DOI: https://doi.org/10.17816/uds633465

# Effect of a Modified Herbst Appliance on the Mandible Assessed by the Finite Element Method

Nikita D. Pirskii [1], Roman A. Fadeev [2]

[1] Medical center "Romanovsky", Saint Petersburg, Russia;
[2] North-Western State Medical University named after. I. I. Mechnikov, Saint Petersburg, Russia

ABSTRACT

***BACKGROUND:*** The finite element method is a computational tool widely used in engineering and biomechanics, which is becoming increasingly relevant in the field of orthodontics. The ability to model a complex biological structures has made it a valuable tool for understanding the interactions that occur during tooth movement. Orthodontic treatment is based on the application of mechanical forces to move the teeth to a more desirable position, but these forces also affect the surrounding tissues, including the periodontal ligament and alveolar bone. The finite element method allows you to predict how these tissues will respond to various exposures, which helps to develop more effective and safe treatment methods

***AIM:*** To assess the effect of a Herbst appliance on bone structures of the mandible using the finite element method.

***MATERIALS AND METHODS:*** A 3D model of the mandible in a 25-year-old adult patient was built, and the effect of a modified Herbst appliance on the mandible was assessed by the finite element method.

***RESULTS:*** The physical properties of a viscoelastic material were determined for the 3D model, using a Kelvin model as the most appropriate best-case scenario for the cortical bone. The model of a static position of the mandible showed that the maximum mandibular displacement was 1.97 mm, the maximum elastic strain was 1.2% of the allowable limit, and the stress was less than 0.1% of the allowable limit. The model of mandibular movements during chewing revealed that the maximum displacement was 0.7 mm in the mandibular angle and coronoid process area. The elastic strain reached 2% of the allowable limit, concentrating on the distal surface of the mandibular second molar, and the stress was less than 0.2% of the allowable limit.

***CONCLUSIONS:*** A viscoelastic Kelvin model enabled creating a 3D model of the mandible with properties similar to those of bone tissue. The use of the finite element method to assess the effect of a modified Herbst appliance on the mandible allowed for imaging of the displacement, strain, and stress observed while the appliance was utilized.

**Keywords:** Herbst appliance; finite element method; orthodontics.

**To cite this article**

Pirskii ND, Fadeev RA. Effect of a Modified Herbst Appliance on the Mandible Assessed by the Finite Element Method. *Acta Universitatis Dentistriae et Chirurgiae Maxillofacialis*. 2024;2(3):141–150. DOI: https://doi.org/10.17816/uds633465

**Received:** 16.06.2024 **Accepted:** 28.09.2024 **Published online:** 29.09.2024

The article can be used under the CC BY-NC-ND 4.0 license
© Eco-Vector, 2024

DOI: https://doi.org/10.17816/uds633465

# Изучение действия модифицированного аппарата Гербста на нижнюю челюсть методом конечных элементов

Н.Д. Пирский [1], Р.А. Фадеев [2]

[1] Медицинский центр «Романовский», Санкт-Петербург, Россия;
[2] Северо-Западный государственный медицинский университет им. И. И. Мечникова, Санкт-Петербург, Россия

АННОТАЦИЯ

**Актуальность.** Метод конечных элементов — это вычислительный способ, широко используемый в инженерии и биомеханике, который приобретает все большую актуальность в области ортодонтии. Способность моделировать сложные биологические структуры сделала его ценным инструментом для понимания взаимодействий, происходящих в процессе перемещения зубов. Ортодонтическое лечение основано на применении механических усилий для перемещения зубов в более желательное положение, но эти усилия также воздействуют на окружающие ткани, включая периодонтальную связку и альвеолярную кость. Метод конечных элементов позволяет предсказать, как эти ткани будут реагировать на различные воздействия, что помогает разрабатывать более эффективные и безопасные методы лечения.

**Цель.** Изучение методом конечных элементов воздействия аппарата Гербста на костные структуры нижней челюсти.

**Материалы и методы.** Разработана 3-мерная модель нижней челюсти взрослого пациента 25 лет и произведен анализ действия модифицированного аппарата Гербста на нее методом конечных элементов.

**Результаты.** Для трехмерной модели определены физические свойства вязкоупругого материала на основании модели Kelvin как наиболее удачной идеализации поведения кортикальной кости. При симуляции статического положения нижней челюсти определено, что максимальная величина смещения нижней челюсти составляет 1,97 мм; максимальное значение упругой деформации составляет 1,2 % от предельно допустимого значения; значение напряжений достигает составляют менее 0,1 % от предельно допустимых значений. При симуляции движения нижней челюсти в процессе жевания определено, что максимальное смещение составляет 0,7 мм в области угла нижней челюсти и венечного отростка; упругие деформации достигают 2 % от предельного значения, концентрируясь в области дистальной поверхности нижнего второго моляра; значение напряжений составляет менее 0,2 % от предельно допустимого.

**Выводы.** Использование вязкоупругой модели Kelvin позволяет создать 3-мерную модель нижней челюсти со свойствами, приближенными к костной ткани. Изучение действия модифицированного аппарата Гербста на нижнюю челюсть методом конечных элементов позволило визуализировать явления смещения, деформации и напряжения, возникающие в период действия аппарата.

**Ключевые слова:** аппарат Гербста; метод конечных элементов; ортодонтия.

**Как цитировать**
Пирский Н.Д., Фадеев Р.А. Изучение действия модифицированного аппарата Гербста на нижнюю челюсть методом конечных элементов // Университетская стоматология и челюстно-лицевая хирургия. 2024. Т. 2, № 3. С. 141–150. DOI: https://doi.org/10.17816/uds633465

**Рукопись получена:** 16.06.2024 **Рукопись одобрена:** 28.09.2024 **Опубликована online:** 29.09.2024

ЭКО • ВЕКТОР

Статья доступна по лицензии CC BY-NC-ND 4.0 International
© Эко-Вектор, 2024

## INTRODUCTION

Modern orthodontic treatment planning must be based on reliable research findings and clinical data. Before initiating treatment, it is critical to understand how maxillofacial structures will respond to a specific treatment modality.

Computer technology has made it possible to use the finite element method for the assessment of orthodontic forces and their effect on bone tissues [1]. This method is currently regarded as an important tool for biomechanics studies in orthodontics.

The finite element method (FEM) is a method for numerically solving differential equations and problems in mathematical modeling. It is used for approximating geometric regions and calculating physical field distributions within them. The initial region is reduced into more simple subregions known as finite elements, and boundary-condition equations are then solved for each element. As a result, the regions are visualized with numerical representations of physical values. FEM computational packages typically feature visualization, which aids in the monitoring of internal stress, deformation, and displacement during interactions over time. It is critical to analyze stress patterns in the maxillofacial area observed during orthodontic treatment, because tooth movement occurs when the orthodontic force applied to the teeth and compact bone influences the entire periodontal ligament, which triggers cell-mediated response. Bone remodeling is determined by the nature of applied stress through the respective stress in the soft tissue matrix or the external force [1–4].

Advantages of FEM:

1) It is applicable to any structure with any geometry;

2) The method is non-invasive and allows the visualization of pre-, intra-, and postoperative treatment stages;

3) The reproducibility does not affect material properties;

4) The method is cost-effective;

5) The method takes less time compared to clinical studies.

The disadvantages of FEM include confusing results if incorrect data is entered into the software. Due to the complex geometry of biological structures, FEM becomes more reliable when the correct physical properties of biological tissues are used. The method does not take into account biological tissue growth; it only represents stress and displacement distributions. The examined structure is loaded without adding or removing any materials [5].

*STUDY AIM.* To assess the effect of the Herbst appliance on mandibular bone structures using the finite element method.

Study objectives: 1) To develop a mandible model compatible with FEM and assess whether it can produce clinically comparable results; 2) To analyze the model by calculating the maximum stress, maximum displacement, deformation, equivalent stresses, and principal stress observed in the mandible when using a modified Herbst appliance.

## MATERIALS AND METHODS

For the purposes of the study, a viscoelastic mandible model was developed, and forces applied to the mandible by the modified Herbst appliance were tested.

According to biomechanics, compact bone is a viscoelastic material, hence this modeling approach was justified [5, 6]. Viscoelasticity is a property of materials that exhibits both viscous and elastic characteristics when deformed. Materials thus behave as both liquids and solids.

The Maxwell and Voigt models (Fig. 1, *a*, *b*) used to describe mandibular bone tissue.

The Maxwell model is a sequential damper-spring system. This model shows a similar force applied to the spring and damper; however, when the force is removed, the spring returns to its initial state, whereas the damper does not. With an initial displacement (deformation), this model allows for a gradual decrease in stress, while with a constant load, a gradual displacement (the so-called creeping) is observed [7].

The Voigt model, which is used for the analysis of biological tissues such as cortical bone, allows for a parallel action of the damper and spring. In this model, the force is concentrated in the damper from the moment when the force is applied to the moment of reaching the maximum force. The maximum force is the spring is achieved simultaneously.

In this study, we used a modified Maxwell model with a parallel elastic element (the Kelvin model). It is also known as a standard linear model (Fig. 1, *c*). The Kelvin model, which combines the features of the Maxwell and Voigt models, best describes the behavior of the majority of actual viscoelastic materials. Thus, this model is optimal for assessing cortical bone behavior.

To assess the bone tissue state taking into account the presence of collagen, we used Prony parameters, which serve to model the material's response to loads over time, particularly in cases of deformation or restoration. This allowed representing the mandibular bone tissue as a material containing elastic and viscous elements, making it possible to identify simple components of a complex rheological characteristic, simplifying the analysis and interpretation of study findings. Determining the maximum principal stress, as well as the von Mises stress, is the gold standard for assessing stress distribution in the cortical bone. This helps to assess the deformation capacity (or destruction) of a plastic material. The assessment of both stresses is based on the fact that the von Mises stress indicates the total stress distributed

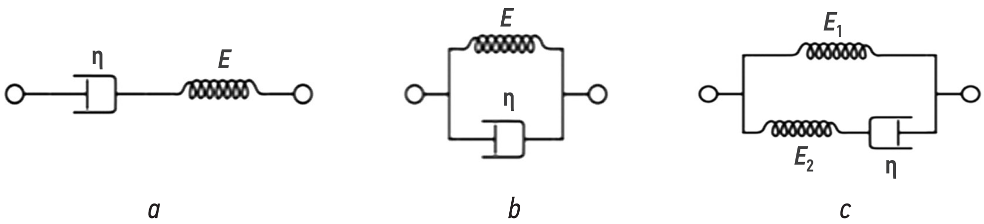



**Fig. 1.** *a*, Maxwell model; *b*, Voigt model; *c*, Kelvin model. Explanations are provided in the text
**Рис. 1.** *a* — Модель Maxwell; *b* — модель Voigt; *c* — модель Kelvin. Пояснения в тексте

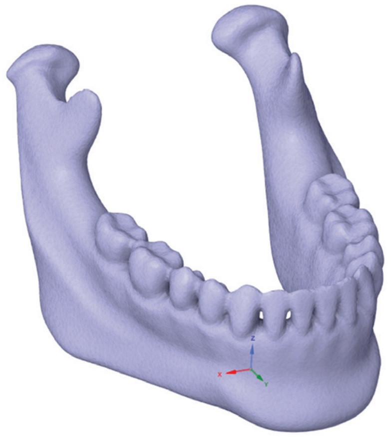


**Fig. 2.** 3D model of the mandible
**Рис. 2.** Трехмерная модель нижней челюсти

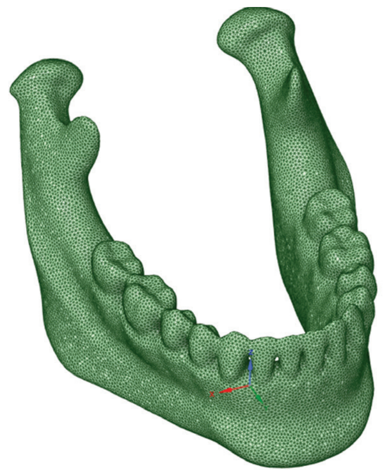


**Fig. 3.** Finite element method grid
**Рис. 3.** Сетка метода конечных элементов

in the mandible in all axial planes. On the contrary, the maximum principal stress is limited by the stress in a specific area under single-axis loading.

The mandible model was created by transforming cone beam computed tomography (CBCT) images of the mandible into 3D models (Fig. 2). CBCT images of an adult male patient (25 years old) with a distal occlusion were selected. The 3D model was analyzed using the ANSYS software. The model geometry was imported, and a grid was built using various modules of the ANSYS software (Fig. 3). The model had the following dimensions: width 140 mm, length 180 mm, and height 100 mm. Material parameters included the Young's modulus (modulus of elasticity) and the Poisson's ratio (a mechanical property of the material that indicates its deformation perpendicular to the loading direction) (Table 1) [8–13].

In the first molar area, forces of 200 N (vertical) and 300 N (horizontal) were applied to model the force applied by masseter muscles to the mandible and dental arches in a static position using the Herbst appliance. When modeling the maximum stress in mandibular elevator muscles, the total applied force was 582 N, with a loading time of 3 s: loading – exposure – unloading (1 s per stage). These forces were based on the mean masticatory force and the forces generated by masseter muscles described in the literature [8]. The finite element analysis included three stages: 1) preprocessing; 2) processing, and 3) post-processing.

*Preprocessing stage*. After developing the model and determining the grid density, the grid was generated as shown in Fig. 3. Table 2 represents Prony distributions. These properties will determine the behavior of materials after applying a specific load. Relative modules are ratios of the modules of elasticity (or rigidity) of various Prony distribution components to the general model; they are used to calculate the effect of each component on the total rigidity of the material. The relaxation time is the rate at which a material responds to applied forces and changes its form or structure in response to these forces.

After determining the properties of the material, it is critical to establish boundary conditions (limitation of node movement in one or several directions along the X, Y, and Z axes). This ensures the stability of a mandible model and enables the visualization of deformation and stress. Boundary conditions were applied to mandibular articular processes (Fig. 4).

Moreover, a mandible model with physiologically attached masseter muscles was created to simulate the maximum stress observed when using a fixed modified Herbst appliance (Fig. 5).

*Processing stage.* The purpose of this stage was to assess the development and changes in stress and deformation of the mandibular bone tissue during 6 months of treatment. This study focused on the displacement rate and changes in stress due to creeping.

DOI: https://doi.org/10.17816/uds633465

**Table 1.** Modulus of elasticity, Poisson's ratio and other characteristics of materials

**Таблица 1.** Модуль упругости, коэффициент Пуассона и другие характеристики материалов

| Measuring area | Material properties | | | | |
|---|---|---|---|---|---|
| | Modulus of elasticity, hPa | Poisson's ratio | Density, g/cm$^3$ | Creep limit, MPa | Ultimate strength, MPa |
| Enamel | 20 | 0.3 | 1.45 | 250 | 360 |
| Cortical bone | 17 | 0.3 | 2 | 250 | 460 |

**Table 2.** Prony distributions

**Таблица 2.** Распределения Prony

| Relative modules, i | Relaxation time, s |
|---|---|
| 0.45 | 5 |
| 0.07 | 35 |
| 0.04 | 400 |

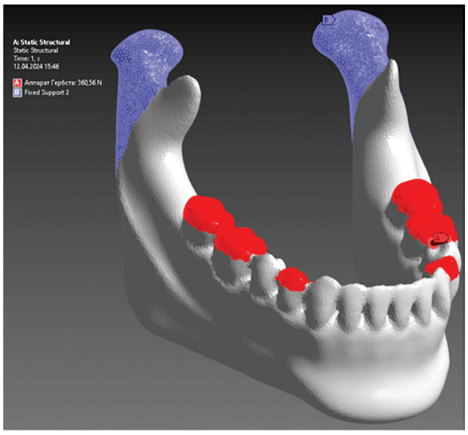



**Fig. 4.** The force corresponds to the use of a modified Herbst appliance. Viscoelastic properties of the cortical bone we added. Boundary conditions were applied to articular processes of the mandible

**Рис. 4.** Усилия соответствуют наложению модифицированного аппарата Гербста. Добавлены вязкоупругие характеристики кортикальной кости. Граничные условия наложены на суставные отростки нижней челюсти

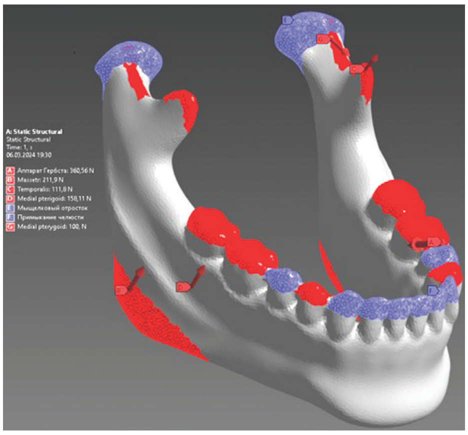



**Fig. 5.** Model of the mandible with physiologically attached masseter muscles and a fixed modified Herbst appliance

**Рис. 5.** Модель нижней челюсти с физиологическим креплением жевательных мышц и фиксированным модифицированным аппаратом Гербста

The behavior of a viscoelastic mandible model during 1 s at the start, middle, and end of treatment was simulated.

*Post-processing stage*. This stage demonstrates how applied forces affect bone tissue in terms of displacement and stress distribution. The results are presented as graphic colored contours with values. This helps to identify various output data patterns. The colors vary from red to blue.

## RESULTS AND DISCUSSION

*First simulation case.* The forces correspond to a fixed modified Herbst appliance; viscoelastic properties of the cortical bone were added.

The maximum displacement was 0.89 mm and 1.97 mm at the start of treatment and after 6 months, respectively. The displacement was observed in the anterior and inferior directions (clockwise rotation). The displacement rate decreased from incisors to the last molars. Thus, the mandibular teeth and mandibular body are displaced in the anterior and inferior directions (Fig. 6).

Maximum return elastic deformations are observed in the retromolar area, mandibular notch, and mandibular ramus, as well as at molar-premolar contact points. The articular process, incisor contact surfaces, mandibular body, and chin show the greatest compression stress. The maximum elastic deformation was 0.6% and 1.2% of the threshold value at the start of treatment and after

6 months, respectively. We can conclude that the expected elastic deformation will increase over time. However, these values are not associated with a risk of cortical bone fracture or enamel defects, because the bone tissue and enamel have a high elastic limit (250 MPa). The strength of biomaterials varies significantly; however, the enamel typically has a greater strength.

The von Mises stress is observed in the retromolar area, mandibular notch, and mandibular ramus, as well as at molar-premolar contact points. Equivalent stress values reach 0.28 MPa and 0.37 MPa at the start of treatment and after 6 months, respectively. The creep limit for the cortical bone and enamel is 250 MPa. The resulting stress values amount to <0.1% of this value; thus, the requirements for the margin of safety are met (Fig. 8). In some cases, we use orthodontic implants in the retromolar area in combination with a modified Herbst appliance. The resulting stress is not associated with a risk of impaired stability of orthodontic implants in this area.

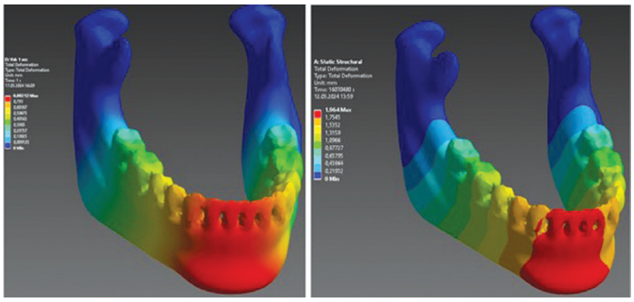
Principal stress areas at the start of treatment and after 6 months are localized along the mandible and dental arch (Fig. 9). The maximum value was observed in the retromolar area and the center of the mandibular ramus, amounting to 0.317 MPa and 0.32 MPa at the start of treatment and after 6 months, respectively. The risk of cortical bone defects and impaired stability of orthodontic implants in this area is minimal, because the ultimate strength of the bone tissue is high.

Table 3 presents the values of studied parameters and their characteristics.

The von Mises stress in the viscoelastic material model increases by approximately 37% from the start of treatment to 6 months, while the principal stress remains the same. This is due to the continuous application of a multi-axis load during a specific period of time. However, these forces generally have little impact on bone tissue, enamel, and additional fixed orthodontic appliances.

*Second simulation case.* The forces correspond to the fixation of a modified Herbst appliance and mandibular elevator muscles; viscoelastic properties of the cortical bone were added.

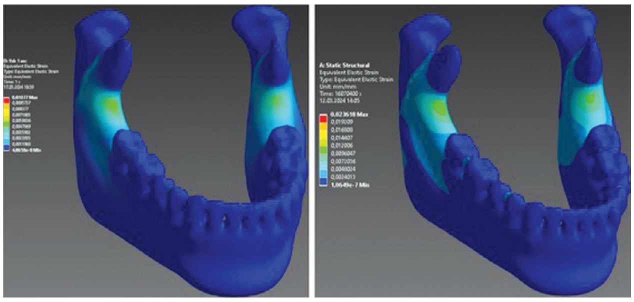
The maximum displacement is observed in the mandibular angle and coronoid process areas, amounting to 0.7 mm (Fig. 10). Notably, these areas are where the masseter and temporal muscles are attached; these muscles are directly involved in the action of the appliance during mastication. The displacement in viscoelastic materials is non-linear, as shown in Fig. 11. The deformation increases under a constant load.



*a* *b*

**Fig. 6.** Maximum displacement at the start of treatment (*a*) and in 6 months (*b*)

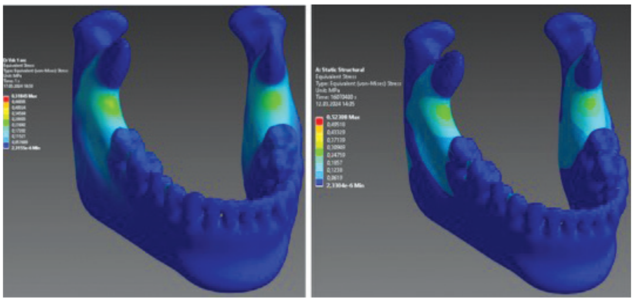
**Рис. 6.** Максимальное смещение в начале лечения (*a*) и через 6 мес. (*b*)



*a* *b*

**Fig. 7.** Return elastic strain at the start of treatment (*a*) and in 6 months (*b*)

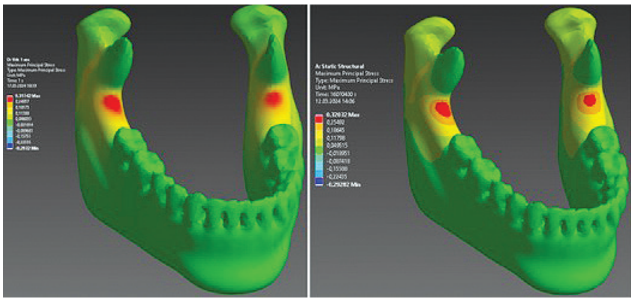
**Рис. 7.** Возвратные упругие деформации в начале лечения (*a*) и через 6 мес. (*b*)



*a* *b*

**Fig. 8.** Von Mises strain at the start of treatment (*a*) and in 6 months (*b*)

**Рис. 8.** Напряжения von Mises в начале лечения (*a*) и через 6 мес. (*b*)



*a* *b*

**Fig. 9.** Key areas of strain at the start of treatment (*a*) and in 6 months (*b*)

**Рис. 9.** Области главного напряжения в начале лечения (*a*) и через 6 мес. (*b*)

DOI: https://doi.org/10.17816/uds633465

**Table 3.** Comparison of von Mises voltage and main voltage before treatment and after 6 months
**Таблица 3.** Сравнение напряжения von Mises и главного напряжения до лечения и спустя 6 мес.

| Changes | Von Mises stress | Principal stress |
|---|---|---|
| At the start of treatment, MPa | 0.28 | 0.317 |
| After 6 months, MPa | 0.37 | 0.32 |
| Difference, % | 37 | 0.94 |

Maximum return elastic deformations are observed on the distal surface of the mandibular second molar (2%). They amount to 0.7% in the articular and coronoid process areas, as well as the mandibular angle area, and to 1% in the lingual area of the cortical bone, near the mandibular second molar (Fig. 12). These values are not associated with a risk of cortical bone fracture or enamel defects, because the bone tissue and enamel have a high elastic limit (250 MPa).

The von Mises stress peaks in the lingual area of the cortical bone (0.9 MPa; 0.2% of the threshold value); in the articular and coronoid process areas, as well as the mandibular angle area, it amounts to 0.45 MPa (0.01% of the threshold value) (Fig. 13).

Principal stress areas are localized along the mandible and dental arch (from 3.4 to 4.4). The maximum value is observed in the mandibular ramus area, amounting to 0.48 MPa (Fig. 14). The risk of cortical bone defects is minimal.

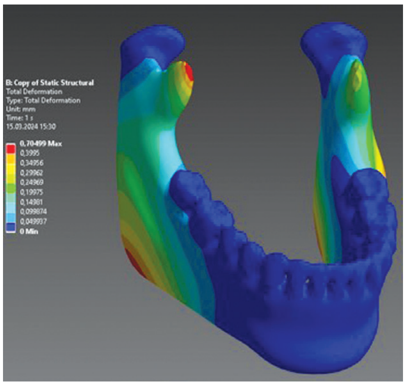


**Fig. 10.** Maximum displacement during the maximum strain of mandibular elevator muscles with a fixed appliance
**Рис. 10.** Максимальное смещение при максимальном напряжении мышц, поднимающих нижнюю челюсть, с фиксированным аппаратом

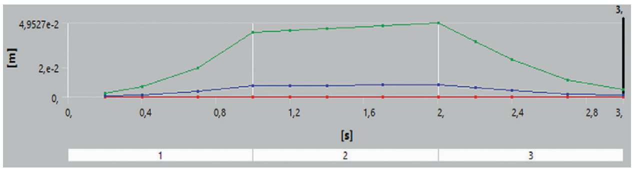



**Fig. 11.** Strain curve (X-axis: time, seconds; Y-axis: strain)
**Рис. 11.** График деформации (ось абсцисс — время в секундах, по оси ординат — деформация)

## CONCLUSIONS

1. A 3D mandible model has been developed using the finite element method, with properties similar to those of the bone tissue. The resulting displacement was similar to the effects observed in clinical practice.

2. The 3D mandible model was employed to assess the bone tissue when using the Herbst appliance. The maximum displacement 6 months after the start of treatment was 1.964 mm; the maximum elastic deformation was 1.2% of the threshold value; and the stress was less than 0.1% of the threshold value. During masticatory force modeling, the maximum displacement was observed in the mandibular angle and coronoid process areas, amounting to 0.7 mm. Maximum elastic deformations were observed on the distal surface of the mandibular second molar, amounting to 2% of the threshold value.

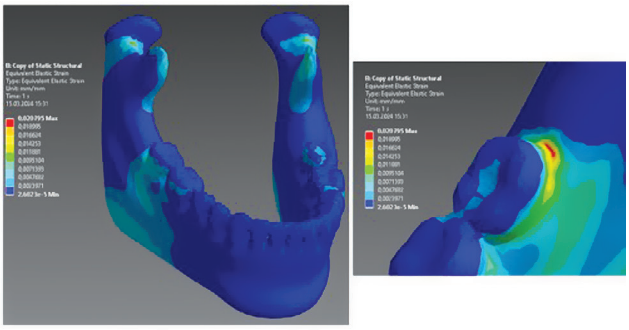


**Fig. 12.** Return elastic strain during the maximum strain of mandibular elevator muscles with a fixed appliance
**Рис. 12.** Возвратные упругие деформации при максимальном напряжении мышц, поднимающих нижнюю челюсть, с фиксированным аппаратом

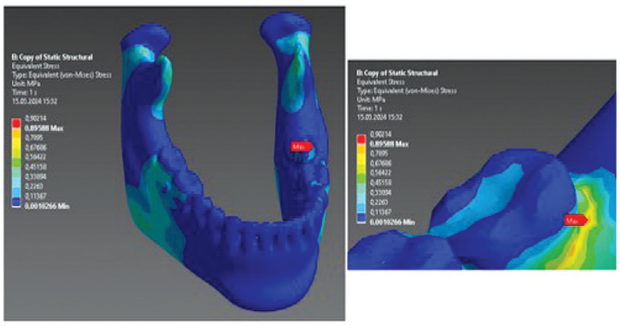


**Fig. 13.** Von Mises strain during the maximum strain of mandibular elevator muscles with a fixed appliance
**Рис. 13.** Напряжения von Mises при максимальном напряжении мышц, поднимающих нижнюю челюсть, с фиксированным аппаратом

DOI: https://doi.org/10.17816/uds633465

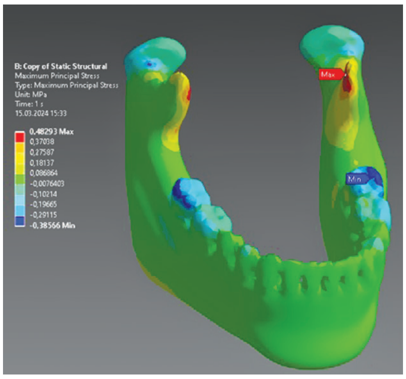



**Fig. 14.** Key areas of strain during the maximum strain of mandibular elevator muscles with a fixed appliance

**Рис. 14.** Области главного напряжения при максимальном напряжении мышц, поднимающих нижнюю челюсть, с фиксированным аппаратом

## CONCLUSION

Further research into the behavior of orthodontic materials and appliances using the finite element method has a huge potential [14, 15]. Viscoelastic mandible models allow simulating the effects most similar to those observed in real-world clinical practice. Given the limitations of this method, it is critical to specify the widest range of parameters of studied objects, from model dimensions to physical properties of biological media, in order to produce the most reliable results. We hope that our study will be followed by further research on the subject.

## ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

**Вклад авторов.** Все авторы внесли существенный вклад в подготовку статьи, прочли и одобрили финальную версию перед публикацией. Вклад каждого автора: Н.Д. Пирский — сбор и обработка материалов, написание текста; Р.А. Фадеев — концепция и дизайн исследования.

**Источник финансирования.** Авторы заявляют об отсутствии внешнего финансирования при написании статьи.

**Конфликт интересов.** Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

## ADDITIONAL INFORMATION

**Authors' contribution.** All authors have made a significant contribution to the development of the concept, research, and preparation of the article, as well as read and approved the final version before its publication. Personal contribution of the authors: N.D. Pirskii — collecting and preparation of samples, writing the text; R.A. Fadeev — experimental design.

**Funding source.** The authors claim that there is no external funding when writing the article.

**Competing interests.** The authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.

## REFERENCES

**1.** Sun Z, Lee E, Herring SW. Cranial sutures and bones: Growth and fusion in relation to masticatory strain. *Anat Rec*. 2004;276A(2):150–161. doi: 10.1002/ar.a.20002

**2.** Gröning F, Liu J, Fagan MJ, O'Higgins P. Why do humans have chins? Testing the mechanical significance of modern human symphyseal morphology with finite element analysis. *Am J Phys Anthropol.* 2011;144(4):593–606. doi: 10.1002/ajpa.21447

**3.** Trivedi S. Finite element analysis: A boon to dentistry. *J Oral Biol Craniofac Res*. 2014;4(3):200–203. doi: 10.1016/j.jobcr.2014.11.008

**4.** Oh S, Choi Y-K, Kim S-H, et al. Biomechanical analysis for different mandibular total distalization methods with clear aligners: A finite element study. *Korean J Orthod.* 2023;53(6):420–430. doi: 10.4041/kjod23.035

**5.** Mohammed SD, Desai H. Basic concepts of finite element analysis and its applications in dentistry: An overview. *J Oral Hyg Heal.* 2014;2:156. doi: 10.4172/2332–0702.1000156

**6.** Johnson TPM, Socrate S, Boyce MC. A viscoelastic, viscoplastic model of cortical bone valid at low and high strain rates. *Acta Biomater.* 2010;6(10):4073–4080. doi: 10.1016/j.actbio.2010.04.017

**7.** Chawla KK, Meyers MA. *Mechanical behavior of materials*. Prentice Hall; 1999.

**8.** Edmonds HM, Glowacka H. The ontogeny of maximum bite force in humans. *J Anat*. 2020;237(3):529–542. doi: 10.1111/joa.13218

**9.** Huang H-L, Chang C-H, Hsu J-T, et al. Comparison of implant body designs and threaded designs of dental implants: a 3-dimensional finite element analysis. *Int J Oral Maxillofac Implants*. 2007;22(4):551–562.

**10.** O'Brien WJ. *Dental materials and their selection. 2nd ed.* Chicago: Quintessence; 2002. 347 p.

**11.** Yang H-S, Lang LA, Molina A, Felton DA. The effects of dowel design and load direction on dowel-and-core restorations. *J Prosthet Dent*. 2001;85(6):558–567. doi: 10.1067/mpr.2001.115504

**12.** Khlusov IA, Pichugin VF, Surmeneva MA, Surmenev RA. *Fundamentals of biomechanics of biocompatible materials and biological tissues: textbook (revised and supplemented)*. Tomsk: TPU Publ.; 2023. 163 p. (In Russ.)

**13.** Nyashin YuI, Rogozhnikov GI, Rogozhnikov AG, et al. Biomechanical analysis of dental implants made of titanium and zirconium dioxide alloys. *Russian journal of biomechanics*. 2012;16(1):102–109. EDN: OXALAV (In Russ.)

**14.** Vilanova L, Bellini-Pereira SA, Patel MP, et al. Finite element analysis of two skeletally anchored maxillary molar distalisation methods. *J Orthod*. 2023;50(4):344–351. doi: 10.1177/14653125231166437

**15.** Duggal I, Singh N, Tripathi T. Queries regarding clinical finite element analysis of mandibular displacement model treated with Twin-block appliance. *Am J Orthod Dentofacial Orthop*. 2023;164(4): 461–462. doi: 10.1016/j.ajodo.2023.06.019

## СПИСОК ЛИТЕРАТУРЫ

**1.** Sun Z., Lee E., Herring S.W. Cranial sutures and bones: Growth and fusion in relation to masticatory strain // Anat Rec. 2004. Vol. 276A, N 2. P. 150–161. doi: 10.1002/ar.a.20002

**2.** Gröning F., Liu J., Fagan M.J., O'Higgins P. Why do humans have chins? Testing the mechanical significance of modern human symphyseal morphology with finite element analysis // Am J Phys Anthropol. 2011. Vol. 144, N 4. P. 593–606. doi: 10.1002/ajpa.21447

**3.** Trivedi S. Finite element analysis: A boon to dentistry // J Oral Biol Craniofac Res. 2014. Vol. 4, N 3. P. 200–203. doi: 10.1016/j.jobcr.2014.11.008

**4.** Oh S., Choi Y.-K., Kim S.-H., et al. Biomechanical analysis for different mandibular total distalization methods with clear aligners: A finite element study // Korean J Orthod. 2023. Vol. 53, N 6. P. 420–430. doi: 10.4041/kjod23.035

**5.** Mohammed S.D., Desai H. Basic concepts of finite element analysis and its applications in dentistry: An overview // J Oral Hyg Heal. 2014. Vol. 2. ID 156. doi: 10.4172/2332–0702.1000156

**6.** Johnson T.P.M., Socrate S., Boyce M.C. A viscoelastic, viscoplastic model of cortical bone valid at low and high strain rates // Acta Biomater. 2010. Vol. 6, N 10. P. 4073–4080. doi: 10.1016/j.actbio.2010.04.017

**7.** Chawla K.K., Meyers M.A. Mechanical behavior of materials. Prentice Hall, 1999.

**8.** Edmonds H.M., Glowacka H. The ontogeny of maximum bite force in humans // J Anat. 2020. Vol. 237, N 3. P. 529–542. doi: 10.1111/joa.13218

**9.** Huang H.-L., Chang C.-H., Hsu J.-T., et al. Comparison of implant body designs and threaded designs of dental implants: a 3-dimensional finite element analysis // Int J Oral Maxillofac Implants. 2007. Vol. 22, N 4. P. 551–562.

**10.** O'Brien W.J. Dental materials and their selection. 2nd ed. Chicago: Quintessence, 2002. 347 p.

**11.** Yang H.-S., Lang L.A., Molina A., Felton D.A. The effects of dowel design and load direction on dowel-and-core restorations // J Prosthet Dent. 2001. Vol. 85, N 6. P. 558–567. doi: 10.1067/mpr.2001.115504

**12.** Хлусов И.А., Пичугин В.Ф., Сурменева М.А., Сурменев Р.А. Основы биомеханики биосовместимых материалов и биологических тканей: учебное пособие (переработанное и дополненное). Томск: Изд-во ТПУ, 2023. 163 с.

**13.** Няшин Ю.И., Рогожников Г.И., Рогожников А.Г., и др. Биомеханический анализ зубных имплантатов из сплава титана и диоксида циркония // Российский журнал биомеханики. 2012. Т. 16, № 1. С. 102–109. EDN: OXALAV

**14.** Vilanova L., Bellini-Pereira S.A., Patel M.P., et al. Finite element analysis of two skeletally anchored maxillary molar distalisation methods // J Orthod. 2023. Vol. 50, N 4. P. 344–351. doi: 10.1177/14653125231166437

**15.** Duggal I., Singh N., Tripathi T. Queries regarding clinical finite element analysis of mandibular displacement model treated with Twin-block appliance // Am J Orthod Dentofacial Orthop. 2023. Vol. 164, N 4. P. 461–462. doi: 10.1016/j.ajodo.2023.06.019

## AUTHORS' INFO

***Nikita D. Pirskii,** orthodontist, Medical center "Romanovsky";
address: 40 Nekrasova str., Saint Petersburg, 191014, Russia;
Russia; ORCID: 0009-0008-1853-9510;
eLibrary SPIN: 5157-9593;
e-mail: nikita1996pirskii@gmail.com

## ОБ АВТОРАХ

***Никита Дмитриевич Пирский,** врач-ортодонт
медицинского центра «Романовский»; адрес: Россия, 191014,
Санкт-Петербург, ул. Некрасова, д. 40;
ORCID: 0009-0008-1853-9510; eLibrary SPIN: 5157-9593;
e-mail: nikita1996pirskii@gmail.com

* Corresponding author / Автор, ответственный за переписку

## AUTHORS' INFO

**Roman A. Fadeev,** MD, Dr. Sci. (Med.), professor, Head of the Department of Orthopedic Dentistry, Orthodontics and Gnathology, North-Western State Medical University named after I.I. Mechnikov, Saint Petersburg, Russia; ORCID: 0000-0003-3467-4479; eLibrary SPIN: 4556-5177; e-mail: sobol.rf@yandex.ru

## ОБ АВТОРАХ

**Роман Александрович Фадеев,** д-р мед. наук, профессор, заведующий кафедрой ортопедической стоматологии, ортодонтии и гнатологии, Северо-Западный государственный медицинский университет им. И.И. Мечникова, Санкт-Петербург, Россия; ORCID: 0000-0003-3467-4479; eLibrary SPIN: 4556-5177; e-mail: sobol.rf@yandex.ru