Original Article
https://doi.org/10.17816/2311-2905-1989

Comparative Biomechanical Analysis of Ankle Arthrodesis Techniques: Experimental Study

Vladimir V. Khominets [1], Sergey V. Mikhailov [1], Sayan E. Zhumagaziev [1], Alexey V. Shchukin [1], Dmitry V. Ivanov [2]

[1] *Kirov Military Medical Academy, St. Petersburg, Russia*

[2] *Chernyshevsky Saratov National Research State University, Saratov, Russia*

Background. Despite the existing significant number of various techniques for ankle arthrodesis, a number of authors point to certain technical difficulties of these operations, the loss of the talus and tibia position during ankylosing, nonunion. The problem of the ankle arthrodesis technique improving requires new solutions.
The aim of the study was to compare the stability of various fixation systems in ankle arthrodesis by the finite element method.
Methods. The finite element method was used to evaluate the biomechanical characteristics of three variants of ankle arthrodesis systems: three cancellous screws, the originally designed plate combined with two cancellous screws, when the screw in the proximal plate's hole is cortical, and the same plate combined with two cancellous screws, when the screw in the proximal plate's hole with angular stability. The stresses and strains under the application of various types of loads are studied.
Results. In the anterior plate ankle fixation model combined with two cancellous screws and a proximal cortical screw, the implants and the talus experienced the least stresses compared to the other two models. Thus, the maximum equivalent stress in implants in the second variant was 68-124 MPa, in the first variant 92-147 MPa, in the third variant — 130-331 MPa. The equivalent stress in the talus in the second version of fixation ranged from 20 to 46 MPa, in the first and third versions — 28-58 MPa and 47-65 MPa, respectively. The indicators of maximum contact pressure at the border of the tibia and talus turned out to be the highest in the first variant compared to the other two models (34 MPa, 31 MPa and 31 MPa, respectively).
Conclusions. Among the studied ankle fixation systems for arthrodesis, an anterior plate combined with two cancellous screws and a proximal cortical screw is the most preferable in terms of biomechanics.

Keywords: biomechanical modeling, ankle arthrodesis, plate, cancellous screws, finite element method.

Cite as: Khominets V.V., Mikhailov S.V., Zhumagaziev S.E., Shchukin A.V., Ivanov D.V. [Comparative Biomechanical Analysis of Ankle Arthrodesis Techniques: Experimental Study]. *Travmatologiya i ortopediya Rossii* [Traumatology and Orthopedics of Russia]. 2022;28(4):136-147. (In Russian). https://doi.org/10.17816/2311-2905-1989.

✉ *Vladimir V. Khominets*; e-mail: vkhominets@yandex.ru

Submitted: 02.09.2022. Accepted: 01.11.2022. Published Online: 25.11.2022.

Научная статья
УДК 616.728.48-089.881:612.76
https://doi.org/10.17816/2311-2905-1989

Сравнительный биомеханический анализ способов артродезирования голеностопного сустава: экспериментальное исследование

В.В. Хоминец [1], С.В. Михайлов [1], С.Е. Жумагазиев [1], А.В. Щукин [1], Д.В. Иванов [2]

[1] *ФГБВОУ ВО «Военно-медицинская академия им. С.М. Кирова» Минобороны России, г. Санкт-Петербург, Россия*

[2] *ФГБОУ ВО «Саратовский национальный исследовательский государственный университет им. Н.Г. Чернышевского» Минобрнауки России, г. Саратов, Россия*

Актуальность. Несмотря на значительное количество разнообразных методик, применяемых для артродеза голеностопного сустава, ряд авторов указывают на определенные технические сложности указанных операций, потерю коррекции заданного положения таранной и большеберцовой костей в процессе анкилозирования, несращения. Проблема совершенствования методики фиксации при артродезе голеностопного сустава требует новых решений.

Цель — сравнить методом конечных элементов стабильность различных вариантов систем фиксации при артродезе голеностопного сустава.

Материал и методы. Методом конечных элементов выполнена оценка биомеханических характеристик трех вариантов систем фиксации голеностопного сустава при артродезе: три спонгиозных винта, разработанная пластина, комбинируемая с двумя спонгиозными винтами, проксимальный винт в пластине кортикальный, а также разработанная пластина, комбинируемая с двумя спонгиозными винтами, проксимальный винт в пластине с угловой стабильностью. Изучены напряжения и деформации при приложении различных видов нагрузок.

Результаты. В модели фиксации голеностопного сустава передней пластиной, комбинируемой с двумя спонгиозными винтами и проксимальным кортикальным винтом, имплантаты и таранная кость испытывали наименьшие напряжения по сравнению с двумя другими моделями. Так, максимальное эквивалентное напряжение в имплантатах при втором варианте составило 68–124 МПа, при первом варианте — 92–147 МПа, при третьем — 130–331 МПа. Эквивалентное напряжение в таранной кости во втором варианте фиксации составило от 20 до 46 МПа, в первом и третьем вариантах — 28–58 МПа и 47–65 МПа соответственно. Показатели максимального контактного давления на границе большеберцовой и таранной костей оказались наибольшими в первом варианте по сравнению с двумя другими моделями (34 МПа, 31 МПа и 31 МПа соответственно).

Заключение. Среди изученных систем фиксации голеностопного сустава при артродезе применение передней пластины, комбинируемой с двумя спонгиозными винтами и проксимальным кортикальным винтом, является наиболее предпочтительным с точки зрения биомеханики.

Ключевые слова: биомеханическое моделирование, артродез голеностопного сустава, пластина, спонгиозные винты, метод конечных элементов.

Хоминец В.В., Михайлов С.В., Жумагазиев С.Е., Щукин А.В., Иванов Д.В. Сравнительный биомеханический анализ способов артродезирования голеностопного сустава: экспериментальное исследование. *Травматология и ортопедия России*. 2022;28(4):136-147. https://doi.org/10.17816/2311-2905-1989.

Хоминец Владимир Васильевич; e-mail: vkhominets@yandex.ru

Рукопись получена: 02.09.2022. Рукопись одобрена: 01.11.2022. Статья опубликована онлайн: 25.11.2022.

BACKGROUND

Enhancement of ankle arthrodesis techniques when treating patients with the end-stage osteoarthritis still remains one of the main problems of modern traumatology and orthopedics. Nowadays many authors consider ankle arthrodesis as a gold standard for the treatment of patients with this pathology [1, 2, 3].

It is known that one of the main aspects, indispensable for the ankle bone ankylosing is to create conditions for the foot fixation at a functionally advantageous or specified position [1, 4, 5]. Screws, plates, intramedullary nails, external fixators and their combinations are applied to definitively fix the attained optimal position of the talus in relation to the tibia [6, 7, 8]. Screws and plates are the most frequent in case of the ankle arthrodesis. They provide sufficient stability and adequate compression between the ankylosed tibial and talar surfaces [2, 9, 10]. However, some authors report on the loss of correct position of the ankylosed bones during the treatment due to the implant failure. This problem particularly often occurs when starting the axial load (1.5-2.0 months after the surgery). It might be caused by poor bone quality, insufficient contact between the bones, lysis of bone transplants used during the surgery, joint contracture of the forefoot [3, 11, 12]. Limitation of movements mentioned above does not contribute to the rock-up from heel to toe when walking, while the cyclic load leads to the construct loosening [13]. Thus, the problem of reliable fixation of the ankle joint do exist and pushes for new decisions.

In the hospital of military trauma and orthopedics of the Kirov Military Medical Academy we developed a method of the ankle arthrodesis with the use of 3 cancellous screws (patent RU 2633945). The first 2 screws are introduced through the anterior margin of the distal metaepiphysis of the tibia into the trochlea of the talus, while the third screw is introduced through the posteromedial part towards the neck of the talar bone. To perform that, it is necessary to turn over the patient on one side or raise his leg and hold it in this position during a certain time that is needed to introduce a guide wire, make a hole with a cannulated drill bit, select the cancellous screw of appropriate length and insert it [7]. All these indispensable procedures increase the surgery duration and C-arm operating period, creating some difficulties for the surgical team [14].

Taking this into account, on the basis of the hospital of military trauma and orthopedics of the Military Medical Academy we developed an anterior plate for the ankle arthrodesis that is used instead of the third screw and is combined with 2 cancellous screws inserted through the anterior surface of the distal tibial metaepiphysis.

Several biomechanical studies concerning the stability of different implants for the ankle joint fixation when performing arthrodesis have been published in the special literature [15, 16, 17]. Nowadays the comparative analysis of various types of metal fixators is more often carried out by applying biomechanical (or math) modeling. Among them is the finite element method [17, 18, 19]. However, there are only few studies dedicated to the evaluation of stability of different variants of the ankle fixation with the use of this method [18, 19]. Despite a big number of existing techniques of ankle arthrodesis, we chose for our comparative analysis the method of 3 cancellous screws for the following reasons. Firstly, it is sufficiently studied by many authors concerning the surgery technique and the long-term treatment results. Secondly, according to the specialists, ankle arthrodesis with screws is the most frequently used and is considered as a gold standard [3, 10]. Thus, to facilitate the surgical intervention, we suggested our originally designed plate that substitutes the third screw, introduced through the posterior part of the distal tibial metaepiphysis towards the talar neck. Due to this reason, we did not include in our study the variant of ankle joint arthrodesis with serial plates.

Aim of the study – to compare the stability of various fixation systems in ankle joint arthrodesis, using the finite element method.

METHODS

Anterior plate for the ankle arthrodesis was developed by the employees of the Military Trauma and Orthopedics department of the Military Medical Academy in collaboration with "Osteomed" company. The implant is made of Ti6Al4V titanium alloy according to the

National State Standard R ISO 5832-3 (application for an invention RF №2022123335). L-shaped implant with preset anatomic angle can be optimally positioned over the ankle joint and has minimal profile. The plate has a short and widened arm that allows to place it on the talar neck eliminating the risk of impingement syndrome in the talonavicular joint between the plate and the navicular bone. Long arm of the plate has combination holes that enable the use of both cortical and angular-stable screws (Fig. 1).

Fig. 1. Anterior plate for ankle arthrodesis

Virtual reconstruction of the variants of ankle arthrodesis was made using the computed tomography (CT). Initial processing of CT scans of the left ankle joint (1051 axial slices) of the patient (born in 1967) was carried out with the use of Mimics software (Materialise, Belgium). As a result, surface models of the distal third of the tibia and the talar bone were obtained. After that the surface models were transformed in 3Matic software (Materialise, Belgium) into solid ones which were exported to the Step format (universal standard of data model exchange of the product). Solid models of the screws and the plate were designed using SolidWorks automatic design system and were combined together in this system. Thus, three variants of ankle joint fixation for arthrodesis in functionally advantageous position were simulated. The first variant of fixation implies the use of three 6.5 mm cancellous screws with partial thread and 16 mm thread length (patent RU 2633945) (Fig. 2a). In case of the second and the third variants, the fixation is performed with our designed plate in combination with two 6.5 mm cancellous screws with partial thread and 16 mm thread length (Fig. 2b, c).

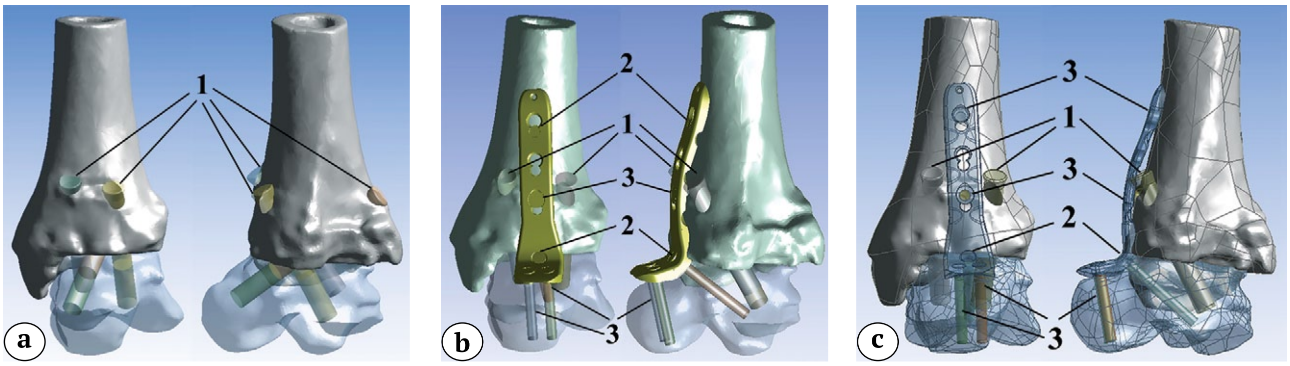

Fig. 2. 3D models in two projections (frontal and lateral) of ankle arthrodesis:
a — with three cancellous screws; b — the originally designed plate and two cancellous screws, the proximal screw is cortical; c — the originally designed plate and two cancellous screws, proximal screw with angular stability 1 — cancellous screw, 2 — cortical screw, 3 — screw with angular stability

The models were constructed as follows. The first two cancellous screws were inserted through the anterior margin of the distal mataepiphysis of the tibia into the trochlea of the talus. Then the plate was fixed to the talar bone with one cortical screw, introduced via the hole at the curve of the plate, and with two angular-stable screws, inserted via the holes of the short arm of the plate. At the next stage, the implant was secured to the tibia with an angular-stable screw, introduced via the distal hole, and with a cortical screw via the proximal hole (the second variant) or with two angular-stable screws (the third variant).

The problems of "bone-fixator" system loading by external forces and the moments in static position are described in details in the study of A.V. Dolya et al. [20]. They were solved numerically using the finite element method and Ansys software (Ansys Inc., USA). Coordinate axes, relative to which the external forces were applied, were aligned as follows: Z-axis – along the axis of the tibia and vertically upwards, Y-axis – along the axis of the foot from calcaneus to toes, X-axis – perpendicular to Y- and Z-axes (Fig. 3).

As an external load, the force acting along the axis of the tibia was applied with a rigid fixation of the talar bone to the horizontal surface. That force was equivalent to the half of human weight. Bending and torsion moments with the value of 10 N·m were also applied. Authors of the publication concerning the study of the ankle joint with the use of the finite element method, had recommended exactly these values [19]. Bending and torsion moments with the force value of 400 N and the moment value of 10 N·m were applied to the lower third of the tibia. They acted in the following directions: valgus load (around Y-axis), varus load (around Y-axis), dorsiflexion (around X-axis), plantar flexion (around X-axis), inversion (around Z-axis), eversion (around Z-axis). Fixation systems' behaviour under the load while walking (body weight multiplied by 3.3) was also studied. Recommendations, suggested by T. Wehner et al., were used for calculations [21].

Bones and implants were considered isotropic and linear elastic [18, 19, 23]. Young's modulus and Poison's ratio are the quantitative characteristics of elastic properties of isotropic material. Mechanical properties of materials for the tibia according to Young's modulus were 837 MPa, for the talar bone – 13000 MPa, for the implants (titanium alloy) – 110,000 MPa; according to Poison's ratio they were 0.3 and equal [18, 19].

While modeling, we took into account the contact interaction between the tibia and the talar bone and between the bones and fixation systems, that are recommended by M. Zhu et al. [19]. Properties of contact pairs were the following: bone-to-bone – with friction, index of friction 0.1; bone-to-screw – with friction, index of friction 0.5; bone-to-plate – full contact without friction and sliding [19].

Threads of the screws were modeled by Ansys tool, simulating a thread joint [22]. The pressure of 50 MPa was applied to the tops of the screwheads, simulating the tightening force. These parameters were preset to standardize the experiment and were adapted from the similar studies of other authors [18, 19].

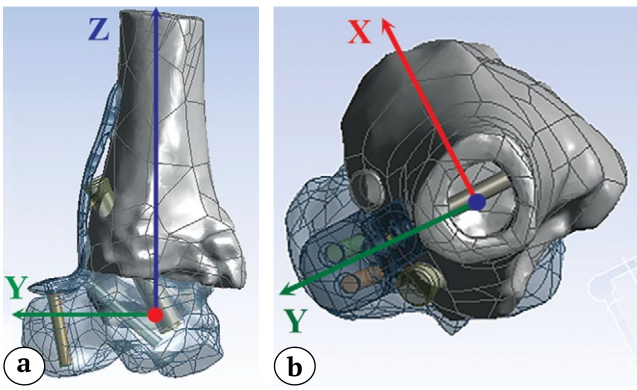

Fig. 3. The axes of the model coordinate system, relative to which the external loads were set:
a — side view; b — top view

Analysis of necessary mesh independence was performed in order to maximally approximate the study to real biologic objects [23]. It allowed to determine the typical dimension of computing mesh element, minimally affecting the results of simulation. Computing mesh was significantly condensed around the threads of the screws in order to register with high precision the thread contact interaction between the screw and the bone. Total amount of finite element for each model was 600.000, which corresponded to approximately 1.900.000 nodes.

RESULTS

The following characteristics of stress-strain state of the talar bone, the tibia and the implants were analyzed for each model: maximum equivalent stress in the bones and the implants (Fig. 4); maximum contact pressure at the border of the tibia and the talar bone (Fig. 5).

Obtained results of all studied variants of movements attest to the fact that the maximum equivalent stress in the implants was noted in the third variant in case of foot dorsiflexion (331 MPa), while the minimum equivalent stress – in the second variant in case of plantar flexion of the foot (124 MPa).

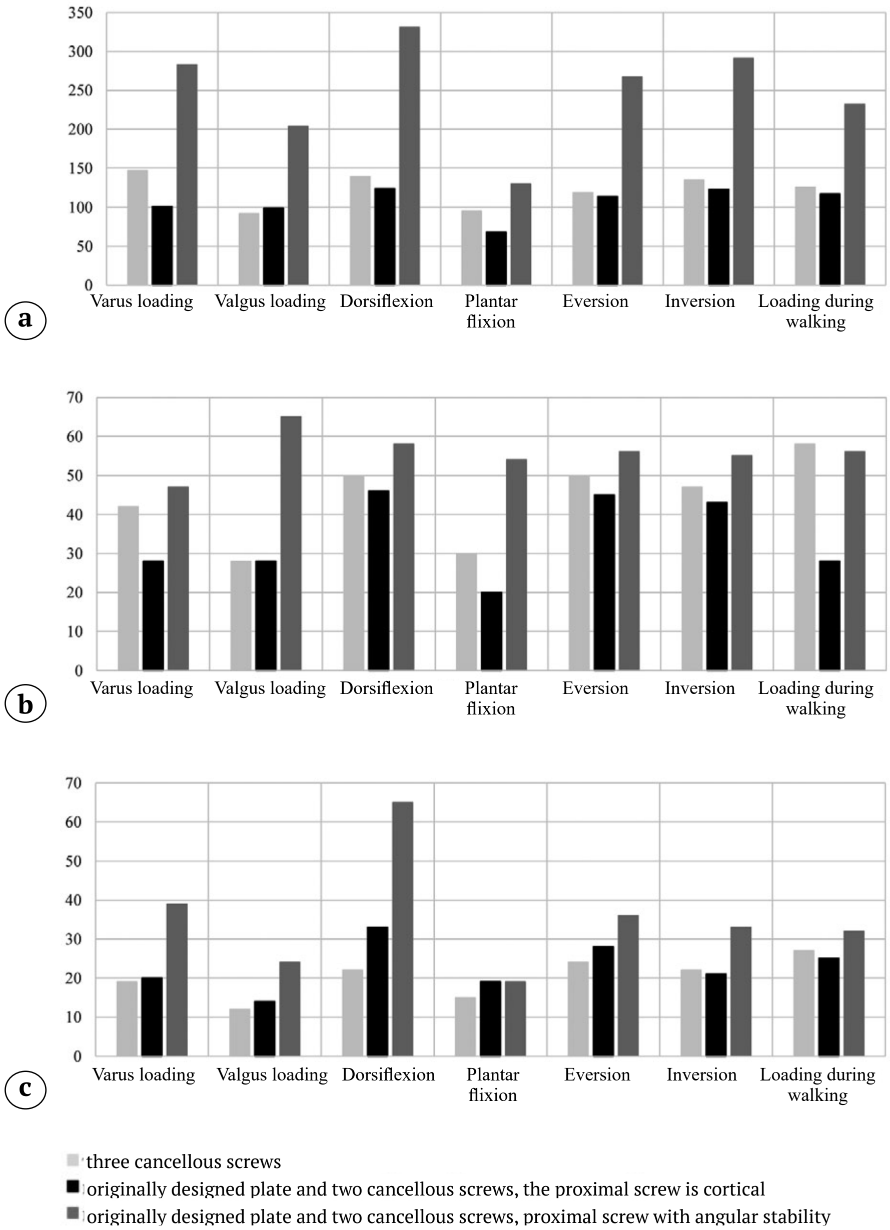

Fig. 4. Maximum equivalent stresses for various types loads of on the ankle joint, MPa:
a — in the studied implants;
b — in the talus;
c — in the tibia

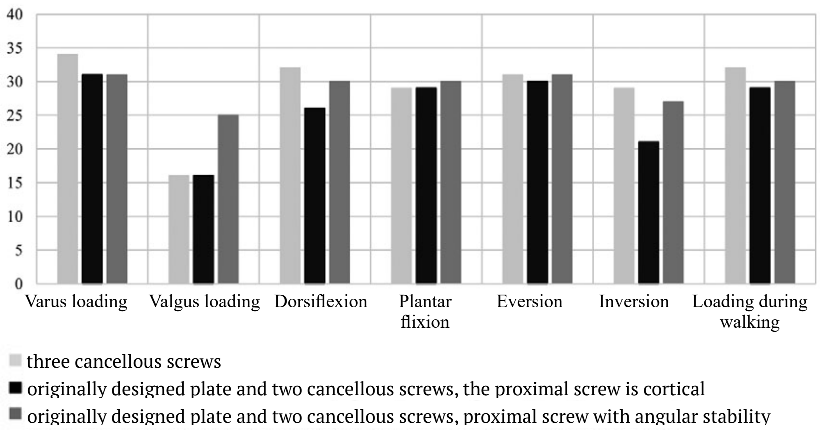

Fig. 5. Contact pressure at the border of the tibia and talus when using various options for fixation and loads on the ankle, MPa

Equivalent stresses in the talar bone being studied, the maximum loads were observed in the third variant in case of valgus displacement, while the minimum loads – in the second variant in case of plantar flexion of the foot. They were equal to 65 MPa and 20 MPa respectively.

The maximum equivalent stress in the tibia was registered in the third variant in case of plantar flexion, while the minimum stress – in the first variant in case of valgus load. They were equal to 65 MPa and 12 MPa respectively.

Obtained results showed that the maximum values of contact pressure at the boarder of the tibia and the talar bone were observed in the first variant in case of varus load, while the minimum load – in the first and the second variants in case of valgus load. They were equal to 34 MPa and 16 MPa respectively (see Fig. 5).

As the dorsiflexion of the foot, according to literature data, is the main stress factor for the ankle joint ankylosis while walking [25], we present below more detailed results of the study of stress-strain state while simulating this load.

Figure 6 shows the example of typical areas of full displacement for all models in case of dorsiflexion of the foot. The maximum displacement for fixation model with three cancellous screws was 1.2 mm (Fig. 6a), for the third variant – 1.04 mm (Fig. 6c), while for the second variant the displacement did not exceed 1 mm (Fig. 6b). At the same time, the maximum displacement in all models was observed in the distal third of the tibia above the implants' insertion sites.

Typical areas of equivalent stresses for all implant models in case of dorsiflexion of the foot are calculated to identify the optimal variant of fixation. It should be noted, that the maximum equivalent stress was concentrated around the upper screw that fixed the plate to the tibia in the second and the third models. The values were 124 MPa and 331 MPa respectively. The maximum equivalent stress of implants in the first model was 139 MPa (Fig. 7).

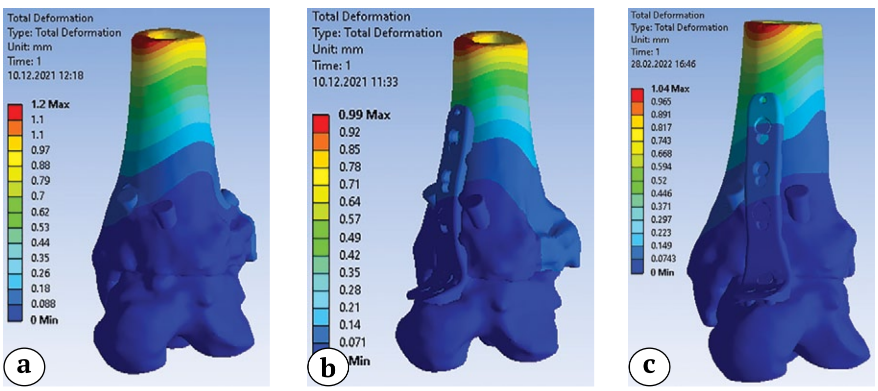

Fig. 6. Total displacement fields for three models of dorsiflexion fixation, mm:
a — three cancellous screws; b — the plate and two cancellous screws, the proximal screw is cortical;
c — the plate and two cancellous screws, proximal screw with angular stability

The maximum equivalent stresses in the talar bone in case of dorsiflexion of the foot were equal to 50 MPa, 46 MPa and 58 MPa in the first, the second and the third model variants respectively (Fig. 8).

In the models of ankle fixation with the plate and two cancellous screws under all studied loads the maximum equivalent stress in the tibia was observed around the hole for the upper screw, fixing the plate. For example, these parameters were equal to 33 and 65 MPa in the second and the third variants in case of dorsiflexion of the foot respectively (Fig. 9).

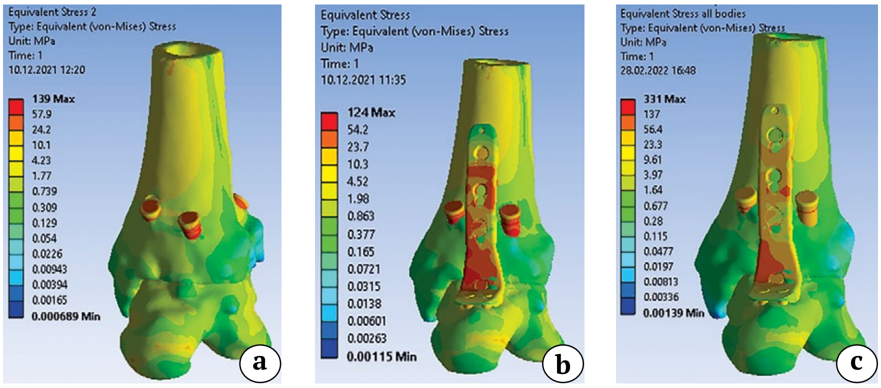

Fig. 7. Equivalent stress fields for dorsiflexion models, MPa:
a — three cancellous screws; b — the plate and two cancellous screws, the proximal screw is cortical;
c — the plate and two cancellous screws, proximal screw with angular stability

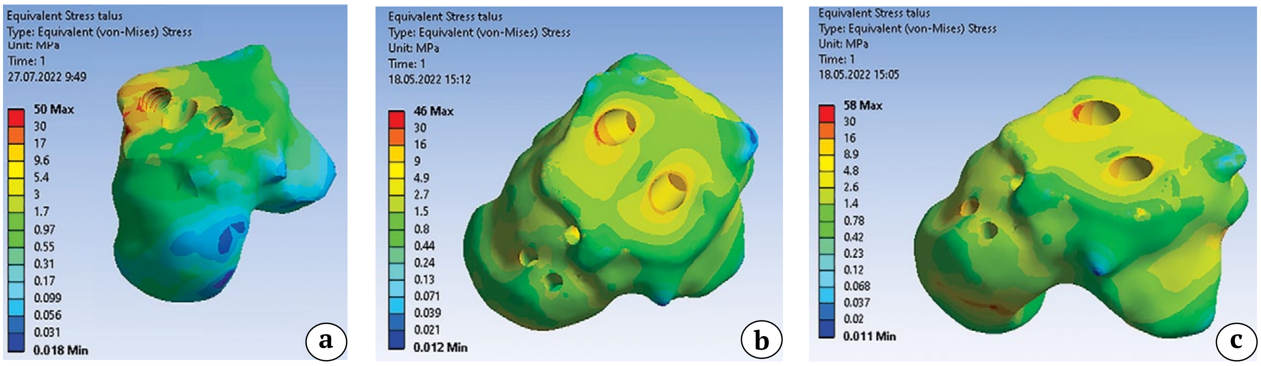

Fig. 8. Equivalent stresses in the talus during loading simulating dorsiflexion of the foot, MPa:
a — three cancellous screws; b — the plate and two cancellous screws, the proximal screw is cortical;
c — the plate and two cancellous screws, proximal screw with angular stability

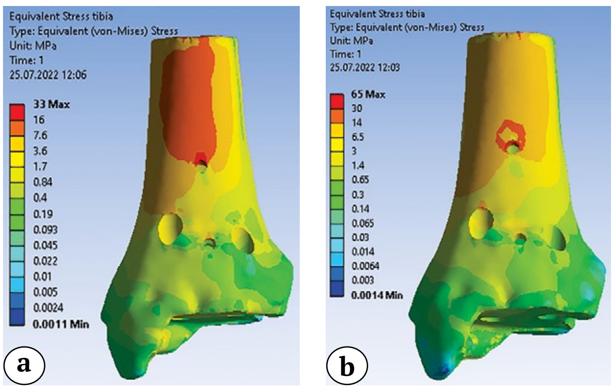

Fig. 9. Equivalent stresses in the tibia during a load simulating dorsiflexion of the foot, MPa:
a — second option; b — third option

DISCUSSION

Although the ankle arthrodesis as osteoarthritis treatment method exists for more than 140 years, the searches for the best implants enabling tight bone contact between the tibia and the talar bone and their stable fixation until complete bone union still continue. In order to evaluate the stability of ankle fixation when performing the arthrodesis, some biomechanical studies are still carried out to make quantitative analysis of strength and stiffness of the used implants as well as relative motions between the talar and the tibial bones [5, 15, 26, 27]. Nowadays different methods of digital modeling of biological objects and their loads are frequently used along with the bench tests on cadaver extremities or artificial bones and joints. The infinite model method is one of the most common instruments for calculation of stress-strain state of the musculoskeletal system as well as of the load-bearing implants [17, 18, 28, 29].

Some studies have recently been published concerning the application of biomechanical modeling of ankle arthrodesis with screw fixation in different combination and quantity. Thus, M. Zhu et al. performed the finite element modeling of ankle arthrodesis with two cancellous screws with the offered combination with two previously used combinations. Basing on biomechanical characteristics of developed models, the authors concluded that the offered combination of two cancellous screws had great initial stability and equivalent stress distribution [19]. Using the finite model method, A.A. Vázquez et al. carried out biomechanical validation of the optimal insertion angle of two cancellous screws in relation to the long axis of the tibia when performing the ankle arthrodesis [30].

Our study presents the results of numerical biomechanical modeling of 3 fixation variants in ankle arthrodesis. We analyzed 6 types of static loads as well as the load imitating the walk and evaluated the stability and the strength of each fixation variant.

Ankle fixation with two cancellous screws combined with the designed plate and the proximal cortical screw resulted more preferable in terms of implant strength in all load types. Analysis of equivalent stress in the implants is performed to measure their maximal values and compare with the strength limit (strength margin coefficient equals to 3)*. The implants are made of Ti6Al4V titanium alloy, their strength limit is 970 MPa) [24]. Thus, the allowable stress is no more than 323 MPa. It is worth mentioning that the equivalent stress in the first two studied constructions do not exceed the allowable values for titanium alloys. This means that the systems of fixation provide the maximum strength in case of the tested loads. Analyzing the third variant of ankle fixation, the maximum equivalent stress in implants surpasses the allowable value. The maximum stress in this model is registered in case of dorsiflexion of the foot around the proximal screw that fixes the plate to the tibia. It is also worth pointing out that the maximum equivalent stress in the second and the third models is concentrated around the upper screw that secures the plate to the tibia, but it is 2.5-fold higher in the third model than in the second one. Meanwhile the maximum equivalent stress in the first model is concentrated around all three inserted screws. The implants resulted less loaded during the varus load and the plantar flexion of the foot in the first variant of fixation and during the plantar flexion only in the second and the third variants.

Analyzing the results of equivalent stress in the talar bone, we noticed that the latter was less loaded in case of ankle fixation with the anterior plate combined with two cancellous screws and one cortical screw comparing to other models. It is necessary to emphasize that the maximum equivalent stress in the talar bone in the second variant of ankle fixation resulted 2 times less under the load imitating the walk and 1.5 times less in case of varus flexion and plantar foot flexion than in the first and the third variants. The lowest stress in the talus was registered in the first model of ankle fixation in case of varus load, in the second one - in case of plantar foot flexion and in the third one - under the varus load.

Equivalent stress in the tibia was lower than in the talar bone under the similar loads. The maximum stress in the tibia in the first and the second variants of ankle fixation was almost the same and 1.5 times higher - in the third variant. When modeling the variants of ankle fixation with the plate and two cancellous screws, we found out that the hole in the tibia for the upper screw fixing the

* National State Standard R 52857.1-2007 Vessels and apparatus. Norms and methods of strength calculation. General requirements.

plate was under the maximum stress comparing with other parts of the bone. This conclusion is true for all studied types of load. The tibia resulted the less loaded in case of varus load.

As for the contact pressure at the boarder of the tibia and the talar bone, its maximum values were observed in case of varus load in all ankle fixation variants. It was equal to 34 MPa in the first fixation variant and 31 MPa – in the second and the third ones. The model of ankle joint fixation with the plate and two cancellous screws showed slightly better biomechanical properties under the majority of load types. It should be noted, that excessive contact pressure under the load is a negative factor, as it can lead to local osteolysis and loss of correct position of ankylosed bones.

It is worth mentioning, that the majority of parameters of the first model stress-strain state are similar to those, presented in the publication of S. Wang et al. For example, the authors had studied parameters of stress-strain state of ankle joint arthrodesis models, secured with three cancellous screws in five different combinations, and had reported close values of maximum stress in the talar bone and the tibia, that equaled to 45.8 and 23.4 MPa respectively [18].

CONCLUSION

Minimum parameters of stress-strain state of the “bone-fixator” model were identified in the second variant among all studied fixation systems of ankle joint arthrodesis. Thus, the obtained results showed that the most biomechanically preferable variant of arthrodesis was the combination of our designed plate with two cancellous screws and the proximal cortical screw. Conducted biomechanical study allows to recommend ankle arthrodesis for clinical use in patients with the end-stage osteoarthritis, although ankle joint ankylosing depends not only on mechanical factors, but on biological as well.

DISCLAIMERS

Author contribution

Khominets V.V. — study concept and design, analysis of the data.

Mikhailov S.V. — analysis and interpretation of data; editing the text.

Zhumagaziev S.E. — collection, analysis and interpretation of data; writing the text.

Shchukin A.V. — analysis and interpretation of data; editing the text.

Ivanov D.V. — collection and processing of material; analysis and interpretation of data.

All authors have read and approved the final version of the manuscript of the article. All authors agree to bear responsibility for all aspects of the study to ensure proper consideration and resolution of all possible issues related to the correctness and reliability of any part of the work.

Funding source. This study was not supported by any external sources of funding.

Competing interests. The authors declare that they have no competing interests.

Ethics approval. Not applicable.

Consent for publication. Not required.

REFERENCES

1. Morash J., Walton D.M., Glazebrook M. Ankle Arthrodesis Versus Total Ankle Arthroplasty. *Foot Ankle Clin.* 2017;22(2):251-266. doi: 10.1016/j.fcl.2017.01.013.
2. Prissel M.A., Simpson G.A., Sutphen S.A., Hyer C.F., Berlet G.C. Ankle Arthrodesis: A Retrospective Analysis Comparing Single Column, Locked Anterior Plating to Crossed Lag Screw Technique. *J Foot Ankle Surg.* 2017;56(3):453-456. doi: 10.1053/j.jfas.2017.01.007.
3. Suo H., Fu L., Liang H., Wang Z., Men J., Feng W. End-stage Ankle Arthritis Treated by Ankle Arthrodesis with Screw Fixation Through the Transfibular Approach: A Retrospective Analysis. *Orthop Surg.* 2020;12(4):1108-1119. doi: 10.1111/os.12707.
4. DeHeer P.A., Catoire S.M., Taulman J., Borer B. Ankle arthrodesis: a literature review. *Clin Podiatr Med Surg.* 2012;29(4):509-527. doi: 10.1016/j.cpm.2012.07.001.
5. Somberg A.M., Whiteside W.K., Nilssen E., Murawski D., Liu W. Biomechanical evaluation of a second generation headless compression screw for ankle arthrodesis in a cadaver model. *Foot Ankle Surg.* 2016;22(1):50-54. doi: 10.1016/j.fas.2015.04.010.

6. Mikhaylov K.S., Emelyanov V.G., Tikhilov R.M., Kochish A.Yu., Sorokin E.P. [Substantiation of surgery method in patient with ankle osteoarthritis: arthrodesis or arthroplasty]. *Travmatologiya i ortopediya Rossii* [Traumatology and orthopedics of Russia]. 2016;(1):21-32. (In Russian). doi: 10.21823/2311-2905-2016-0-1-21-32.
7. Khominets V.V., Mikhailov S.V., Shakun D.A., Shumagaziev S.E., Komarov A.V. [Ankle Arthrodesis with Three Cancellous Screws]. *Travmatologiya i ortopediya Rossii* [Traumatology and Orthopedics of Russia]. 2018;24(2):117-126. (In Russian). doi: 10.21823/2311-2905-2018-24-2-117-126.
8. Onodera T., Majima T., Kasahara Y., Takahashi D., Yamazaki S., Ando R. et al. Outcome of transfibular ankle arthrodesis with Ilizarov apparatus. *Foot Ankle Int.* 2012;33:964-968.
9. Teramoto A. Nozaka K., Kamiya T., Kashiwagura T., Shoji H., Watanabe K. et al. Screw Internal Fixation and Ilizarov External Fixation: A Comparison of Outcomes in Ankle Arthrodesis. *J Foot Ankle Surg.* 2020;59(2):343-346. doi: 10.1053/j.jfas.2019.09.012.
10. Heuvel S.B.M., Doorgakant A., Birnie M.F.N., Blundell C.M., Schepers T. Open Ankle Arthrodesis: a Systematic Review of Approaches and Fixation Methods. *Foot Ankle Surg.* 2021;27(3):339-347. doi: 10.1016/j.fas.2020.12.011.
11. Steginsky B.D., Suhling M.L., Vora A.M. Ankle Arthrodesis With Anterior Plate Fixation in Patients at High Risk for Nonunion. *Foot Ankle Spec.* 2020;13(3):211-218.doi:10.1177/1938640019846968.
12. van den Heuvel S.B.M., Penning D., Schepers T. Open Ankle Arthrodesis: A Retrospective Analysis Comparing Different Fixation Methods. *J Foot Ankle Surg.* 2022;61(2):233-238. doi: 10.1053/j.jfas.2021.07.012.
13. Ross B.J., Savage-Elliott I., Wu V.J., Rodriguez R.F. Complications Following Total Ankle Arthroplasty Versus Ankle Arthrodesis for Primary Ankle Osteoarthritis. *Foot Ankle Spec.* 2021:1938640020987741. doi: 10.1177/1938640020987741.
14. Zwipp H., Rammelt S., Endres T., Heineck J. High union rates and function scores at midterm followup with ankle arthrodesis using a four screw technique. *Clin Orthop Relat Res*. 2010;468(4):958-968. doi: 10.1007/s11999-009-1074-5.
15. Clifford C., Berg S., McCann K., Hutchinson B. A biomechanical comparison of internal fixation techniques for ankle arthrodesis. *J Foot Ankle Surg.* 2015;54(2):188-191. doi: 10.1053/j.jfas.2014.06.002.
16. Gutteck N., Martin H., Hanke T., Matthies J.B., Heilmann A., Kielstein H. et al. Posterolateral plate fixation with Talarlock® is more stable than screw fixation in ankle arthrodesis in a biomechanical cadaver study. *Foot Ankle Surg.* 2018;24(3):208-212.
17. Dubrov V.E., Zyuzin D.A., Kuzkin I.A., Shcherbakov I.M., Donchenko S.V., Saprykina K.A. [Finite element modelling of biologic system in orthopedic trauma]. *Rossiiskii zhurnal biomekhaniki* [Russian Journal of Biomechanics]. 2019;23(1):140-152. (In Russian). doi: 10.15593/RZhBiomeh/2019.1.12.
18. Wang S., Yu J., Ma X., Zhao D., Geng X., Huang J., Wang X. Finite element analysis of the initial stability of arthroscopic ankle arthrodesis with three-screw fixation: posteromedial versus posterolateral home-run screw. *J Orthop Surg Res.* 2020;15(1):252. doi: 10.1186/s13018-020-01767-7.
19. Zhu M., Yuan C.S., Jin Z.M., Wang Y.J., Shi Y.X., Yang Z.J. et al. Initial stability and stress distribution of ankle arthroscopic arthrodesis with three kinds of 2-screw configuration fixation: a finite element analysis. *J Orthop Surg Res.* 2018;13(1):263. doi: 10.1186/s13018-018-0972-1.
20. Dol A.V., Dol E.S., Ivanov D.V. [Biomechanical modelling of surgical reconstructive treatment of spinal spondylolisthesis at l4–l5 level]. *Rossiiskii zhurnal biomekhaniki* [Russian Journal of Biomechanics]. 2018;22(1):31-44. (In Russian). doi: 10.15593/RZhBiomeh/2018.1.03.
21. Wehner T., Claes L., Simon U. Internal loads in the human tibia during gait. *Clin Biomech (Bristol, Avon).* 2009;24(3):299-302. doi: 10.1016/j.clinbiomech.2008.12.007.
22. López-Campos J.A., Segade A., Casarejos E., Fernández J.R., Vilán J.A., Izquierdo P. Finite Element Study of a Threaded Fastening: The Case of Surgical Screws in Bone. *Symmetry*. 2018;10(8):335. doi: 10.3390/sym10080335.
23. Ivanov D.V., Dol A.V. [Biomechanical Modeling]. Saratov: Amirite, 2021. 250 p.
24. Zherebtsov S., Salishchev G., Galeyev R., Maekawa K. Mechanical Properties of Ti–6Al–4V Titanium Alloy with Submicrocrystalline Structure Produced by Severe Plastic Deformation. *Materials Transactions.* 2005;46(9):2020-2025. doi: 10.2320/matertrans.46.2020.
25. Nasson S., Shuff C., Palmer D., Owen J., Wayne J., Carr J. et al. Biomechanical comparison of ankle arthrodesis techniques: crossed screws vs. blade plate. *Foot Ankle Int.* 2001;22(7):575-580. doi: 10.1177/107110070102200708.
26. Friedman R.L., Glisson R.R., Nunley J.A. A biomechanical comparative analysis of two techniques for tibiotalar arthrodesis. *Foot Ankle Int.* 1994;15(6):301-305. doi: 10.1177/107110079401500604.
27. Miller R.A., Firoozbakhsh K., Veitch A.J. A biomechanical evaluation of internal fixation for ankle arthrodesis comparing two methods of joint surface preparation. *Orthopedics.* 2000;23(5):457-460. doi: 10.3928/0147-7447-20000501-14.

28. Erdemir A., Guess T.M., Halloran J., Tadepalli S.C., Morrison T.M. Considerations for reporting finite element analysis studies in biomechanics. *J Biomech.* 2012;45(4):625-633. doi: 10.1016/j.jbiomech.2011.11.038.
29. Kluess D., Wieding J., Souffrant R., Mittelmeier W., Bader R. Finite element analysis in orthopaedic biomechanics. In: Moratal D., ed. Finite Element Analysis. València; 2010. p. 151-170.
30. Vázquez A.A., Lauge-Pedersen H., Lidgren L., Taylor M. Finite element analysis of the initial stability of ankle arthrodesis with internal fixation: flat cut versus intact joint contours. *Clin Biomech (Bristol, Avon).* 2003;18(3):244-253. doi: 10.1016/s0268-0033(02)00207-3.

Authors' information

🖂 *Vladimir V. Khominets* — Dr. Sci. (Med.), Professor
Address: 6, St. Petersburg, Akademika Lebedeva st., 194044 Russia
http://orcid.org/0000-0001-9391-3316
e-mail: khominets_62@mail.ru

Sergey V. Mikhailov — Cand. Sci. (Med.)
https://orcid.org/0000-0002-0098-8085
e-mail: msv06@mail.ru

Sayan E. Zhumagaziev
https://orcid.org/0000-0002-5169-2022
e-mail: shumagasiev@mail.ru

Alexey V. Shchukin — Cand. Sci. (Med.)
https://orcid.org/ 0000-0001-7754-8478
e-mail: ossa.76@mail.ru

Dmitry V. Ivanov — Cand. Sci. (Phys.-Math.)
https://orcid.org/0000-0003-1640-6091
e-mail: ivanovdv.84@ya.ru