

## BIOMECHANICAL EVALUATION OF MANDIBULAR SPLINTING METHOD FOR FRACTURES WITHIN THE DENTAL ARCH

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Treatment of mandibular fractures remains a pressing issue in maxillofacial surgery. This paper presents a novel single-jaw splinting technique (RF patent No. 2735258) for the immobilization of bone fragments in fractures located within the dental arch. Mathematical modeling using the finite element method (FEM), based on computed tomography data from one volunteer, was performed to assess its biomechanical efficiency. A 3D model of the mandible with the fixation construct and an indenter (simulating occlusal load up to 50 N) was constructed. The modeling results showed that the relative movement between the fragments was approximately 25 µm, which is comparable with literature data for two-titanium-plate osteosynthesis. The maximum equivalent stress values in the metal splint reached 100 MPa, and in the splint these reached 3 MPa. The developed method ensures stable fixation without involvement of the maxilla. The analysis involved only a single model and no experimental validation; therefore, confirmation in further research is required. Nevertheless, the obtained data suggest that the method is promising as an alternative to existing immobilization techniques.

**Keywords:** mandibular fracture, bone fragment immobilization, finite element method, single-jaw splinting, biomechanics

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## БИОМЕХАНИЧЕСКАЯ ОЦЕНКА МЕТОДА ШИНИРОВАНИЯ НИЖНЕЙ ЧЕЛЮСТИ ПРИ ПЕРЕЛОМАХ В ПРЕДЕЛАХ ЗУБНОГО РЯДА

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Лечение переломов нижней челюсти остается актуальной проблемой челюстно-лицевой хирургии. В исследовании представлен новый метод одночелюстного шинирования (патент РФ №2735258) для иммобилизации отломков при переломах в пределах зубного ряда. Для оценки его биомеханической эффективности использовали математическое моделирование методом конечных элементов (МКЭ) на основе компьютерной томографии одного добровольца. Построена трехмерная модель нижней челюсти с фиксирующей конструкцией и импактором, имитирующим жевательную нагрузку до 50 Н. Результаты моделирования показали, что относительное смещение между отломками составляет около 25 мкм, что сопоставимо с данными литературы по остеосинтезу двумя титановыми пластинами. Максимальные эквивалентные напряжения в металлической шине достигают 100 МПа, в капле — до 3 МПа. Разработанный метод обеспечивает стабильную фиксацию без вовлечения верхней челюсти. Анализ выполнен на единственной модели без экспериментальной валидации, что требует подтверждения в дальнейших работах. Тем не менее, полученные данные свидетельствуют о перспективности метода как альтернативы существующим способам иммобилизации.

**Ключевые слова:** перелом нижней челюсти, иммобилизация отломков, метод конечных элементов, одночелюстное шинирование, биомеханика

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Mandibular fractures hold a significant position in maxillofacial surgery worldwide and represent one of the most prevalent types of jaw injuries [1]. Treatment of mandibular fractures should be aimed at preserving the integrity of the anatomical structures and stabilizing bone fragments in a fixed position until healing, while restoring the correct occlusal relationship and maintaining the proportions of the lower third of the face.

In recent years, surgical intervention using bone fixation with various types of bone plates has become widely adopted. However, there is debate regarding their rigidity and stability, as well as depending on the clinical case: the location of the fracture (within or outside the dental arch), displaced mandibular fractures depending on the severity of the injury, and the increase in the cost of medical services provided [2, 3].

An important condition for the provision of qualified medical care is the physician's level of training and valid manual skills, which allow correct screw positioning, a competent approach to plate selection considering tissue resources and the type of injury, and consideration of the clinical and anatomical features of the mandibular structures, including abnormalities. In the absence of these factors, dangerous precedents of deficiencies in the provision of medical care or harm are created, which, under local legislation, may be considered a criminally punishable act.

Conservative treatment methods for fractures using intermaxillary fixation with dental splints and elastic tension are also accepted. Along with a large number of advantages, these methods have a number of disadvantages, the most significant of which are a marked decrease in oral hygiene and the patient's quality of life during the period of bite fixation [4, 5].

It should be noted that splinting remains a compromise method for treating mandibular fractures in areas with low population density or complex geographic landscape. Moreover, an important role in the care provision protocol is played by factors such as the clinic's material and technical resources, the professional skills of healthcare staff, etc.

In terms of prevalence, mandibular fractures account for 57–82% of all facial bone fractures [6]. According to a large epidemiological study by Morris et al. (2015), fractures of the mandibular body are the most common (16.8%) [7]. Similar patterns have been reported for the Russian population: according to Shashkov et al. (2021) [8], fractures of the mandibular body were distributed as follows: in the incisor area — 3.9%, in the canine and premolar area — 15.9%, and in the molar area — 15.3%. Such fractures significantly decrease patients' quality of life, including influencing their socialization and eating habits, the alteration of which may worsen the comprehensive rehabilitation process. We should also note the deterioration of dental health resulting from treatment with splints of previous generations: according to the literature, there is an increase in the rate of carious lesions of hard dental tissues and inflammatory diseases of periodontal tissues, which is associated with difficulties in hygiene when using classic dental splints [9, 10].

In this regard, the development of new methods for fragment immobilization in mandibular fractures remains an urgent problem and requires further solution; therefore, we have developed a novel single-jaw splinting technique for mandibular fractures (RF invention patent No. 2735258 dated 29.10.20).

For null hypothesis testing, the use of mathematical modeling by the finite element method, widely used in physical and mathematical modeling, would be a rational solution. Such an approach is an important experimental instrument that makes it possible to assess the efficacy of the planned treatment method. The main purpose of finite element analysis in medicine, as in other fields, is to analyze the effects of force

on a given structure, evaluate the stability and resistance of the structure to pressure, force, and other external influences [11]. Today, this method allows us to effectively assess biomechanical stability, calculate the stress between bone fragments of the facial skull, and their fixation strength in the context of specific mandibular injuries [12, 13]. The data obtained that confirm the null hypothesis can be transferred into clinical practice without fear of adverse effects on biological tissues, thereby increasing the quality of skilled care provision in the field of maxillofacial surgery.

This study aimed to perform a finite element analysis of the efficacy of a novel mandibular fracture fixation method.

## METHODS

### Data

Computer modeling and the finite element method (FEM) were used to simulate the stress-strain state (SSS) of two configurations of the fractured mandible: with the proposed fixation construct and with the conventional treatment approach using osteosynthesis, the results of which were reported in a previous study [14]. The jaw and teeth were segmented on multiplanar reconstruction from dental CBCT data (KaVo ORTHOPANTOMOGRAPH OP300 Maxio cone beam computed tomography scanner, 312 slices, pixel size 250  $\mu\text{m}$ ) of a volunteer (male, born in 1989) with no pathological changes detected in the mandibular region, using a trial version of the software (Inobitec PRO 2.10, Voronezh, Russia) (Fig. 1A).

Routine segmentation in three projections was performed for each anatomical structure. The contours obtained were used to generate a voxel model, which was then converted into an STL model (Fig. 1B).

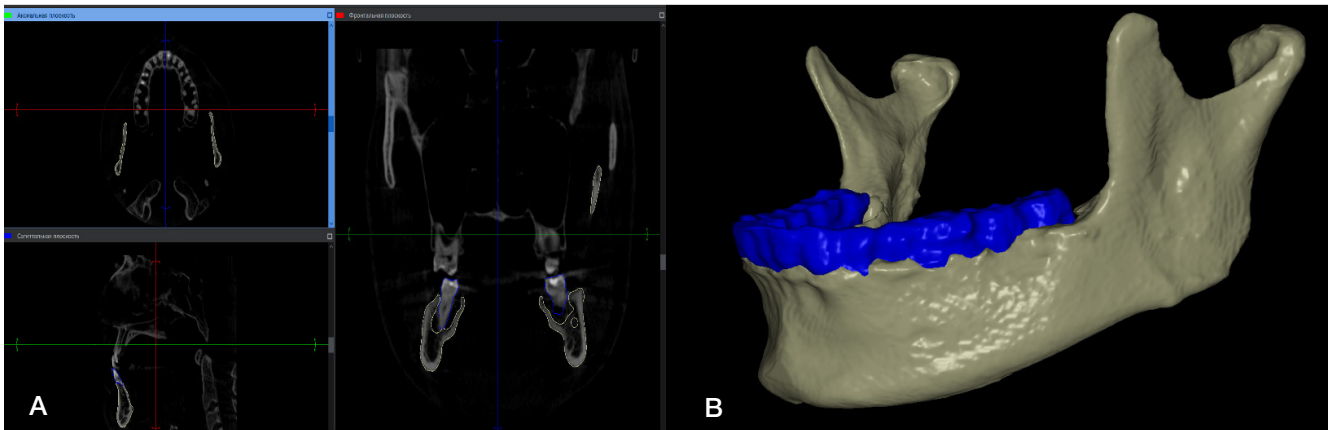
### NURBS modeling

Reverse engineering of the STL models was performed in SolidWorks (Dassault Systèmes SE, Vélizy-Villacoublay, France). The ScanTo3D utility was used to generate NURBS models (NURBS — Non-uniform rational B-spline) of the mandible and teeth (Fig. 2A). In the STL model of the dental arch, each tooth was segmented and converted into a NURBS model (Fig. 2B). Using the basic tools of SolidWorks, a linear fracture region with a gap of 0.1 mm, corresponding to a simple uncomplicated fracture, was modeled between teeth 44 and 45, along with a pair of temporomandibular joints, a fixation construct, and an indenter mimicking food (Fig. 2).

Pre-processing of the NURBS model for finite element analysis was performed in HyperMesh (Altair Engineering Inc., Troy, Michigan, USA). A tetrahedral mesh was generated for each anatomical structure (two mandibular segments, 15 teeth, two temporomandibular joints), the indenter, and the fixation construct. Mesh quality was controlled using the Jacobian (threshold  $\geq 0.1$ ) and Tet collapse (threshold  $\leq 0.1$ ) metrics. At least 98% of the elements met these criteria; elements that failed the test were rebuilt manually. The final mesh contained 800,604 elements (Fig. 3) [15]. The resulting finite element models were imported as orphan meshes into Abaqus CAE (Simulia, Johnston, Rhode Island, USA) to assign mechanical properties to materials and to set boundary conditions for biomechanical analysis of the model [16].

### Assumptions and mathematical formulation of the problem

From a mathematical point of view, a static problem in elasticity theory was solved in each of the locally homogeneous



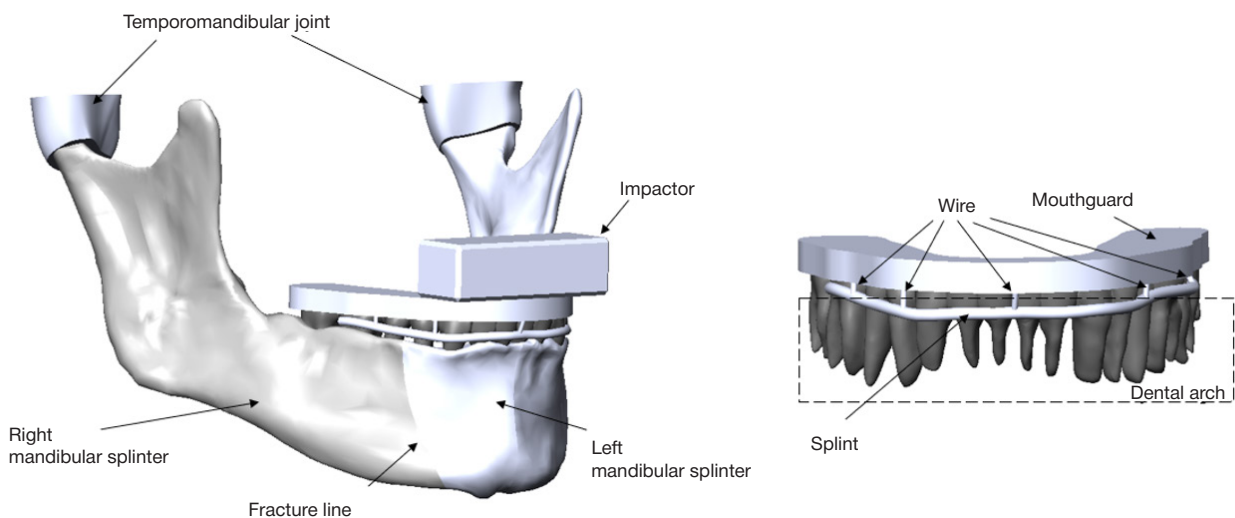
**Fig. 1. A.** Interface of the Inobitec PRO software for segmentation of medical images: multiplanar reconstruction with highlighted contours of the zone of interest. **B.** Segmentation result in the form of voxel 3D model of the mandible and dental arch

subregions of the heterogeneous functional element of the model, considering the effect of a moment of force to simulate the indentation of the fixed jaw segments into the elastic indenter. To connect the jaw segments and teeth, the joints and condylar processes, the mouthguard and the wire, multiple contact without relative movement was employed, which constitutes a critical assumption within the model. Contacts between the jaw segments, teeth and mouthguard, and between the mouthguard and the indenter were set as tangential with a friction coefficient of 0.1 and normal "hard contact" behavior. The upper surface of the fixator and the temporomandibular joints were rigidly fixed (no degrees of freedom for any node on the surface). The masseteric tuberosity regions (Fig. 4, highlighted in pink) were kinematically connected at the mental protuberance (Fig. 4, RP-3), to which a moment of force was applied, linearly increasing to 500 N·mm (0.5 N·m). An isotropic linear elastic material model was used for all materials [17, 18]. The mechanical characteristics taken from the literature are provided in the Table.

In this study, a deterministic finite element analysis was performed; no statistical processing was applied, because the analysis was based on a single model.

## RESULTS

The finite element method was used to obtain the stress-strain state (SSS) of the mandibular segments with a fracture and a fixation construct. It was found that the relative displacement



**Fig. 2.** NURBS model of the mandible with the fixing construct and impactor

in the proposed configuration increases linearly with a linearly increasing load. Under a load of 50 N, a relative displacement of 25  $\mu\text{m}$  was achieved between the fragments. The results were compared with those of the two-plate fragment immobilization method in two different configurations [14] (Fig. 5). Outliers on the graph are associated with an increase in the solver increment. The contact pressure between the fragments is shown in Fig. 6A and reaches 2 MPa. In the deformed configuration, the relative displacement is marked with a dotted line.

The maximum stress in the entire configuration is concentrated on the metal splint (Fig. 6B) and reaches 100 MPa. In turn, the maximum stress on the mouthguard is distributed over the fracture area (Fig. 6B), reaching a value of 3 MPa.

The finite element analysis has shown that the proposed fixation method demonstrates satisfactory displacement between the fragments of about 25  $\mu\text{m}$  with a linear increase in the indenter load (mimicking food) to 50 N. The relative displacement achieved with the proposed method is comparable to the displacement obtained from the finite element calculation for the fixation construct with two titanium plates.

## DISCUSSION

The present study has a number of limitations. First, the finite element analysis was performed based on CT data from a single volunteer whose clinical and anatomical characteristics met the indications for the use of the developed splinting device, which does not allow for consideration of anatomical variability.

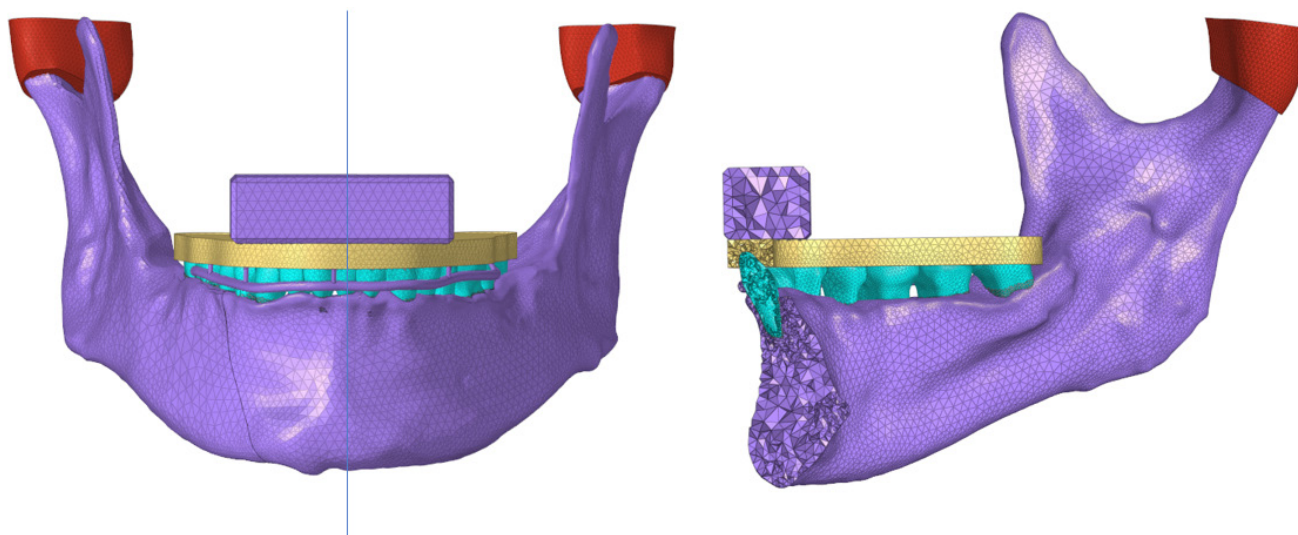


Fig. 3. Finite element model of the estimated area: left — frontal view, right — cutaway model (midsagittal plane)

Second, the model was not validated in a field experiment, either on synthetic jaw models or on biological material. Third, the efficacy of the developed splint was compared with literature data on condylar process fixation using two plates [14], which is not a direct analogue due to the lack of valid literature data on similar constructs. Further research involving an expanded sample of virtual models and experimental verification is required to obtain more reliable data.

As previously stated in the modeling methods, multiple contact without relative movement was used for dentoalveolar structures, which is justified by the strategy of uniform load redistribution over the entire surface of the splinting construct and between the fragments.

Rigid tooth–splint contact ( $\mu = 0.1$ , slip-free) reflects the clinical stability of dental splinting with multiple supports (4–6 teeth) in adult patients, ensuring uniform load redistribution without relative movement of the fragments [25]. Microdisplacement ( $< 0.1$  mm) does not exceed the physiological mobility of the periodontium and does not affect fracture consolidation.

All mandibular fracture treatment methods are aimed at fixing bone fragments until they fuse and the masticatory load provided by several muscle groups is restored. Due to the complex anatomy of the mandible, which is determined by its functions, the application of forces to the fracture line or to the selected fixation system (plates) may inadequately affect the restoration of physiological load. Indeed, there is ongoing debate in the literature regarding the selection of the most appropriate fixation system for each specific case. Some surgeons prefer to use mini-plates and screws, while others prefer titanium plates to stabilize fractures, believing that such a system ensures sufficient rigidity and minimizes resistance to physiological load. Furthermore, two-jaw dental splints can be used for stabilization and fixation of the fracture during healing.

These splints have a specific design that helps maintain the correct position of the jaw and prevents unwanted movement or displacement of the fracture. Experimental data obtained by Claes et al. [26] using a sheep model of metatarsal osteotomy with an adjustable gap size and interfragmentary movement show that with a gap of 1–2 mm and interfragmentary movement of up to 0.5 mm (500  $\mu$ m), successful fusion with high mechanical stability (bending rigidity  $> 20$  Nm/mm) is achieved. The authors note that it is not the quantity but the quality of the forming bone callus that determines the healing outcome. In our study, the interfragmentary displacement was only 25  $\mu$ m, which is an order of magnitude lower than the values at which stable fusion was observed in that study. Thus, the results obtained can be extrapolated to our data, as they indicate sufficient stability of the developed splinting construct, ensuring fracture consolidation.

According to the generalized results of experimental studies and clinical trials, when the gap between bone fragments is no more than 3 mm, the interfragmentary displacement range optimal for stimulation of bone fusion is 0.15–0.4 mm, and the threshold exceeded by more than 1.0 mm is associated with the risk of fusion failure [26–29]. In our study, the displacement of splinters relative to each other under the load of 50 N was as small as 0.025 mm (25  $\mu$ m), which was almost an order of magnitude below the optimal range lower limit.

Given the results, the fixation system for the mandibular bone splinters should be selected based on the clinical anatomy, fracture type, patient's condition, and the aim of surgery. It is important for the surgeon to select the most appropriate fixation system, which would ensure the splinters' stability without altering the physiological load on the jaw, based on his/her experience and knowledge.

In the study, we used the one-jaw splinting method for mandibular fractures we had developed, designed for fixation of

Table. Mechanical characteristics of the anatomical structures being parts of the segment assessed

Anatomical structure	Young's modulus E (MPa)	Poisson's ratio	Element type	Reference
Bone	15 000	0.3	C3-D4	[19, 20]
Teeth	18 600	0.31	C3-D4	[21]
Temporomandibular joints	10.4	0.4	C3-D4	[22]
Impactor	0.1	0.45	C3-D4	
Mouth guard (Ftorax)	1860	0.3	C3-D4	[23]
Wire (aluminum)	71 000	0.33	C3-D4	[24]

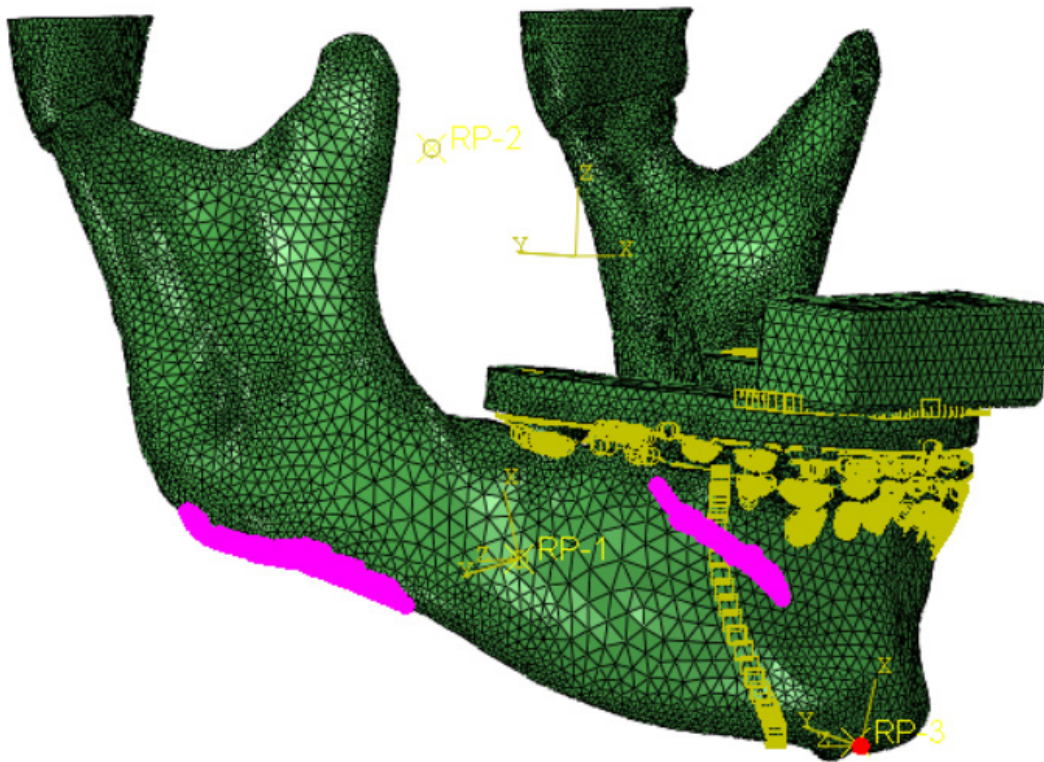


Fig. 4. Determination of contact interactions in the Abaqus CAE 6.14 software

fractures within the dental arch, which seems to be an optimal solution for the distant regions and FAS, where high-tech medical care is not always available in the required quantities and with the necessary urgency.

The limits of force applied to various parts of the mandible have been reported. Thus, in the symphysis zone the value was 82 MPa with the mouth closed and 117 MPa with the mouth open, which allows one to predict the position of the jaws clenched more beneficial in terms of the fracture prognosis [30]. The angle, at which force is applied, is of great importance. According to some data, the condylar process (in case of direct injury to the body) or angle of the jaw is a common area of fracture [31].

In the literature, papers can be found focusing on non-removable treatment techniques, in which, among other findings, conclusions are drawn about the advantages of splinting constructs for the rehabilitation of patients with maxillofacial injuries [32–34]. Nevertheless, despite good

planning, detailed analysis of force loads, and fracture prediction, there is very little information in the literature on the finite element analysis of removable appliances. Our study showed that the proposed fixation method demonstrates satisfactory fragment displacement of about 25 μm with a linear increase in indenter load to 50 N, which is comparable to the displacement obtained from the finite element calculation for a fixation construct with two titanium plates.

Summarizing and generalizing the data, we can state that the developed splinting construct is physiological and comparable in its characteristics to non-removable devices. The findings of Graillon et al. [35], who concluded that mini-plates have a traumatic effect, altering mandibular biomechanics and even leading to more complex fractures, support the method we propose. The developed method may be considered a promising alternative to existing immobilization techniques, provided it is further clinically evaluated.

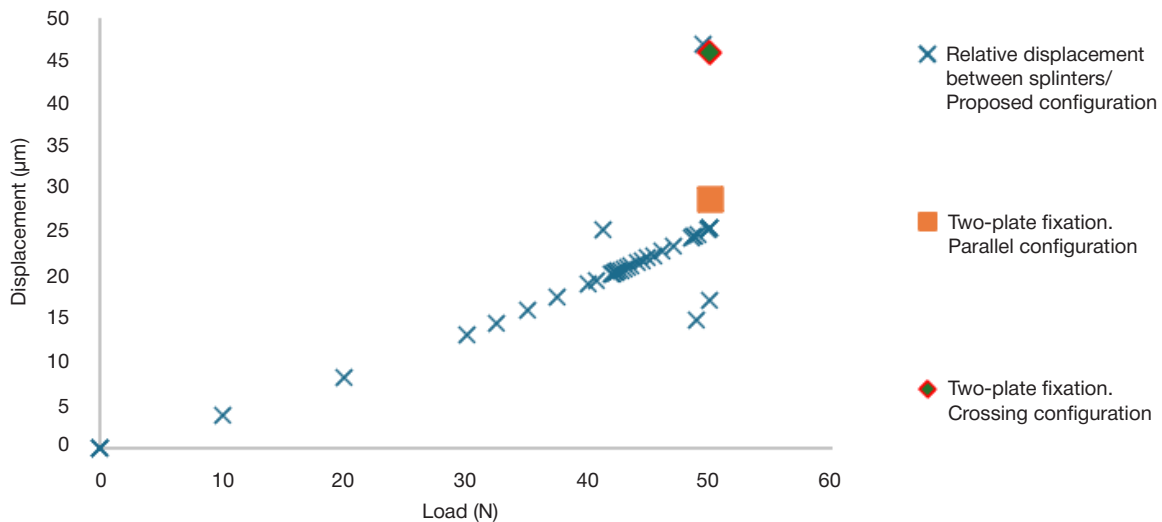
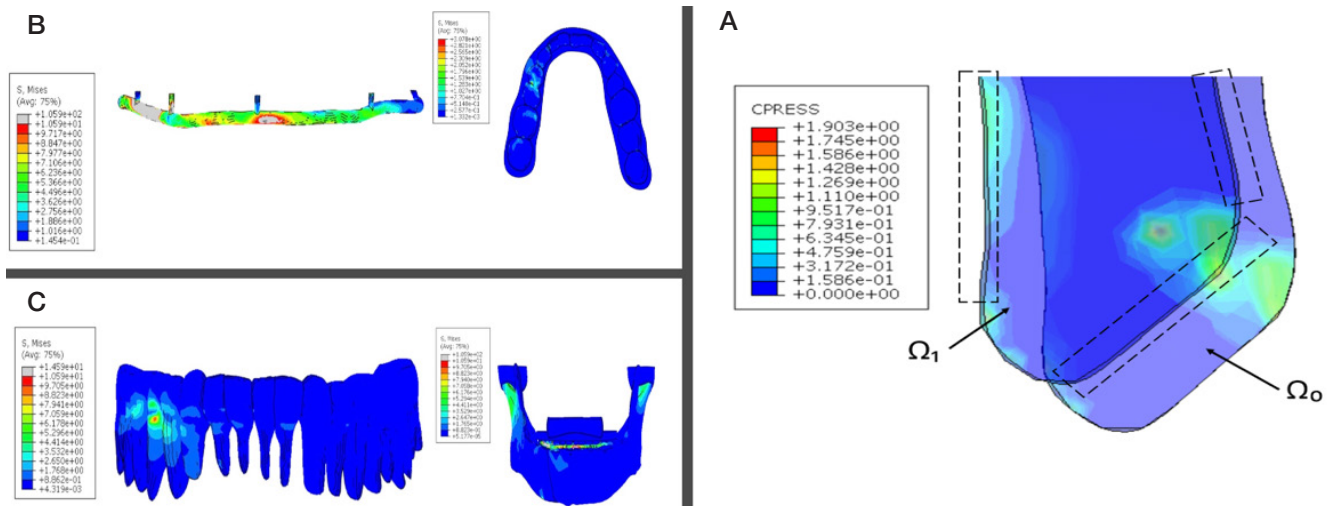


Fig. 5. Relative displacement between splinters as a function of the load applied to the mandibular segment



**Fig. 6.** A. Diagram of the contact pressure distribution in the fracture area.  $\Omega_0$  — unloaded configuration,  $\Omega_1$  — loaded configuration, areas of displacement between splinters are highlighted with the dotted line. B. Diagrams of the stress distribution across splinters of the mandible fixed using the construct proposed. C. Diagrams of the stress distribution across splinters of the mandible fixed using the construct proposed, and across the teeth

## CONCLUSIONS

This paper presents a finite element analysis of the efficacy of a novel single-jaw splinting method for mandibular fractures within the dental arch. The developed splinting construct ensures a relative displacement of the bone fragments of about 25  $\mu\text{m}$  with a linear increase in masticatory load to 50 N, which is comparable to fixation with two titanium plates and is far below the threshold critical for fracture consolidation (150–400  $\mu\text{m}$ ). This provides reliable apposition of the mandibular fragments without involving the maxilla in immobilization. The maximum equivalent stress values in the metal splint are 100 MPa, and

in the mouthguard these reach 3 MPa, which does not exceed the tensile strength of the materials used. Immobilization is achieved without maxillary involvement, thereby improving oral hygiene and the patient's quality of life during treatment. The proposed method may represent an effective and safe alternative to conventional osteosynthesis, especially in settings with limited access to high-tech surgery and in patients with contraindications to open reduction. However, validation of the results is necessary in field experiments using synthetic and biological models, as well as in clinical trials with an expanded sample, to confirm long-term stability and optimize the construct.

## References

- Hesham A, Geiger J, Alshamrani Y, Sawatari Y. Can the Mechanism of Injury Impact the Location of a Mandibular Fracture? A Systematic Review. *J Maxillofac Oral Surg.* 2024; 23 (2): 363–70. DOI: 10.1007/s12663-022-01750-1. Epub 2022 Jul 31. PMID: 38601229; PMCID: PMC11001800.
- Savelev AL, Samutkina MG. Sovremennyy podhod k lecheniyu pacientov s perelomami nizhnej chelyusti. *Operativnaya hirurgiya i klinicheskaya anatomiya (Pirogovskij nauchnyj zhurnal).* 2021; 5 (1): 29–34. Dostupno po ssylke: <https://doi.org/10.17116/operhirurg2021501129>. Russian.
- Vitkos EN, Papadopoulos KA, Dimasis P, Weissinger C, Kyrgidis A. One miniplate versus two miniplates in the fixation of mandibular angle fractures. An updated systematic review and meta-analysis. *J Stomatol Oral Maxillofac Surg.* 2022; 123 (6): e865–e873. DOI: 10.1016/j.jomas.2022.07.008. Epub 2022 Jul 21. PMID: 35872351.
- Tsolov R, Firkova EI. Periodontal status in patients with mandibular fractures. *J of IMAB.* 2022; 28 (1): 4247–50. DOI: <https://doi.org/10.5272/jimab.2022281.4247>.
- Jain A, Rai A. Is the Use of Intermaxillary Fixation Screws an Alternative to Erich Arch Bars for Maxillomandibular Fixation During Management of Maxillofacial Fractures? A Systematic Review and Meta-Analysis. *Craniofacial Trauma Reconstr.* 2021; 14 (3): 236–45. Available from: <https://doi.org/10.1177/1943387520971410>.
- Nasser M, Pandis N, Fleming PS, Fedorowicz Z, Ellis E, Ali K. Interventions for the management of mandibular fractures. *Cochrane Database Syst Rev.* 2013; 2013 (7): CD006087. Available from: <https://doi.org/10.1002/14651858.CD006087.pub3>.
- Morris C, Bebeau NP, Brockhoff H, Tandon R, Tiwana P. Mandibular fractures: an analysis of the epidemiology and patterns of injury in 4,143 fractures. *J Oral Maxillofac Surg.* 2015; 73 (5): 951.e1–951.e12. DOI: 10.1016/j.joms.2015.01.001. Epub 2015 Jan 13. PMID: 25883009.
- SHashkov VA, Gajvoronskij IV, Gajvoronskaya MG, Iordanishvili AK, Rodionov AA, Nichiporuk GI. Rasprostranennost' razlichnykh vidov perelomov nizhnej chelyusti u vzroslykh. *Vyatskij medicinskij vestnik.* 2021; 1 (69): 41–47. DOI: 10.24411/2220-7880-2021-10149. Russian.
- Akkina SR, Bevans SE, Johnson AW. Techniques for maxillomandibular fixation: old and new. *Curr Opin Otolaryngol Head Neck Surg.* 2025; 33 (4): 216–21. Available from: <https://doi.org/10.1097/MOO.0000000000001043>.
- Johnson AW, Akkina SR, Bevans SE. Maxillomandibular Fixation: Understanding the Risks and Benefits of Contemporary Techniques in Adults. *Facial Plastic Surgery & Aesthetic Medicine.* 2025; 27 (1): 98–105. DOI: 10.1089/fpsam.2024.0113.
- Pigolkin Yul, Kislov MA, Krupin KN. Matematicheskoe modelirovanie s pomoshch'yu konechno-elementnogo analiza v sudebno-medicinskoj ekspertize. *Sudebno-medicinskaya ekspertiza.* 2023; 66 (1): 9–13. Dostupno po ssylke: <https://doi.org/10.17116/sudmed2023660119>. Russian.
- Xu X, Cheng KJ, Liu Yf, et al. Experimental validation of finite element simulation of a new custom-designed fixation plate to treat mandibular angle fracture. *BioMed Eng OnLine.* 2021; 20 (15). Available from: <https://doi.org/10.1186/s12938-021-00851-1>.
- Dacij Q, Roossien CC, Wubs FW, van Minnen B. Biomechanical assessment of mandibular fracture fixation using finite element analysis validated by polymeric mandible mechanical testing. *Sci Rep.* 2024; 14 (1): 11795. Available from: <https://doi.org/10.1038/s41598-024-62011-4>.

14. Aquilina P, Chamoli U, Parr WC, Clausen PD, Wroe S. Finite element analysis of three patterns of internal fixation of fractures of the mandibular condyle. *Br J Oral Maxillofac Surg.* 2013; 51 (4): 326–31. Available from: <https://doi.org/10.1016/j.bjoms.2012.08.007>.
15. Mańkowski J, Piękoś J, Dominiak K, Klukowski P, Fotek M, Zawisza M, Źach P. A Mandible with the Temporomandibular Joint-A New FEM Model Dedicated to Strength and Fatigue Calculations of Bonding Elements Used in Fracture and Defect Surgery. *Materials (Basel).* 2021; 14 (17): 5031. DOI: 10.3390/ma14175031. PMID: 34501120; PMCID: PMC8434464.
16. Darawsheh HM, Safronova AA, Vasilev YL, Makarova NI, Diachkova EY, Saleeva GT, et al. Choosing the optimal mandible position for inferior alveolar nerve block (IANB) using finite element analysis. *Ann Anat.* 2023; 247: 152055. DOI: 10.1016/j.aanat.2023.152055. Epub 2023 Jan 22. PMID: 36696926.
17. Panagiotopoulou O, Iriarte-Diaz J, Wilshin S, Dechow PC, Taylor AB, Mehari Abraha H, et al. In vivo bone strain and finite element modeling of a rhesus macaque mandible during mastication. *Zoology (Jena).* 2017; 124: 13–29. DOI: 10.1016/j.zool.2017.08.010. Epub 2017 Sep 1. PMID: 29037463; PMCID: PMC5792078.
18. Tomioka Takahiro, Ito Daisuke, Murai Takato, Takeda Arisa, Nakamura Mami, Koshinuma Shinya, et al. Analysis of Mechanisms of Mandible Fractures by Lateral Impact: A Biomechanical Approach Using Finite Element Models. *Applied Sciences.* 2025; 15: 1205. Available from: <https://doi.org/10.3390/app15031205>.
19. Pinheiro M, Willaert R, Khan A, Krairi A, Van Paeppegem W. Biomechanical evaluation of the human mandible after temporomandibular joint replacement under different biting conditions. *Sci Rep.* 2021; 11 (1): 14034. Available from: <https://doi.org/10.1038/s41598-021-93564-3>.
20. Hedeşiu M, Pavel DG, Almăşan O, Pavel SG, Hedeşiu H, Rafiroiu D. Three-Dimensional Finite Element Analysis on Mandibular Biomechanics Simulation under Normal and Traumatic Conditions. *Oral.* 2022; 2, 221–237. Available from: <https://doi.org/10.3390/oral2030021>.
21. Sarrafpour B, Swain M, Li Q, Zoellner H. Tooth eruption results from bone remodelling driven by bite forces sensed by soft tissue dental follicles: a finite element analysis. *PLoS One.* 2013; 8 (3): e58803. Available from: <https://doi.org/10.1371/journal.pone.0058803>
22. Mengoni M. Biomechanical modelling of the facet joints: a review of methods and validation processes in finite element analysis. *Biomech Model Mechanobiol.* 2021; 20 (2): 389–401. DOI: 10.1007/s10237-020-01403-7. Epub 2020 Nov 22. PMID: 33221991; PMCID: PMC7979651.
23. Raszewski Z, Nowakowska D. Mechanical Properties of Hot Curing Acrylic Resins after Reinforced with Different Kinds of Fibers. *Int J Biomed Mater Res.* 2013; 1 (1): 9–13. Available from: <https://doi.org/10.11648/j.ijbmr.20130101.12>.
24. Anderson K, Weritz J, Kaufman JG, editors. *ASM Handbook*, Volume 2B: Properties and Selection of Aluminum Alloys. ASM International. 2019.
25. Klinicheskie rekomendacii «Perelom nizhej cheljusti». *Utv. Minzdravom Rossii* 2021. Dostupno po ssylke: <https://www.garant.ru/products/ipo/prime/doc/402775975/> (data obrashcheniya: 22.03.2026).
26. Claes L, Augat P, Suger G, Wilke HJ. Influence of size and stability of the osteotomy gap on the success of fracture healing. *J Orthop Res.* 1997; 15 (4): 577–84. DOI: 10.1002/jor.1100150414. PMID: 9379268.
27. Ng BW, Abdul Wahab AH, Abdul Wahid AM, Abdullah NNA, Abdul Kadir MR, Ammarullah MI, et al. Finite element analysis and clinical evaluation of cross locking external fixator configuration for distal tibia fracture. *Sci Rep.* 2025; 15 (1): 13310. DOI: 10.1038/s41598-025-97090-4. PMID: 40247025; PMCID: PMC12006471.
28. Glatt V, Evans CH, Tetsworth K. A Concert between Biology and Biomechanics: The Influence of the Mechanical Environment on Bone Healing. *Front Physiol.* 2017; 7: 678. DOI: 10.3389/fphys.2016.00678. PMID: 28174539; PMCID: PMC5258734.
29. Bowers KM, Anderson DE. Delayed Union and Nonunion: Current Concepts, Prevention, and Correction: A Review. *Bioengineering (Basel).* 2024; 11 (6): 525. DOI: 10.3390/bioengineering11060525. PMID: 38927761; PMCID: PMC11201148.
30. Sancar B, Çetiner Y, Dayı E. Evaluation of the pattern of fracture formation from trauma to the human mandible with finite element analysis. Part 1: Symphysis region. *Dent Traumatol.* 2023; 39 (4): 352–60. Available from: <https://doi.org/10.1111/edt.12825>.
31. Sancar B, Çetiner Y, Dayı E. Evaluation of the pattern of fracture formation from trauma to the human mandible with finite element analysis. Part 2: The corpus and the angle regions. *Dent Traumatol.* 2023; 39 (5): 437–47. Available from: <https://doi.org/10.1111/edt.12841>.
32. Kahveci K, Ayranci F. Finite element analysis of different internal fixation methods for the treatment of atrophic mandible fractures. *J Stomatol Oral Maxillofac Surg.* 2023; 124 (1S): 101276. Available from: <https://doi.org/10.1016/j.jormas.2022.08.019>.
33. Jindal P, Worcester F, Walia K, Gupta A, Breedon P. Finite element analysis of titanium alloy-graphene based mandible plate. *Comput Methods Biomech Biomed Engin.* 2019; 22 (3): 324–30. Available from: <https://doi.org/10.1080/10255842.2018.1555244>.
34. Krennmair S, Winterhalder P, Hunger S, Rupperti S, Holberg C. The effects of frontal trauma on 4 interforaminal dental implants: a 3-dimensional finite element analysis comparing splinted and unsplinted implant configurations. *J Oral Maxillofac Surg.* 2020; 78 (6): 961–72. Available from: <https://doi.org/10.1016/j.joms.2019.12.007>.
35. Grailon N, Foletti JM, Godio-Raboutet Y, Guyot L, Varazzani A, Thollon L. Mandibular titanium miniplates change the biomechanical behaviour of the mandible in the case of facial trauma: a three-dimensional finite element analysis. *Bioengineering (Basel).* 2023; 10 (9): 994. Available from: <https://doi.org/10.3390/bioengineering10090994>.

## Литература

1. Hesham A, Geiger J, Alshamrani Y, Sawatari Y. Can the Mechanism of Injury Impact the Location of a Mandibular Fracture? A Systematic Review. *J Maxillofac Oral Surg.* 2024; 23 (2): 363–70. DOI: 10.1007/s12663-022-01750-1. Epub 2022 Jul 31. PMID: 38601229; PMCID: PMC11001800.
2. Савельев А. Л., Самуткина М. Г. Современный подход к лечению пациентов с переломами нижней челюсти. *Оперативная хирургия и клиническая анатомия (Пироговский научный журнал).* 2021; 5 (1): 29–34. Доступно по ссылке: <https://doi.org/10.17116/operhirurg2021501129>.
3. Vitkos EN, Papadopoulos KA, Dimasis P, Weissinger C, Kyrgidis A. One miniplate versus two miniplates in the fixation of mandibular angle fractures. An updated systematic review and meta-analysis. *J Stomatol Oral Maxillofac Surg.* 2022; 123 (6): e865–e873. DOI: 10.1016/j.jormas.2022.07.008. Epub 2022 Jul 21. PMID: 35872351.
4. Tsolov R, Firkova EI. Periodontal status in patients with mandibular fractures. *J of IMAB.* 2022; 28 (1): 4247–50. DOI: <https://doi.org/10.5272/jimab.2022281.4247>.
5. Jain A, Rai A. Is the Use of Intermaxillary Fixation Screws an Alternative to Erich Arch Bars for Maxillomandibular Fixation During Management of Maxillofacial Fractures? A Systematic Review and Meta-Analysis. *Craniomaxillofac Trauma Reconstr.* 2021; 14 (3): 236–45. Available from: <https://doi.org/10.1177/1943387520971410>.
6. Nasser M, Pandis N, Fleming PS, Fedorowicz Z, Ellis E, Ali K. Interventions for the management of mandibular fractures. *Cochrane Database Syst Rev.* 2013; 2013 (7): CD006087. Available from: <https://doi.org/10.1002/14651858.CD006087.pub3>.
7. Morris C, Bebeau NP, Brockhoff H, Tandon R, Tiwana P. Mandibular fractures: an analysis of the epidemiology and patterns of injury in 4,143 fractures. *J Oral Maxillofac Surg.* 2015; 73 (5): 951.e1–951.e12. DOI: 10.1016/j.joms.2015.01.001. Epub 2015 Jan 13. PMID: 25883009.
8. Шашков В. А., Гайворонский И. В., Гайворонская М. Г., Иорданишвили А. К., Родионов А. А., & Ничипорук Г. И. Распространенность различных видов переломов нижней челюсти у взрослых. *Вятский медицинский вестник.* 2021; 1 (69): 41–47. DOI: 10.24411/2220-7880-2021-10149.
9. Akkina SR, Bevans SE, Johnson AW. Techniques for maxillomandibular fixation: old and new. *Curr Opin Otolaryngol*

- Head Neck Surg. 2025; 33 (4): 216–21. Available from: <https://doi.org/10.1097/MOO.0000000000001043>.
10. Johnson AW, Akkina SR, Bevans SE. Maxillo-mandibular Fixation: Understanding the Risks and Benefits of Contemporary Techniques in Adults. *Facial Plastic Surgery & Aesthetic Medicine*. 2025; 27 (1): 98–105. DOI: 10.1089/fpsam.2024.0113.
  11. Пиголкин Ю. И., Кислов М. А., Крупин К. Н. Математическое моделирование с помощью конечно-элементного анализа в судебно-медицинской экспертизе. *Судебно-медицинская экспертиза*. 2023; 66 (1): 9–13. Доступно по ссылке: <https://doi.org/10.17116/sudmed2023660119>.
  12. Xu X, Cheng KJ, Liu Yf, et al. Experimental validation of finite element simulation of a new custom-designed fixation plate to treat mandibular angle fracture. *BioMed Eng OnLine*. 2021; 20 (15). Available from: <https://doi.org/10.1186/s12938-021-00851-1>.
  13. Daqiq O, Roossien CC, Wubs FW, van Minnen B. Biomechanical assessment of mandibular fracture fixation using finite element analysis validated by polymeric mandible mechanical testing. *Sci Rep*. 2024; 14 (1): 11795. Available from: <https://doi.org/10.1038/s41598-024-62011-4>.
  14. Aquilina P, Chamoli U, Parr WC, Clausen PD, Wroe S. Finite element analysis of three patterns of internal fixation of fractures of the mandibular condyle. *Br J Oral Maxillofac Surg*. 2013; 51 (4): 326–31. Available from: <https://doi.org/10.1016/j.bjoms.2012.08.007>.
  15. Mańkowski J, Piękoś J, Dominiak K, Klukowski P, Fotek M, Zawisza M, Zach P. A Mandible with the Temporomandibular Joint-A New FEM Model Dedicated to Strength and Fatigue Calculations of Bonding Elements Used in Fracture and Defect Surgery. *Materials (Basel)*. 2021; 14 (17): 5031. DOI: 10.3390/ma14175031. PMID: 34501120; PMCID: PMC8434464.
  16. Darawsheh HM, Safronova AA, Vasilev YL, Makarova NI, Diachkova EY, Saleeva GT, et al. Choosing the optimal mandible position for inferior alveolar nerve block (IANB) using finite element analysis. *Ann Anat*. 2023; 247: 152055. DOI: 10.1016/j.aanat.2023.152055. Epub 2023 Jan 22. PMID: 36696926.
  17. Panagiotopoulou O, Iriarte-Diaz J, Wilshin S, Dechow PC, Taylor AB, Mehari Abrahama H, et al. In vivo bone strain and finite element modeling of a rhesus macaque mandible during mastication. *Zoology (Jena)*. 2017; 124: 13–29. DOI: 10.1016/j.zool.2017.08.010. Epub 2017 Sep 1. PMID: 29037463; PMCID: PMC5792078.
  18. Tomioka Takahiro, Ito Daisuke, Murai Takato, Takeda Arisa, Nakamura Mami, Koshinuma Shinya, et al. Analysis of Mechanisms of Mandible Fractures by Lateral Impact: A Biomechanical Approach Using Finite Element Models. *Applied Sciences*. 2025; 15: 1205. Available from: <https://doi.org/10.3390/app15031205>.
  19. Pinheiro M, Willaert R, Khan A, Krairi A, Van Paeppegem W. Biomechanical evaluation of the human mandible after temporomandibular joint replacement under different biting conditions. *Sci Rep*. 2021; 11 (1): 14034. Available from: <https://doi.org/10.1038/s41598-021-93564-3>.
  20. Hedeşiu M, Pavel DG, Almăşan O, Pavel SG, Hedeşiu H, Rafiroiu D. Three-Dimensional Finite Element Analysis on Mandibular Biomechanics Simulation under Normal and Traumatic Conditions. *Oral*. 2022; 2, 221–237. Available from: <https://doi.org/10.3390/oral2030021>.
  21. Sarrafpour B, Swain M, Li Q, Zoellner H. Tooth eruption results from bone remodelling driven by bite forces sensed by soft tissue dental follicles: a finite element analysis. *PLoS One*. 2013; 8 (3): e58803. Available from: <https://doi.org/10.1371/journal.pone.0058803>
  22. Mengoni M. Biomechanical modelling of the facet joints: a review of methods and validation processes in finite element analysis. *Biomech Model Mechanobiol*. 2021; 20 (2): 389–401. DOI: 10.1007/s10237-020-01403-7. Epub 2020 Nov 22. PMID: 33221991; PMCID: PMC7979651.
  23. Raszewski Z, Nowakowska D. Mechanical Properties of Hot Curing Acrylic Resins after Reinforced with Different Kinds of Fibers. *Int J Biomed Mater Res*. 2013; 1 (1): 9–13. Available from: <https://doi.org/10.11648/j.ijbmr.20130101.12>.
  24. Anderson K, Weritz J, Kaufman JG, editors. *ASM Handbook, Volume 2B: Properties and Selection of Aluminum Alloys*. ASM International. 2019.
  25. Клинические рекомендации «Перелом нижней челюсти». Утв. Минздравом России 2021. Доступно по ссылке: <https://www.garant.ru/products/ipo/prime/doc/402775975/> (дата обращения: 22.03.2026).
  26. Claes L, Augat P, Suger G, Wilke HJ. Influence of size and stability of the osteotomy gap on the success of fracture healing. *J Orthop Res*. 1997; 15 (4): 577–84. DOI: 10.1002/jor.1100150414. PMID: 9379268.
  27. Ng BW, Abdul Wahab AH, Abdul Wahid AM, Abdullah NNAA, Abdul Kadir MR, Ammarullah MI, et al. Finite element analysis and clinical evaluation of cross locking external fixator configuration for distal third tibia fracture. *Sci Rep*. 2025; 15 (1): 13310. DOI: 10.1038/s41598-025-97090-4. PMID: 40247025; PMCID: PMC12006471.
  28. Glatt V, Evans CH, Tetsworth K. A Concert between Biology and Biomechanics: The Influence of the Mechanical Environment on Bone Healing. *Front Physiol*. 2017; 7: 678. DOI: 10.3389/fphys.2016.00678. PMID: 28174539; PMCID: PMC5258734.
  29. Bowers KM, Anderson DE. Delayed Union and Nonunion: Current Concepts, Prevention, and Correction: A Review. *Bioengineering (Basel)*. 2024; 11 (6): 525. DOI: 10.3390/bioengineering11060525. PMID: 38927761; PMCID: PMC11201148.
  30. Sancar B, Çetiner Y, Dayı E. Evaluation of the pattern of fracture formation from trauma to the human mandible with finite element analysis. Part 1: Symphysis region. *Dent Traumatol*. 2023; 39 (4): 352–60. Available from: <https://doi.org/10.1111/edt.12825>.
  31. Sancar B, Çetiner Y, Dayı E. Evaluation of the pattern of fracture formation from trauma to the human mandible with finite element analysis. Part 2: The corpus and the angle regions. *Dent Traumatol*. 2023; 39 (5): 437–47. Available from: <https://doi.org/10.1111/edt.12841>.
  32. Kahveci K, Ayranci F. Finite element analysis of different internal fixation methods for the treatment of atrophic mandible fractures. *J Stomatol Oral Maxillofac Surg*. 2023; 124 (1S): 101276. Available from: <https://doi.org/10.1016/j.jormas.2022.08.019>.
  33. Jindal P, Worcester F, Walla K, Gupta A, Breedon P. Finite element analysis of titanium alloy-graphene based mandible plate. *Comput Methods Biomech Biomed Engin*. 2019; 22 (3): 324–30. Available from: <https://doi.org/10.1080/10255842.2018.1555244>.
  34. Krennmair S, Winterhalder P, Hunger S, Rupperti S, Holberg C. The effects of frontal trauma on 4 interforaminal dental implants: a 3-dimensional finite element analysis comparing splinted and unsplinted implant configurations. *J Oral Maxillofac Surg*. 2020; 78 (6): 961–72. Available from: <https://doi.org/10.1016/j.joms.2019.12.007>.
  35. Grallion N, Foletti JM, Godio-Raboulet Y, Guyot L, Varazzani A, Thollon L. Mandibular titanium miniplates change the biomechanical behaviour of the mandible in the case of facial trauma: a three-dimensional finite element analysis. *Bioengineering (Basel)*. 2023; 10 (9): 994. Available from: <https://doi.org/10.3390/bioengineering10090994>.