UDC: 616.71–001.5–089.2:004.94
DOI: 10.24061/3083-5887.j.nmsmme.2025.2.II.1

The computer modeling study of diaphyseal bone fracture after internal fixation by titanium and stainless steel plates with angular stability screws

Olexii Dudko
: *0000-0003-1848-5053* @: *dudko.oleksii@bsmu.edu.ua*

Bukovinian State Medical University, Chernivtsi, Ukraine

Keywords:
osteosynthesis;
bone plates;
stainless steel;
titanium;
computer modeling

Abstract

The rate of limb fractures is growing from year to year, so an improved approach is needed to make the treatment quicker, less expensive and more convenient for a patient. The operative treatment with plates can provide these advantages, but still it requires continuous research to improve techniques, devices and treatment results. The biomechanical interaction between a plate, screws and bone fragments is one of the critical factors that affect the stability of a fracture. The variety of fracture types, plate types and materials that are used for their manufacturing makes it complicated to predict the mechanical behavior of each component, so it remains not completely researched until now. The effect of plate material and load was studied by a computer modeling with a finite element analysis to determine high stress areas and displacement.

The aim of the study*. To determine the effect of material, particularly stainless steel and titanium, on the stress in plate's body and displacement of bone fragments under flexion, abduction and rotational loads for plate with angular stability screws.*

Materials and methods*. The computer modeling with a finite element analysis was performed in Autodesk Inventor. A model of straight 10-holes plate with angular stability screws was created. The static stress study was performed for different loads applied in 90 degree angle to the bone in two planes (simulating flexion and abduction forces) and rotation along the axis of the bone. The displacement and von Mises stress were revealed in 3 different areas of the plate: the central part, just above the fracture, and in the area of two nearest to the center holes. The flexion force applied ranged from 100 N to 1000 N, the abduction force ranged from 100 N to 500 N and the rotational force from 1 Nm to 10 Nm. For statistical analysis of the obtained data the Microsoft Excel 2003 was used.*

Results and discussion*. The increase of the force caused more intensive stresses in the plate body just above the fracture site and in the area of the nearest holes*

Cite as:
Dudko O. The computer modeling study of diaphyseal bone fracture after internal fixation by titanium and stainless steel plates with angular stability screws Natural & Mathematical Sciences in Medicine and Medical Education 1(2) 2025 16-26 DOI: 10.24061/3083-5887.j.nmsmme.2025.2.II.1

to the plate center of the proximal fragment. The stress in stainless steel (SS) plate was higher than in titanium plate for most of the study cases with some exceptions for area just above the fracture site. For almost all bending less intensive loads the stress areas in SS plates were higher than in titanium plate on 10.9 - 47.0 %, with the exception of the central part of a plate. For the highest bending loads the difference between plates material ranged from 14.3 % in the central part to 35.3 % in the proximal part. For most of the abduction load cases the stresses in the SS plate body were higher except the distal part of the plate when less intensive loads were applied. The difference for less intensive loads between SS plate and titanium plate was 0.23 - 7.0 %. For the highest loads the difference of stress between plates material ranged from 26.9 % in the proximal part to 45.1 % in the distal part. For rotational forces the stress areas in SS plates were higher than in titanium plate on 0.47 - 4.3 %, with the larger difference in proximal fragment. The less displacement of bone fragments was found for SS plates comparing to titanium plates under bending, abduction and rotational forces the difference was 5 %, 26.4 % and 79.7 % respectively.

Conclusion. *For the most of the loading conditions the less stress areas were found for titanium material compared with SS. On the other hand the displacement of bone fragments was higher for titanium plates, particularly under rotation loads. For the cases when the magnitude of applied loads is increasing and different forces are combined these differences may become an important factor affecting fracture healing.*

Perspective of further research. *As up to now both types of plate materials are used in clinical practice, the results of the study can be taken into account for planning orthopedics surgeries when plates are used for fixation, as well as for further research on this topic.*

Комп'ютерне моделювання діафізарного перелому при остеосинтезі титановими та сталевими пластинами з кутовою стабільністю гвинтів

Олексій Дудко
: [0000-0003-1848-5053](https://orcid.org/0000-0003-1848-5053) @: dudko.oleksii@bsmu.edu.ua

Буковинський державний медичний університет, Чернівці

Ключові слова:
остеосинтез;
накісткові пластини;
нержавіюча сталь;
титан;
комп'ютерне моделювання.

Анотація

Частота виникнення переломів кінцівок з року в рік постійно зростає, що вимагає вдосконалення підходів до їх лікування, щоб зробити цей процес менш тривалим та недорогим, а також більш комфортним для пацієнта. Оперативне лікування з застосуванням пластин може забезпечити ці переваги, але все ж потребує постійного дослідження направленого на вдосконалення техніки виконання, імплантатів та покращення результатів лікування. Біомеханічні взаємодії між пластиною, гвинтами та кістковими фрагментами є одним із критичних факторів, що впливають на стабільність перелому. Наявність різноманіття типів переломів, видів пластин та матеріалів, що використовуються для їх виробництва, ускладнюють можливість перебачити механічні взаємодії, що відбуваються при застосуванні даних конструкцій і багато аспектів залишаються недостатньо вивченими. Вплив матеріалу з якого виготовлена пластина та навантаження були досліджені шляхом комп'ютерного моделювання з застосуванням методики скінчених елементів для визначення найбільш стресових ділянок та зміщення.

Мета дослідження. *Визначити вплив матеріалу з якого виготовлена пластина з кутовою стабільністю, зокрема нержавіючої сталі та титану, на зміни її напружено-деформованого стану та зміщення фрагментів перелому під дією прикладеного згинального, привідного та ротаційного навантаження.*

Матеріали і методи. *Комп'ютерне моделювання з застосуванням методики скінчених елементів було проведено в Autodesk Inventor. Змодельована пряма пластина з кутовою стабільністю гвинтів на 10 отворів. Дослідження статичного навантаження було проведено з прикладанням зусиль під кутом 90° до осі кістки у двох площинах (що симулює згинання та відведення) та ротацію вздовж осі кістки. Зміщення та ділянки підвищеного стресу за фон Мізесом визначалися в 3 частинах пластини: центральна ділянка над зоною перелому, та ділянки навколо найближчих до центру пластини отворів. Діапазон навантажень для згинання складав від 100 Н до 1000 Н, для відведення від 100 Н до 500 Н, а для ротаційного навантаження від 1 Nm до 10 Nm. Статистичний аналіз отриманих результатів проводився з використанням Microsoft Excel 2003.*

Результати та обговорення. *При збільшенні навантаження відмічалося посилення стресу в пластині над зоною перелому та навколо найближчих до центру пластини отворів, при чому для нержавіючої сталі показники були вищими, ніж для титану для більшості режимів навантаження, лише в поодиноких випадках над ділянкою перелому ситуація була протилежною. При прикладанні згинального навантаження низької інтенсивності максимальні показники стресу в пластинах з нержавіючої сталі були вищими ніж у титану на 10,9 – 47,0 %, крім центральної частини пластини. Для більш інтенсивного згинального навантаження відмінності в стресових ділянках між матеріалами складали від 14,3 % в центральній частині до 35,3 % в проксимальній частині. В переважній більшості режимів навантаження у напрямку приведення стрес в пластині з нержавіючої сталі був вищим, за виключенням дистальної ділянки при невеликих силах. Різниця між показниками стресу для навантаженнях низької інтенсивності була 0,23 – 7,0 %, а при підвищених навантаженнях різниця становила від 26,9 % в проксимальній частині до 45,1 % в дистальній. Для ротаційних навантажень стресові ділянки в пластинах з нержавіючої сталі були вищими ніж у титанових пластинах на 0,47 – 4,3 %, переважно в проксимальній ділянці. Менші зміщення кісткових фрагментів були виявлені для пластин з нержавіючої сталі в порівнянні з титановими пластинами і становили відповідно 5 %, 26,4 % та 79,7 % для згинальних, привідних та ротаційних навантажень.*

Висновки. *Для більшості режимів навантаження найменш стресові ділянки були виявлені в титанових конструкціях, порівнюючи з нержавіючою сталлю. З іншого боку, зміщення кісткових фрагментів було більшим для титанових пластин, зокрема під дією ротаційних навантажень. У випадках коли інтенсивність навантаження зростає і при комбінованих навантаженнях, ці відмінності можуть стати вагомим фактором впливу на процес зрощення переломів.*

Перспективи подальших досліджень. *На даний час в клінічній практиці обидва види матеріалів використовуються у пластинах, тому результати даного дослідження можуть бути прийнятими до уваги при плануванні оперативних втручань з накісткового остеосинтезу переломів, а також сприятимуть подальшим дослідженням в даному напрямку.*

Content

ISSN: 3083-5887 online

Actuality

In many countries the rate of limb fractures is growing from year to year [1, 2], so an improved approach is needed to make the treatment more quick, less expensive and more convenient for a patient [3]. The operative treatment with plates can provide these advantages and is considered to be one of the main techniques for fracture treatment [4]. There is still a large field for research according to improvements of techniques, plates and screws that can affect treatment results, so it requires further biomechanical, experimental and clinical studies. The biomechanical interaction between a plate, screws and bone fragments is one of the critical factors for the stability of a fracture [5]. The variety of fracture types, plate types and materials that are used for their manufacturing makes it complicated to predict the mechanical behavior of each component, so it remains not completely researched until now.

Computer modeling is one of modern research methods which are used for different fracture locations. Mischler et al. used it for simulation of proximal humerus fracture fixation with two different plates and various places for screws insertion to calculate optimal combination for fracture healing [6]. Epari et al. performed computational study of distal femoral fractures after internal fixation with bone plates [7]. Other researchers used computer modeling to study biomechanics of tibial osteotomies. MacLeod et al. and Schröter et al. studied the effect of plate design, bridge span, types and locations of screws on the stability of bone fragments fixation [8, 9]. The effect on the stability under static axial loads of plate material and of spaces between bone fragments of fracture, between bone and plate was studied by Fouad [10]. But still there is no clear understanding of the biomechanical interactions after plate osteosynthesis. The guidelines for practical application of plates with angular stability of screws are very general and only the clinical experience of a surgeon advises the proper choice for a particular case. Therefore we decided to perform a study of the effect of plate material and of the load on fracture stability using computer modeling with a finite element analysis to compare high stress areas in SS and titanium plates, as well as displacement of bone fragments.

The aim of the study is to determine the effect of material, particularly stainless steel and titanium, on the stress in plate's body and displacement of bone fragments under flexion, abduction and rotational loads for plate with angular stability screws.

Materials and methods

The computer modeling with a finite element analysis was performed in Autodesk Inventor. A model of straight 10-holes plate with angular stability screws was created with dimensions 210x30x3 mm and six AO 5.0 mm screws were modeled with the threaded connection in the bone and plate body. The bone was modeled as two hollow cylinders of 210 mm length and 40 mm diameter, the wall thickness of 5 mm, which was representing the cortical layer. The bone-plate model was meshed into 60009 finite elements (tetrahedrons) (Fig. 1). Two material types were used for plate and screws – stainless steel 316L and titanium. The mechanical parameters of bone were assigned as 57 MPa ultimate strength, 10.2 GPa Yungs modulus, 0.3 Poisson's ratio. The linear static stress study was performed for different loads applied at 90 degree angle to the bone in two planes, simulating flexion force (Fig. 1a), abduction force (Fig. 1b) and rotation along the axis of the bone (Fig. 1c). The displacement and stress were revealed in 3 different parts of the plate: the central part, just above the fracture, and in

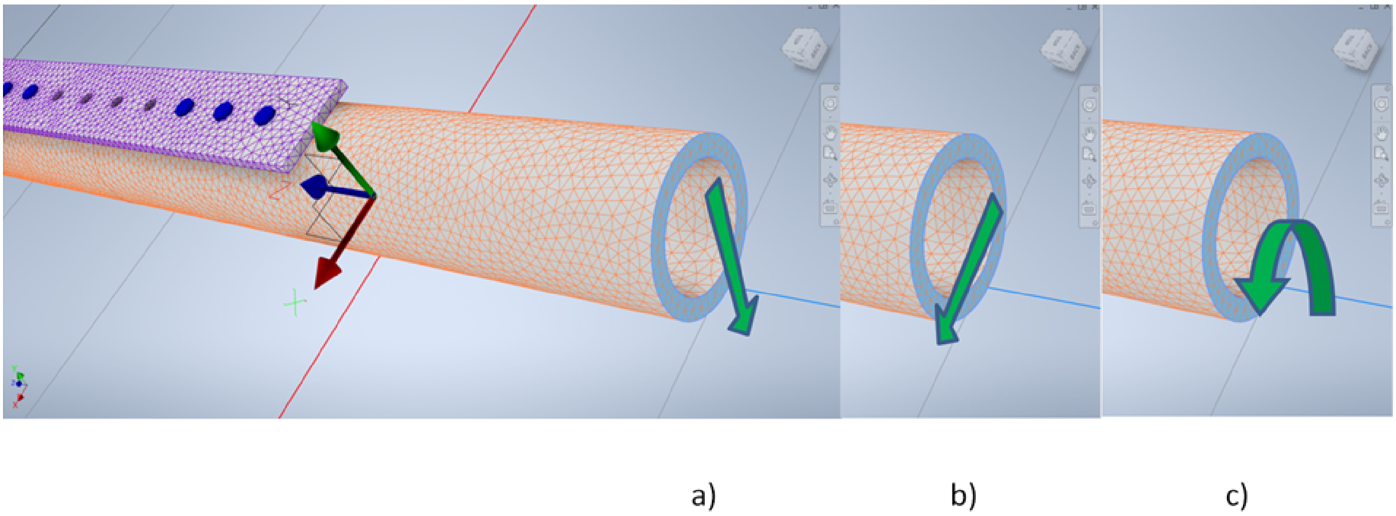

Figure 1 – Finite element model of transverse bone fracture fixed with the plate and screws. The loads applied to the distal face: a) bending; b) abduction; c) rotation

the areas of two nearest to the center holes proximally and distally (Fig. 2). The flexion force applied ranged from 100 N to 1000 N, the abduction force from 100 N to 500 N and the rotational force from 1 Nm to 10 Nm. For statistical analysis of the obtained data the Microsoft Excel 2003 was used.

The model was validated under similar conditions in biomechanical testing on fresh sues bones with plate fixation. The contact surfaces between the plate and the screw were assigned as bonded, that is representing the angular stability of a screw relating to a plate. The contact surfaces between the plate and bone, and between the bone fragments were set as full separation with a friction coefficient of 0.3 and 0.6 respectively. The maximum von Mises stress was measured in control points, as well as the bone ends displacement at the fracture site.

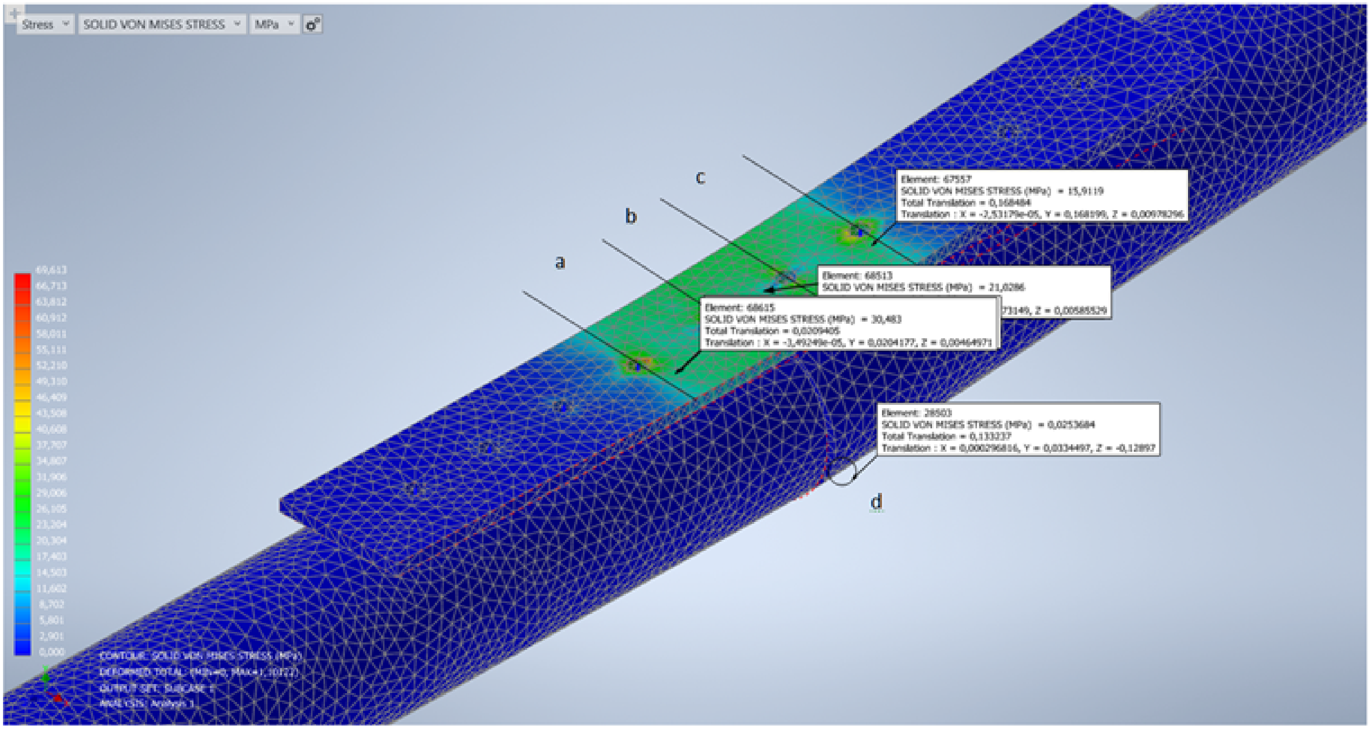

Figure 2 – The location of probes for stress detection in proximal part (zone a), central part (zone b), distal part (zone c), and for detection of distal fragment displacement in distal cortex (zone d)

Results of the study

The computer modeling of plate osteosynthesis was performed for static stress loads that were applied to the distal end of one bone segment and the proximal end of another segment was fixed in all three planes. That was representing the real-life conditions for a transverse limb fracture with two main bone segments, when the proximal one is attached to the proximal part of the body and so its movement is almost completely restricted. Therefore the distal fragment is considered the one which is displaced. The applied force was transferred from one bone segment to another one through the screws in the distal fragment, than the plate body and than the screws in another bone fragment. In this way of the force distribution the different stress areas and strains in each of the materials were developing. The maximum stress areas were detected in different parts of plate above the fracture site. Those were divided in three zones: first zone between two the nearest holes to the plate center (central part), next zones were between the first and the second holes more proximally (proximal part) and distally (distal part) from the plate center (Fig. 2).

The most distal facet of the distal fragment was the place of the main bending force application with the direction perpendicular to the longitudinal axis of the bone and to the plane of the plate at the range from 100 N to 1000 N. For SS plates under 100 N loads the stress was 29.1 MPa, 39.6 MPa and 32.5 MPa in the proximal, central and distal parts respectively. For titanium plates these values were lower – in proximal part 19.8 MPa, in central part 41.2 MPa and in distal part 29.3 MPa (Fig. 3).

The stress distribution in plates under different loads is presented it Table 1. For most of the load cases the stresses in the plate body were significantly higher for SS plates with the exception of central part of the plate. The maximum stresses that exceeded the ultimate strength of material were reached at 1000 N, so these conditions should be avoided to prevent implant failure. For almost all bending less intensive loads the stress areas in SS plates were higher than in titanium plate on 10.9 - 47.0 %, with the exception of the central part of a plate. The largest difference was found in the proximal fragment. For the highest loads the difference between plates material ranged from 14.3 % in the central part to 35.3 % in the proximal part.

The rotational force was applied to the most distal facet of the distal fragment along the longitudinal axis of the bone. It was ranged from 1 Nm to 10 Nm. The stresses in SS plates under 1 Nm torque the stress were 30.5 MPa, 21.0 MPa and 15.9 MPa in the proximal, central and distal parts respectively. For titanium plates these values were lower – in proximal part 29.2 MPa, in central part 20.9 MPa and in distal part 15.4 MPa (Fig. 4).

The stress distribution in plates under different torque is presented it Table 2. The rotational forces are usually acting as additional forces with low intensity. But the negative effect of these forces on the fracture often leads to the delayed healing. For all loading conditions the stress areas in SS plates were higher than in titanium plate on 0.47 - 4.3 %, with the larger difference in proximal fragment.

The abduction force was also applied to the most distal facet of the distal bone fragment. The direction was perpendicular to the longitudinal axis of the bone and parallel to the plane of the plate. In real-life conditions it is acting on the limb, as a part of the complex forces, but its magnitude is less than of flexion force. So in our study this force was applied in the range from 100 N to 500 N. The stresses in SS plate under 100 N load were: in proximal part 60.3 MPa, in central part 43.0 MPa and in distal part 34.7 MPa. For titanium plates

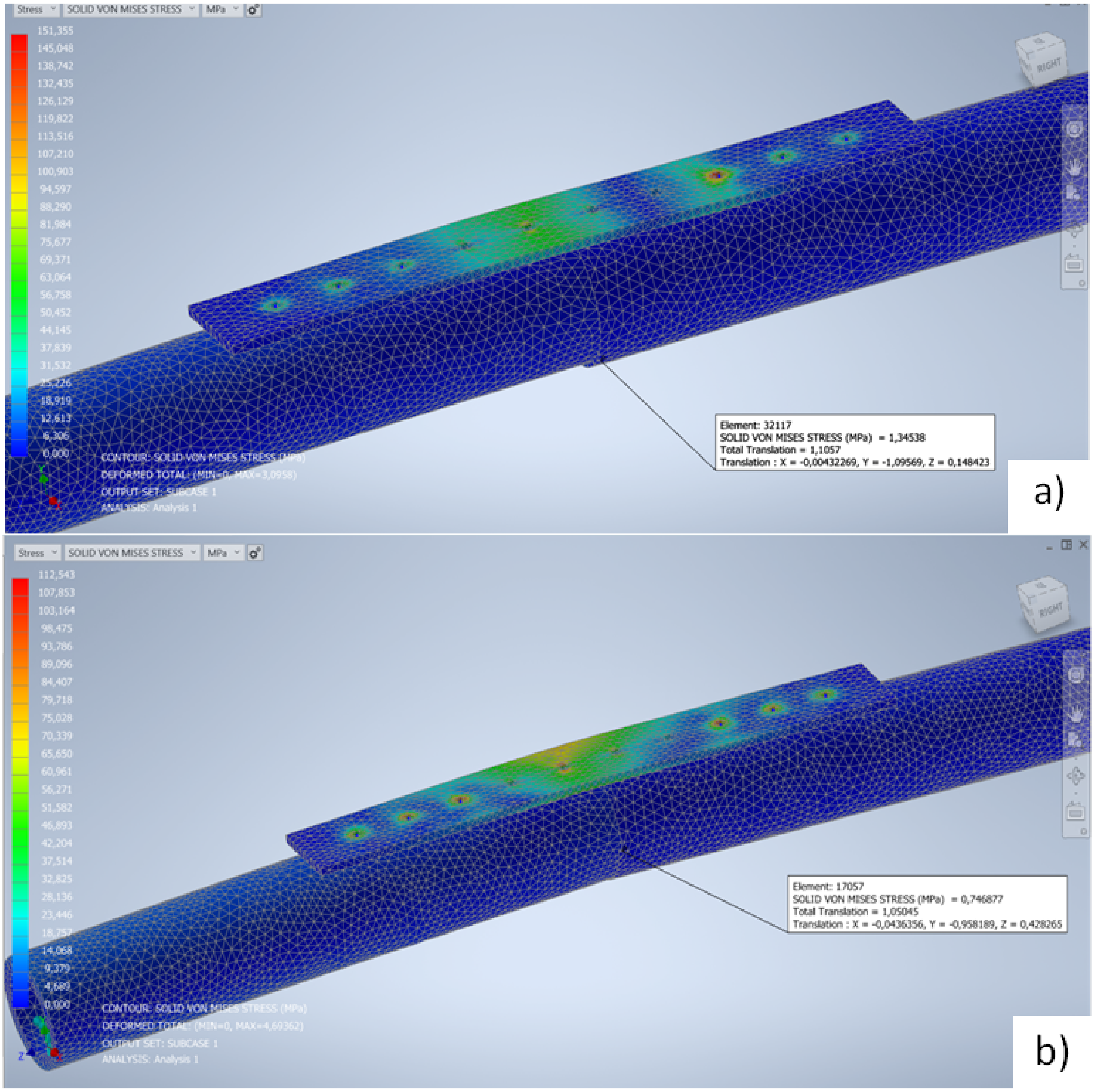

Figure 3 – Stress distribution in the plate and displacement of distal bone fragment in SS (a) and titanium (b) plates under **bending** load 100N

Table 1
The stress distribution in different parts of SS and titanium plates under **bending** loads

Load	Von Mises stress (MPa)					
	Proximal part		Central part		Distal part	
	SS	Ti	SS	Ti	SS	Ti
100 N	29.1	19.8	39.6	41.2	32.5	29.3
500 N	109.9	47.2	156.1	82.6	61.8	32.3
1000 N	226.9	167.7	358.7	313.9	329.8	284.4

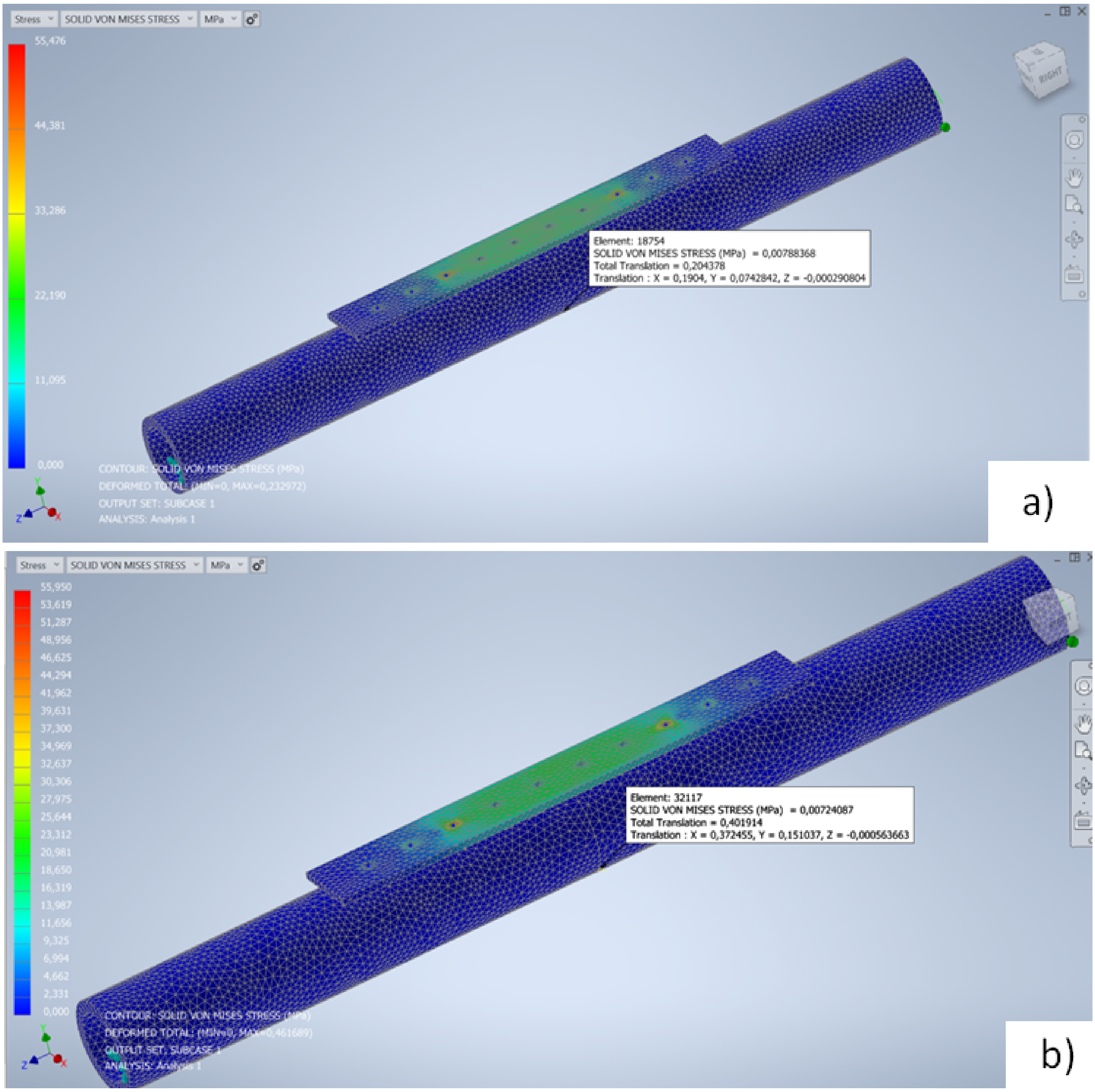

Figure 4 – Stress distribution in the plate and displacement of distal bone fragment in SS and titanium plates under **rotational torque** of 1 Nm

Table 2

The stress distribution in different parts of SS and titanium plates under **rotational force**

Torque	Von Mises stress (MPa)					
	Proximal part		Central part		Distal part	
	SS	Ti	SS	Ti	SS	Ti
1 Nm	30.5	29.2	21.0	20.9	15.9	15.4
5 Nm	152.4	146.1	105.2	104.7	79.6	76.8
10 Nm	304.8	292.2	210.3	209.4	159.1	153.6

these values were lower – in proximal part 56.1 MPa, in central part 42.9 MPa and higher in distal part 35.6 MPa (Fig. 5). The stress distribution in plates under different adduction loads are presented it Table 3. For most of the abduction load cases the

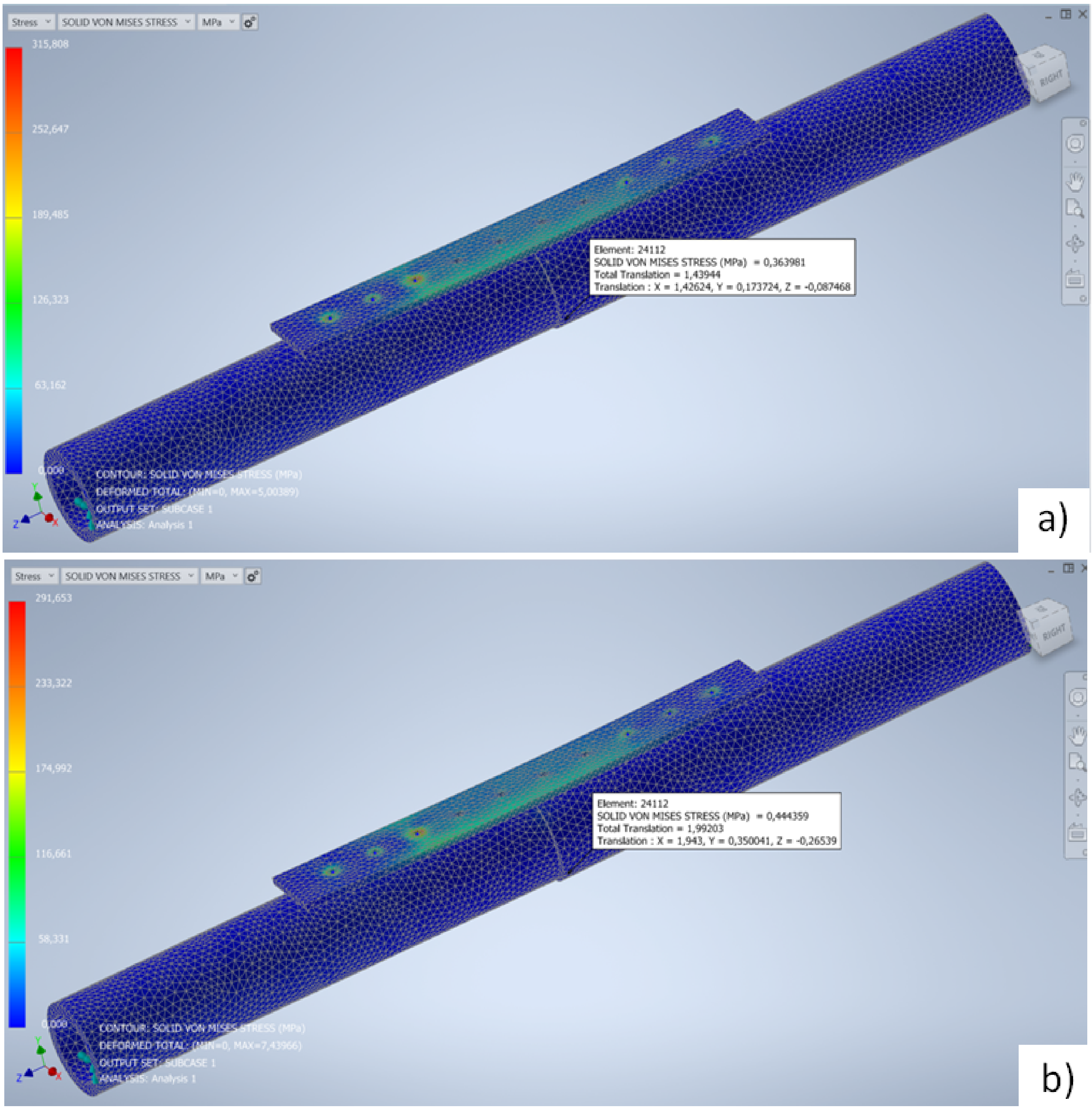

Figure 5 – Stress distribution in the plate and displacement of distal bone fragment in SS and titanium plates under **abduction** loads of 100 N

Table 3
The stress distribution in SS and titanium plates under **abduction** loads

Load	Von Mises stress (MPa)					
	Proximal part		Central part		Distal part	
	SS	Ti	SS	Ti	SS	Ti
100 N	60.3	56.1	43.0	42.9	34.7	35.6
200 N	121.5	112.7	87.9	86.5	71.5	72.1
500N	284.8	224.4	234.0	184.8	202.2	139.4

stresses in the SS plate body were higher except the distal part of the plate when less intensive loads were applied. The difference for less intensive loads between SS plate and titanium plate was 0.23 - 7.0 %. For the highest loads the difference between plates material ranged from 26.9 % in the proximal part to 45.1 % in the distal part.

For different applied loads: bending, abduction and rotational forces the displacement was checked in the distal cortex of the distal bone fragment according to its position before the load. The displacement of bone fragments under bending, abduction and rotational forces is presented on Fig. 6 with the difference between SS and titanium plates of 5 %, 26.4 % and 79.7 % respectively. Due to the mechanical properties of SS it provides more rigid fixation and that was resulted in less displacement of fracture fragments. Though the amount of displacement is not significant for small loads, for the larger loads it may be the cause of delayed fracture healing and non-healing.

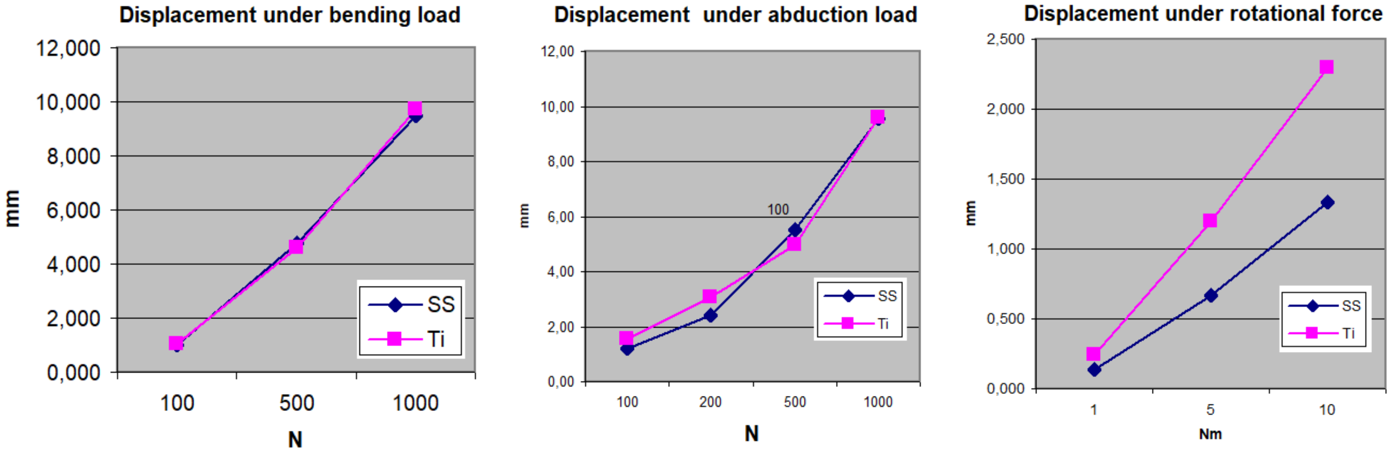

Figure 6 – Displacement of distal bone fragment under bending, abduction and rotational loads

Discussion

The results of our study show that the stress for plates made of different materials was not the same. Under the increasing forces the maximum stress areas were increased in both plates. As the plate material was the only variable that was changed, so the differences between the stresses in the plate body were related with the mechanical properties of SS and titanium. There were several papers that attempted to study the effect of the plate material on the fracture biomechanics after internal fixation. Epari et al., 2021 compared SS plates with biphasic plates for fixation of femoral fractures, with a different respond on applied load. Authors are suggesting biphasic plate concept, as an option that can increase the implant stability and provide adequate flexibility at the fracture site [7]. In most of the biomechanical studies the effect of axial compression load is investigated, as the main load acting during walking activity. But in some papers additional load which is acting in other planes is studied. The Fouad performed a computational study in 2011, comparing the effect of plate material on the stiffness of fracture fixation. The effect on the high-stress areas of the torsional load was shown to be even more significant than compression load. The application of suggested by him function-graded plate was able to reduce shielding effect comparing with the SS or titanium plates. The presence of a gap between the bone and plate was also affecting the stability of fracture fixation [10].

At this moment there were two main materials that are used in clinical practice. The significant price difference between the plates made of SS and titanium was decreases in recent years due to the advances in the manufacturing process. So the plate's mechanical properties, but not the price is the predicting factor for choosing either SS or titanium plate. That makes it more important to study difference between these two materials in various clinical settings. For fractures located at the proximal humerus the studies were performed by Mischler et al [6] and lower limb fractures

DOI: 10.24061/3083-5887.j.nmsmme.2025.2.II.1

located at the distal femur the were studied by Kandemir in 2017 [11], and in the proximal tibia by MacLeod [8]. Of cause the anatomical peculiarities of fracture site makes it complicated to investigate the effect of the material on fracture fixation. Also this effect may vary significantly for different fracture types and locations. But the effect of the plate material should be considered for planning of surgeries on internal fracture fixation, as one of the main factor that will effect on the fracture healing process starting from the day of surgery till the full recovery of the patient. The results of the present study may contribute for further research in this field.

Conclusion

For the most of the loading conditions the less stress areas were found for titanium material compared with SS. On the other hand the displacement of bone fragments was higher for titanium plates, particularly under rotation loads. For the cases when the magnitude of applied loads is increasing and different forces are combined these differences may become an important factor affecting fracture healing.

References

1. Bergh C, Wennergren D, Möller M, Brisby H. Fracture incidence in adults in relation to age and gender: A study of 27,169 fractures in the Swedish Fracture Register in a well-defined catchment area. PLOS ONE. 2020 [дата звернення 19 берез. 2025];15(12):e0244291. https://doi.org/10.1371/journal.pone.0244291.
2. Eckart AC, Ghimire PS, Stavitz J. Predictive Validity of Multifactorial Injury Risk Models and Associated Clinical Measures in the U.S. Population. Sports. 2024 [дата звернення 19 берез. 2025];12(5):123. https://doi.org/10.3390/sports12050123.
3. Ekegren C, Edwards E, de Steiger R, Gabbe B. Incidence, Costs and Predictors of Non-Union, Delayed Union and Mal-Union Following Long Bone Fracture. Int J Environ Res Public Health. 2018 [дата звернення 19 берез. 2025];15(12):2845. https://doi.org/10.3390/ijerph15122845.
4. Augat P, von Rüden C. Evolution of fracture treatment with bone plates. Injury. 2018 [дата звернення 19 берез. 2025];49:S2—S7. https://doi.org/10.1016/s0020-1383(18)30294-8.
5. Foster AL, Moriarty TF, Zalavras C, Morgenstern M, Jaiprakash A, Crawford R, Burch MA, Boot W, Tetsworth K, Miclau T та ін. The influence of biomechanical stability on bone healing and fracture-related infection: the legacy of Stephan Perren. Injury. Черв. 2021 [дата звернення 20 берез. 2025]. https://doi.org/10.1016/j.injury.2020.06.044.
6. Mischler D, Babu S, Osterhoff G, Pari C, Fletcher J, Windolf M, Gueorguiev B, Varga P. Comparison of optimal screw configurations in two locking plate systems for proximal humerus fixation - a finite element analysis study. Clin Biomech. 2020 [дата звернення 20 берез. 2025];78:105097. https://doi.org/10.1016/j.clinbiomech.2020.105097.
7. Epari DR, Gurung R, Hofmann-Fliri L, Schwyn R, Schuetz M, Windolf M. Biphasic plating improves the mechanical performance of locked plating for distal femur fractures. J Biomech. 2021 [дата звернення 19 берез. 2025];115:110192. https://doi.org/10.1016/j.jbiomech.2020.110192.
8. MacLeod AR, Serrancoli G, Fregly BJ, Toms AD, Gill HS. The effect of plate design, bridging span, and fracture healing on the performance of high tibial osteotomy plates. Bone Amp Jt Res. 2018 [дата звернення 19 берез. 2025];7(12):639–649. https://doi.org/10.1302/2046-3758.712.bjr-2018-0035.r1.
9. Foster AL, Moriarty TF, Zalavras C, Morgenstern M, Jaiprakash A, Crawford R, Burch M-A, Boot W, Tetsworth K, Miclau T, et al. The influence of biomechanical stability on bone healing and fracture-related infection: the legacy of Stephan Perren. Injury. 2021;52(1):43–52. http://dx.doi.org/10.1016/j.injury.2020.06.044. doi:10.1016/j.injury.2020.06.044
10. Fouad H. Effects of the bone-plate material and the presence of a gap between the fractured bone and plate on the predicted stresses at the fractured bone. Med Eng Amp Phys. 2010 [дата звернення 20 берез. 2025];32(7):783–789. https://doi.org/10.1016/j.medengphy.2010.05.003.
11. Kandemir U, Augat P, Konowalczyk S, Wipf F, von Oldenburg G, Schmidt U. Implant Material, Type of Fixation at the Shaft, and Position of Plate Modify Biomechanics of Distal Femur Plate Osteosynthesis. J Orthop Trauma. 2017 [дата звернення 19 берез. 2025];31(8):e241-e246. https://doi.org/10.1097/bot.0000000000000860