AT, Jin L, et al. The directional and non-directional associations of periodontitis with chronic kidney disease: A systematic review and meta-analysis of observational studies. *J Periodontal Res.* 2018 Oct;53(5):682-704. doi: 10.1111/jre.12565.
2. Ge LH, Wang NJ, Xia YR, et al. Preliminary study on the relationship between different blood glucose levels and periodontitis in patients with diabetes mellitus type 2[J]. *Chin J Stomatol*, 2021, 56(6): 517-524. DOI: 10.3760/cma.j.cn112144-20210128-00045
3. Sousa V, Mardas N, Farias B, et al. A systematic review of implant outcomes in treated periodontitis patients. *Clin Oral Implants Res.* 2016 Jul;27(7):787-844. doi: 10.1111/clr.12684.
4. Ye ZY, Liu H, Ye PZ, et al. Reconstruction of the 3D digital anatomical model of periodontal mandible with different amounts of bone resorption[J]. *Journal of Wenzhou Medical University*, 2021, 51(5):364-368,374. DOI: 10.3969/j.issn.2095-9400.2021.05.004
5. Kirzioglu Z, Ceyhan D, Sengul F, et al. Three-dimensional finite element analysis of the composite and compomer onlays in primary molars[J]. *Comput Methods Biomech Biomed Engin.* 2019;22(10):936-941. DOI: 10.1080/10255842.2019.1604951.
6. Liu Z, Sun T, Fan Y. Biomechanical influence of anchorages on orthodontic space closing mechanics by sliding method[J]. *Med Biol Eng Comput.* 2020;58(5):1091-1097. DOI: 10.1007/s11517-020-02149-1.
7. Benazzi S, Kullmer O, Grosse IR, et al. Brief Communication Comparing Loading Scenarios in Lower First Molar Supporting Bone Structure Using 3D Finite Element Analysis[J]. *American Journal of Physical Anthropology*, 2011, 147(1):128-134. DOI: 10.1002/ajpa.21607.
8. Kinney JS, Ramseier CA, Giannobile WV. Oral fluid-based biomarkers of alveolar bone loss in periodontitis. *Ann N Y Acad Sci.* 2007 Mar;1098:230-51. DOI: 10.1196/annals.1384.028.
9. Reddy RT, Vandana KL. Effect of hyperfunctional occlusal loads on periodontium: A three-dimensional finite element analysis. *J Indian Soc Periodontol.* 2018 Sep-Oct;22(5):395-400. DOI: 10.4103/jisp.jisp_29_18.
10. Ona M, Wakabayashi N. Influence of alveolar support on stress in periodontal structures. *J Dent Res.* 2006 Dec;85(12):1087-91. DOI: 10.1177/154405910608501204.
11. Karimi A, Razaghi R, Biglari H, et al. Finite element modeling of the periodontal ligament under a realistic kinetic loading of the jaw system. *Saudi Dent J.* 2020 Nov;32(7):349-356. DOI: 10.1016/j.sdentj.2019.10.005.
12. Nikolaus A, Currey JD, Lindtner T, et al. Importance of the variable periodontal ligament geometry for whole tooth mechanical function: A validated numerical study. *J Mech Behav Biomed Mater.* 2017 Mar;67:61-73. DOI: 10.1016/j.jmbbm.2016.11.020.

13. Alkan A, Aykaç Y, Bostanci H. Does temporary splinting before non-surgical therapy eliminate scaling and root planing-induced trauma to the mobile teeth? *J Oral Sci.* 2001 Dec;43(4):249-54.DOI: 10.2334/josnurd.43.249.
14. Sonnenschein SK, Ciardo A, Kilian S, et al. The impact of splinting timepoint of mobile mandibular incisors on the outcome of periodontal treatment-preliminary observations from a randomized clinical trial. *Clin Oral Investig.* 2021 Jul 26:1–10.DOI: 10.1007/s00784-021-04075-4.
15. d'Incau E, Couture C, Maureille B. Human tooth wear in the past and the present: tribological mechanisms, scoring systems, dental and skeletal compensations. *Arch Oral Biol.* 2012 Mar;57(3):214-29.DOI: 10.1016/j.archoralbio.2011.08.021.
16. Bertl K, Subotic M, Heimpl P, et al. Morphometric characteristics of cortical and trabecular bone in atrophic edentulous mandibles. *Clin Oral Implants Res.* 2015 Jul;26(7):780-7.DOI: 10.1111/clr.12340.
17. Ramos A, Nyashin Y, Mesnard M. Influences of geometrical and mechanical properties of bone tissues in mandible behaviour - experimental and numerical predictions. *Comput Methods Bio mech Biomed Engin.* 2017 Jul;20(9):1004-1014.DOI: 10.1080/10255842.2017.1322072.
18. Nikolaus A, Currey JD, Lindtner T, et al. Importance of the variable periodontal ligament geometry for whole tooth mechanical function: A validated numerical study. *J Mech Behav Biomed Mater.* 2017 Mar;67:61-73.DOI: 10.1016/j.jmbbm.2016.11.020.

Figures

Figure 1

Perspective View of Finite Element Models of Mandibles with Varying Degrees of Periodontitis

Figure 2

Cloud Chart of a Finite Element Analysis of Mandibular Root Interface During Vertical Loading

Figure 3

Cloud Chart of a Finite Element Analysis of Mandibular Root Interface During 45° Oblique Loading

Figure 4

Cloud Chart of a Finite Element Analysis of a Periodontal Membrane of Mandibular Dentition During Vertical Loading

Figure 5

Cloud Chart of a Finite Element Analysis of a Periodontal Membrane of Mandibular Dentition During 45° Oblique Loading

A

B

C

D

Figure 6

Cloud Chart of a Finite Element Analysis of a Periodontal Cancellous Bone of Mandible During Vertical Loading

A

B

C

D

Figure 7

Cloud Chart of a Finite Element Analysis of a Periodontal Cancellous Bone of Mandible During 45° Oblique Loading

Figure 8

Cloud Chart of a Finite Element Analysis of a Cancellous Bone of Mandible During Vertical Loading

Figure 9

Cloud Chart of a Finite Element Analysis of a Cancellous Bone of Mandible During 45° Oblique Loading