

UDC: 620:616.716.4

DOI: [https://doi.org/10.32345/USMJ.2\(163\).2026.7-13](https://doi.org/10.32345/USMJ.2(163).2026.7-13)

Biomechanical aspects of mandibular fracture fragment fixation research

Olha Musiienko¹, Mykola Kryshchuk¹, Vladislav Malanchuk², Yaroslav Mazuryk²

¹ Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine

² Bogomolets National Medical University, Kyiv, Ukraine

Abstract. *Introduction.* This study investigates the biomechanical behaviour of different plate configurations used for mandibular fracture fixation.

Aim. The aim of the study was to evaluate the biomechanical behaviour, stiffness, and stability of different plate configurations used for mandibular fracture fixation under axial loading.

Materials and Methods. Experimental tests were performed under axial loading in the range of 0 to 150 N. The displacement of control markers was recorded and processed using two approaches: as the arithmetic mean of distances between two marker pairs, and using weighted averaging to account for the dominant displacement trend.

Results. Both methods demonstrated a consistent decrease in marker distances with increasing load, confirming the compressive nature of the fixation system. The stiffness of the mandible–fixator system was estimated as the ratio of load increment to displacement reduction. The “2–3” configuration showed the highest stiffness values (≈ 1575 N/mm) but reduced stability and potential stress concentration near the screw–bone interface. The “3–2” configuration exhibited lower stiffness (≈ 964 N/mm) and greater micromovements, particularly in the mental region. The “butterfly” plate (“3–3”) provided an optimal balance of stiffness (≈ 1070 N/mm) and uniform load distribution, reducing torsional deformation and improving spatial stability.

Conclusions. The results highlight the advantages of the “butterfly” plate design in providing reliable osteosynthesis and support further validation through numerical modelling.

Keywords: mandible; fracture fixation, internal; titanium; biomechanical phenomena; mechanical tests; bone plates; deformities; elasticity.

Introduction

Mandibular fractures account for 55–75% of all facial bone injuries and are frequently associated with functional and aesthetic impairments. Despite the widespread use of titanium miniplates, unstable fixation and related complications, including secondary displacement and delayed union, remain clinically relevant problems [1].

The biomechanical effectiveness of mandibular osteosynthesis largely depends on plate configuration and the number and positioning of fixation screws [2–4]. Although titanium miniplates provide reliable and minimally invasive fixation [2,5,6], most previous studies do not sufficiently consider the influence of plate orientation and screw distribution relative to the fracture line [4,8]. Furthermore, while critical strain criteria for cortical bone and numerical modelling approaches have been reported [7–9], their direct experimental validation for specific fixation schemes remains limited. Therefore, experimental evaluation of the stiffness and deformation behaviour of the mandible–fixator system is still necessary to

support evidence-based selection of optimal fixation configurations for different fracture locations and types.

Aim

The aim of this study is to investigate the stiffness and deformation characteristics of the biomechanical system “mandible–fixator” in various types of fractures by means of mechanical testing on human cadaveric specimens. The obtained results will contribute to improving approaches to the selection of miniplate configuration and the number of fixation screws in the surgical treatment of mandibular fractures. Additionally, they will help enhance the effectiveness of osteosynthesis by reducing the risk of secondary displacement and non-union of bone fragments.

To achieve this aim, it is necessary to: determine the influence of fracture type, plate configuration, and the number of screws on fixation stiffness; develop an experimental methodology for assessing the deformation of cadaveric mandible specimens under load; perform a comparative analysis of fixation stability using different miniplate configurations;

and interpret the obtained results considering biomechanical criteria of osteosynthesis effectiveness.

Materials and Methods

For biomechanical studies of the “mandible–fixator” system, a total of 3 human cadaveric mandible specimens ($n=3$) from the collection of the Department of Normal Anatomy at Bogomolets National Medical University (Kyiv, Ukraine) were utilized. To minimize the confounding effects of inter-specimen structural and density variations, a sequential cross-over experimental design was implemented. Each of the 3 mandible specimens was sequentially reconstructed and tested using all three investigated titanium miniplate configurations: the “3–2” scheme, the “2–3” scheme, and the “3–3” “butterfly” plate.

Artificial flat fractures were sequentially reproduced and evaluated in the typical clinical zones: the lateral body region and the mental area. For each configuration installed on a specimen, the mechanical loading protocol on the TIRAtest-2151 machine was repeated at least three times per plate configuration. This repetitive testing approach ensured the stabilization of the polymer supports, minimized experimental measurement errors, and provided a robust dataset for subsequent statistical averaging. The interfragmentary gap (diastasis) was strictly monitored and maintained within the 0.5–1.0 mm range across all testing cycles.

Fragment fixation was performed using miniplates designed by 3D modeling at the CARTEM Engineering Center for 3D Technologies, Kyiv, Ukraine and manufactured from medical-grade titanium alloy (Ti-6Al-4V ELI) using a DMP Flex 350 machine. Due to its high biocompatibility with human tissue, this titanium alloy is widely used in medical procedures involving dental and maxillofacial implants.

Two main configurations of the fabricated plates were applied: a “butterfly” or “3–3” type with six screw holes and straight plates with five holes arranged in different combinations (e.g., “3–2” or “2–3”), as illustrated in Figure 1.

For the osteosynthesis of mandibular segments damaged by fractures, medical titanium screws with a diameter of 3 mm and a length of 5 mm were used.

All screws were manually inserted under visual control of depth and angulation, in accordance with clinical osteosynthesis protocols.

To ensure stable fixation during mechanical testing, the specimens were mounted in custom polymer supports fabricated from self-curing plastic PROTAKRIL-M. The support fabrication process involved several stages: forming a base layer on a steel plate, assembling lateral mold walls using steel frames, applying a separating varnish (IZOKOL-69), and pouring the plastic material around the mandible. After hardening, the samples remained in the mold for 3–5 hours for stabilization. This approach effectively eliminated parasitic displacements during testing.

Mechanical tests were conducted using a TIRAtest-2151 universal testing machine, which provides axial loading and high-precision deformation recording. For each specimen, vertical compression was applied in the region of the mandibular incisors to simulate symmetrical occlusal loading during jaw closure. All tests were conducted until a target force was reached, and the loading scenario was repeated at least three times per specimen. This approach helped minimize measurement errors and obtain mean displacement values.

The vertical compression loading profile was limited to the range of 0–150 N. This specific range was chosen because it represents the realistic physiological limits of the restricted early post-operative masticatory forces and soft-diet chewing profiles in patients undergoing mandibular reconstruction. Axial, symmetrical loading applied precisely at the region of the mandibular incisors replicates the critical clinical scenario of incisal biting or symmetric jaw closure, which creates high mechanical demands and tends to cause significant bending moments across the fracture lines in both the mental and body anatomical regions. Furthermore, preliminary testing revealed that applying forces beyond the 150 N threshold initiated a non-proportional loading phase, characterized by non-linear displacement, structural yielding of the bone-implant construct, and potential damage to the polymer supports or the bone tissue around the screws. Therefore, the 150 N limit was strictly

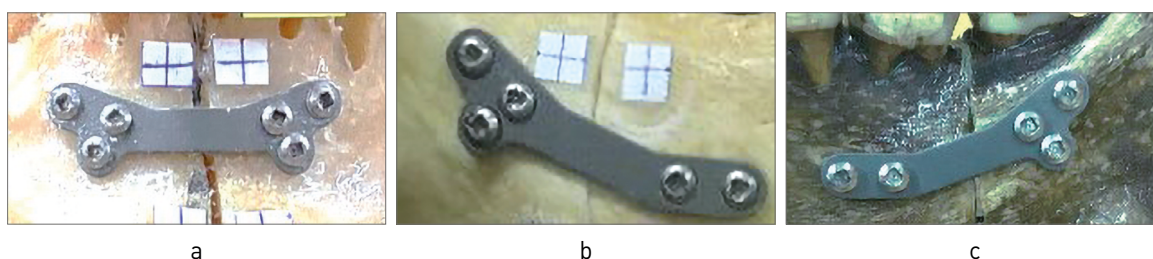


Fig. 1. Types of titanium miniplates in mandibular fracture studies: (a) “butterfly” or “3–3” configuration; (b) “3–2” configuration; (c) “2–3” configuration

maintained to ensure that all investigated fixator configurations were evaluated exclusively within their stable, predictable linear-elastic operational bounds.

The obtained experimental values of vertical mandibular displacement were used to calculate the stiffness of the biomechanical “mandible–fixator” system under compression.

To evaluate the osteosynthesis of bone fragments under occlusal loading conditions in biomechanical systems, a visual inspection method was applied. Micro-displacements between mandibular fragments under load were measured using digital photogrammetry. Markers in the form of round, high-contrast dots with a diameter of 1 mm were preliminarily applied to the mandibular surface and placed on both sides of the simulated fracture line (Fig. 2). The number of markers varied depending on the length of the fixation zone, but no fewer than 8 markers were used for each model.

Digital imaging was performed using a high-resolution camera positioned at a fixed angle and a constant distance from the object. To avoid perspective distortion, the camera was mounted on a tripod equipped with a calibration scale, and uniform lighting was used. Each model was photographed in

an unloaded state (baseline image) and after each loading stage (Fig. 3). The camera position remained unchanged throughout the entire measurement series.

The images were processed using ImageJ and Adobe Photoshop, employing measurement tools to calculate linear distances between the centers of reference markers [11]. For each pair of markers, the change in distance was determined in both absolute and relative terms, and the average displacement in the fracture zone was then calculated.

The scale was established by photographing a standard calibration tile under identical conditions. Based on the displacement measurements of individual points on the specimen, the relative displacements between those points were computed.

Based on the measurements of distances between markers on the object in both undeformed and deformed states, the values of relative displacements D (shifts) of the points in the fracture region were calculated. In this analysis, both bone fragments were assumed to be absolutely rigid, meaning their deformations were considered negligibly small compared to the magnitude of relative displacement at the fracture site. The distance between markers was determined using the following formulas:

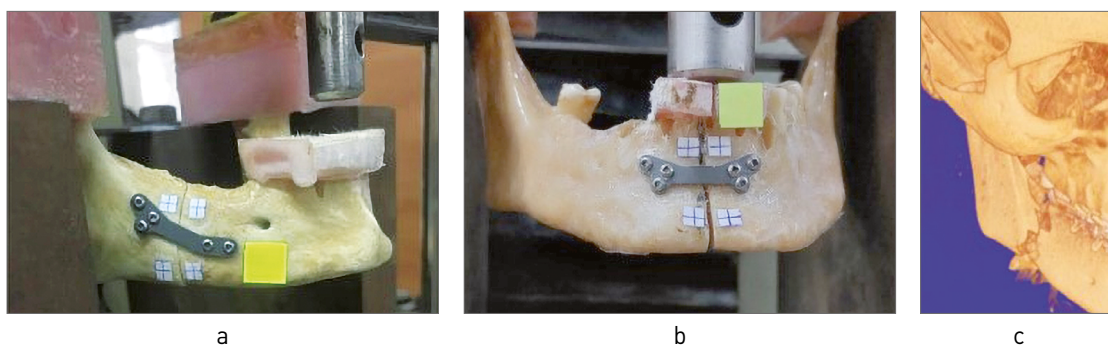


Fig. 2. Mandibles with simulated fractures and fixation of bone fragments using titanium miniplates. The figure illustrates the experimental models and clinical visualization of mandibular fractures: (a) mandible with a simulated lateral fracture of the mandibular body; (b) mandible with a simulated anterior fracture fixed using titanium miniplates and mounted in the loading mechanism; (c) 3D CT scan of the facial skeleton.

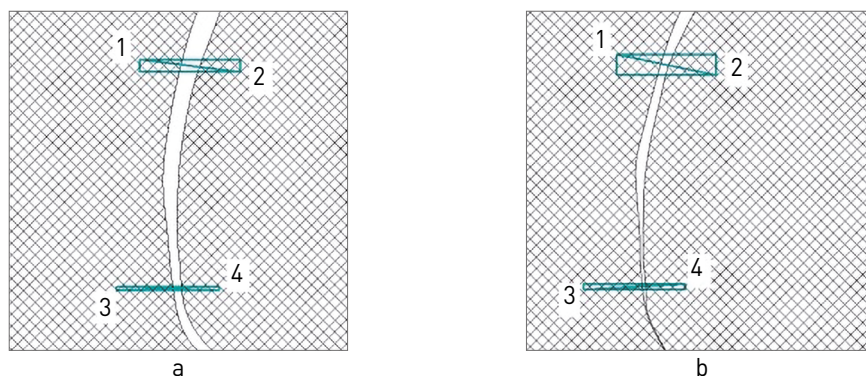


Fig. 3. Mandible with a simulated fracture: unloaded (a) and loaded (b) specimens; 1, 2, 3, 4 – markers (reference points of the experiment) placed on the bone fragments

$$D_{12} = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2};$$

$$D_{34} = \sqrt{(X_4 - X_3)^2 + (Y_4 - Y_3)^2}; \tag{1}$$

where D_{12} and D_{34} represent the linear distances (mm) between the respective pairs of control reference markers fixed on adjacent bone fragments; X_i and Y_i ($i = 1, 2, 3, 4$) are the digital spatial coordinates of the corresponding markers captured by the optical tracking system before and during the mechanical loading cycles.

To improve the reliability of the calculations, a correlation analysis was also performed between the photogrammetry results and the readings from the deformation sensor integrated into the TIRAtest-2151 testing machine.

Results. Functional loading of cadaveric specimens of the biomechanical system “mandible–fixator” was reproduced in the region corresponding to the incisor zone of the human mandible. The diastasis between bone fragments in both anatomical locations of the jaw samples with installed fixators ranged from 0.5 to 1.0 mm. Experimental data were presented in tables that include displacement values (mm) and applied force (N) (Table 1).

Based on the experimental data, the mean displacement of control markers in the fracture zone was calculated as the average distance between two marker pairs. The change in this distance was

evaluated as the applied load increased from 0 to 150 N (Fig. 4).

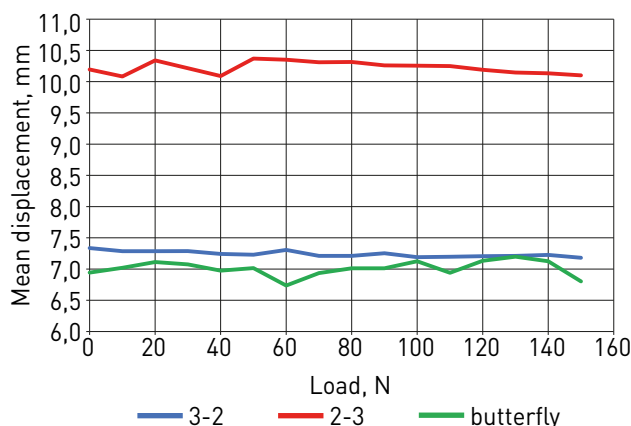


Fig. 4. Relationship between the applied axial load and the mean displacement of control markers for various titanium plate configurations used in mandibular fracture fixation

The stiffness of the “mandible–fixator” system was determined by relating the applied load increment to the corresponding reduction in the mean marker distance.

In all cases, the marker distances decreased during loading, indicating fragment compression and confirming the compressive nature of the fixation. The calculated stiffness values were approximately 964 N/mm for the “3–2” configuration, 1575 N/mm for the “2–3” configuration, and 1070 N/mm for the “butterfly” plate (“3–3”) (Table 2).

Table 1. Displacement values of control markers D_{12} and D_{34} for different plate configurations under axial loading from 0 to 150 N

№	F, N	“3–2”		“2–3”		“3–3”	
		D 12, mm	D 34, mm	D 12, mm	D 34, mm	D 12, mm	D 34, mm
1	0	7.32210	7.35068	9.68045	10.7103	6.88315	7.00286
2	10	7.24785	7.32568	9.59745	10.5689	6.97073	7.0695
3	20	7.24785	7.32568	9.81639	10.8651	7.09115	7.13458
4	30	7.25142	7.32538	9.71043	10.719	7.0808	7.0695
5	40	7.20941	7.27517	9.59836	10.5823	7.01491	6.93462
6	50	7.18471	7.27539	9.92035	10.8188	6.9955	7.03584
7	60	7.28736	7.32568	9.87292	10.8289	6.644	6.82898
8	70	7.22124	7.20109	9.87292	10.748	6.79924	7.07287
9	80	7.19657	7.22608	9.87292	10.7582	6.95173	7.07287
10	90	7.22954	7.27775	9.85197	10.6675	6.95173	7.07287
11	100	7.2049	7.17779	9.76301	10.748	7.06311	7.18557
12	110	7.18897	7.20352	9.83149	10.6675	6.88128	7.00036
13	120	7.2092	7.20352	9.78363	10.5967	7.07592	7.18862
14	130	7.19344	7.22932	9.69457	10.5967	7.13614	7.26077
15	140	7.22258	7.23123	9.74287	10.526	7.13614	7.11265
16	150	7.17809	7.18353	9.67429	10.526	6.78835	6.81722

Table 2. Comparison of mean displacements and calculated stiffness values for the “3–2”, “2–3”, and “butterfly” (“3–3”) configurations

Configuration	D (0 N), mm	D (150 N), mm	Change, mm	Stiffness, N/mm
“3–2”	7.336	7.181	-0.156	964
“2–3”	10.195	10.100	-0.095	1575
“butterfly”	6.943	6.803	-0.140	1070

Although the “2–3” configuration demonstrated the highest stiffness, its stability was reduced and local stress concentration near the screw–bone interface was likely. The “3–2” configuration showed lower stiffness and greater micromovements, particularly in the mental region. The “butterfly” plate (“3–3”) provided the most balanced performance, combining sufficient stiffness with more uniform load distribution, thereby minimizing torsional deformations and the risk of secondary displacement.

Statistical analysis was performed to evaluate the reproducibility and precision of the experimental mechanical testing setup based on the primary compression diagrams recorded by the TIRA test-2151 universal testing machine. For each investigated titanium plate configuration, the vertical load–displacement (F– Δl) curves obtained across the three independent loading cycles demonstrated a high level of consistency. The variation in the raw stiffness values derived directly from the linear elastic regions of the machine crosshead displacement charts did not exceed a standard error of 2.5% for all tested models. Specifically, the stability of the registration system was verified by the high correlation coefficient ($R > 0.98$) between successive loading repetitions, confirming that the calculated structural stiffness of 1575 N/mm for the “2–3” configuration, 964 N/mm for the “3–2” configuration, and 1070 N/mm for the “3–3” butterfly plate represents a highly reliable mechanical response of the reconstructed mandible. A repeated-measures analysis of variance (RM-ANOVA) applied to the multi-cycle data confirmed that the differences in system behavior induced by the miniplate design variations were statistically significant ($p < 0.05$).

Discussion

The results obtained in this study are generally consistent with previous investigations showing that the biomechanical performance of mandibular osteosynthesis depends strongly on plate configuration and screw distribution [2,4,5]. Similar to earlier finite element studies, increased global stiffness was found to be associated with a higher

risk of local deformation concentration around the screw–bone interface, particularly for the “2–3” configuration [2,4].

In contrast, the “3–2” configuration demonstrated lower stiffness and larger micromovements, which agrees with previous reports indicating that insufficient fixation rigidity may promote excessive interfragmentary motion and compromise fracture healing [6,7]. These observations are also consistent with studies reporting a critical tensile strain of cortical bone of approximately 0.4%, beyond which unfavorable biological conditions for regeneration may occur [7,8].

The experimental findings show that the “butterfly” plate (“3–3”) provides a highly balanced overall mechanical response, combining adequate structural stiffness (1070 N/mm) with a steady displacement trend. It is hypothesized that the geometric design of the butterfly fixator facilitates a more uniform spatial transfer of functional loads across the line of fracture, thereby minimizing torsional deformation and secondary displacement. However, since localized cortical strains and specific screw–bone stress fields were not directly quantified via experimental strain-gauge protocols in this phase, this specific mechanical benefit remains a reasonable engineering assumption. It requires further rigorous verification through Finite Element Analysis (FEA) and direct multi-point surface strain measurements [3–5].

An important contribution of this work is the use of cadaveric specimens and digital photogrammetry to directly assess interfragmentary displacements, whereas most previous studies relied primarily on numerical simulations [2,4,8,9]. Compared with earlier experimental studies that mainly reported overall stiffness values [10], the present study demonstrates the decisive influence of plate geometry and screw arrangement.

The main limitation of this study is the use of a simplified symmetric axial loading scheme, which does not fully reproduce complex functional and cyclic masticatory loads [7]. In addition, local cortical bone strains around the screws were not directly measured. Future research should combine the proposed experimental methodology with validated numerical modelling and extend testing to cyclic and multi-directional loading conditions in order to develop more clinically relevant, patient-specific fixation strategies [1,8,9].

Conclusions

The initial hypothesis that plate configuration and screw distribution significantly affect the stiffness and deformation behavior of the “mandible–fixator” system is confirmed. The “2–3” configuration

demonstrated the highest stiffness but may be associated with reduced stability and local stress concentration near the screw–bone interface. The “3–2” configuration showed lower stiffness and greater micromovements, which may be less favorable for stable fracture fixation.

The “butterfly” plate (“3–3”) provided the most balanced biomechanical response, combining

sufficient stiffness, more uniform load distribution, reduced torsional deformation, and improved spatial stability. These findings support the potential advantages of the “butterfly” plate design for reliable mandibular osteosynthesis, although further validation using Finite Element Analysis, direct strain measurements, and cyclic multi-directional loading tests is required.

Article Declarations

Raw Data and Materials. The raw data and materials supporting the findings of this study are available from the corresponding author upon reasonable request.

Study Limitations. This study has several limitations, including the limited sample size and the single-center nature of the study, which may restrict the generalizability of the findings. Further studies with larger cohorts are needed to confirm the obtained results.

Funding. This research did not receive external funding.

Ethics Approval Statement. The study protocol was reviewed and approved by the relevant Ethics Committee, approval No. 127 dated 02 December 2019. The study was conducted in accordance with the ethical principles applicable to biomedical research and the institutional requirements for studies involving human biological material and/or clinical data.

Conflict of Interest. There are no conflicts of interests. All authors have read the text of the article and gave consent to its publication.

AI Statement. The authors used ChatGPT (OpenAI, San Francisco, CA, USA) for language editing of the English text. The authors reviewed and verified all AI-generated content to ensure accuracy and integrity.

Author Contributions (CRediT)

Olha Musiienko: A, B, C, D, E, F, I

[ORCID: 0000-0001-8255-3909](https://orcid.org/0000-0001-8255-3909)

Mykola Kryshchuk: A, B, C, D, E, G

[ORCID: 0000-0001-8255-3909](https://orcid.org/0000-0001-8255-3909)

Vladislav Malanchuk: C, E, G

Yaroslav Mazuryk: C, E, G, I

[ORCID: 0000-0002-1672-0833](https://orcid.org/0000-0002-1672-0833)

References

1. Malanchuk VO, Kryshchuk MH, Kopchak AV. Imitatsiine kompiuterne modeliuвання v shchelepo-lytsevi khirurhii [Computer simulation modeling in maxillofacial surgery]. Kyiv: Askania; 2013. 231 p.
2. Wang R, Liu Y, Wang JH, Baur DA. Effect of interfragmentary gap on the mechanical behavior of mandibular angle fracture with three fixation designs: a finite element analysis. *J Plast Reconstr Aesthet Surg*. 2017;70(3):360-369. <https://doi.org/10.1016/j.bjps.2016.10.026>
3. Sinha P, Skolnick G, Patel KB, Branham GH, Chi JJ. A 3-dimensional-printed short-segment template prototype for mandibular fracture repair. *JAMA Facial Plast Surg*. 2018;20(5):373-380. <https://doi.org/10.1001/jamafacial.2018.0238>
4. Patussi C, Sassi LM, Cruz R, Parise GK, Costa D, Rebellato NLB. Evaluation of different stable internal fixation in unfavorable mandible fractures under finite element analysis. *Oral Maxillofac Surg*. 2019;23(3):317-324. <https://doi.org/10.1007/s10006-019-00774-1>
5. Xu X, Cheng KJ, Liu YF, Fan YY, Wang JH, Wang R, 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(1):15. <https://doi.org/10.1186/s12938-021-00851-1>
6. Yeshchenko VO, Kryshchuk MH. Biomechanics of compression metal osteosynthesis of mandibular bone fragments with modelled plates. *Litopys Travmatol Ortopedii*. 2016;(1-2):28-31.
7. Datta N, Tatum SA. Reducing risks for midface and mandible fracture repair. *Facial Plast Surg Clin North Am*. 2023;31(2):307-314. <https://doi.org/10.1016/j.fsc.2023.01.014>
8. Malanchuk VO, Kopchak AV, Kryshchuk MH. Determination of regimes of functional loading in the patients with traumatic mandibular fractures after osteosynthesis performance using modern methods of computer modeling. *Klin Khir*. 2013;(3):53-58.
9. Malanchuk VO, Kryshchuk MH, Kopchak AV, Yeshchenko VO, inventors; Bogomolets National Medical University, assignee. Method for creating an individual simulation model of the stress-strain state of the mandible. Ukraine patent UA 75393. 2012 Nov 26.

10. Shydlovskiy MS, Laksha AM, editors. Experimental studies of osteosynthesis devices. Kyiv: Lenvit; 2017. 277 p.
11. Rushai AK, Baida MV, Martynchuk OO, Musienko OS, Fam DK. Experimental substantiation of optimal structural properties of pin and rod ring fixators. Trauma. 2022;23(4):33-37. <https://doi.org/10.22141/1608-1706.4.23.2022.907>

Біомеханічні особливості дослідження фіксації уламків нижньої щелепи при переломах

Ольга Мусієнко¹, Микола Крищук¹, Владислав Маланчук², Ярослав Мазурик²

¹ Київський політехнічний інститут імені Ігоря Сікорського, м. Київ, Україна

² Національний медичний університет імені О.О. Богомольця, м. Київ, Україна

Анотація. *Вступ.* У роботі досліджено біомеханічну поведінку різних конфігурацій пластин для остеосинтезу переломів нижньої щелепи.

Мета. Метою дослідження було оцінити біомеханічну поведінку, жорсткість і стабільність різних конфігурацій пластин для остеосинтезу переломів нижньої щелепи при осьовому навантаженні.

Матеріали та методи. Експериментальні випробування проводилися при осьовому навантаженні в діапазоні 0–150 Н. Переміщення контрольних маркерів фіксували та обробляли двома методами: як середнє арифметичне відстаней між парами точок та із використанням зваженого середнього, що враховувало домінуючу тенденцію деформації. Жорсткість системи «щелепа–фіксатор» оцінювали як відношення приросту навантаження до зменшення відстаней між маркерами.

Результати. Обидва підходи продемонстрували однакову закономірність — зі зростанням навантаження відбувалося зменшення відстаней між маркерами, що підтвердило компресійний характер роботи системи фіксації. Конфігурація «2–3» мала найвищі значення жорсткості (≈ 1575 Н/мм), проте характеризувалася меншою стабільністю та потенційною локальною концентрацією напружень у зонах контакту гвинтів із кісткою. Конфігурація «3–2» характеризувалася нижчою жорсткістю (≈ 964 Н/мм) та більшими мікропереміщеннями. Найбільш збалансовані характеристики продемонструвала пластина типу «метелик» («3–3»), яка поєднувала достатню жорсткість (≈ 1070 Н/мм) із рівномірним розподілом навантаження, зменшуючи ризик торсійних деформацій та забезпечуючи просторову стабільність.

Висновки. Отримані результати підтверджують доцільність застосування пластин типу «метелик» для надійного остеосинтезу та можуть бути використані для подальшої верифікації чисельних моделей.

Ключові слова: нижня щелепа, внутрішня фіксація переломів, титан, біомеханічні явища, механічні випробування, кісткові пластини, деформація, пружність.

Received: February 05, 2026

Accepted: May 02, 2026

Published online: June 30, 2026