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BIOMECHANICAL STUDY OF THE STABILITY OF OSTEOSYNTHESIS OF THE FRACTURE OF THE PROXIMAL HUMERUS BY THE DEVELOPED DEVICE IN COMPARISON WITH A STANDARD BONE LOCKING PLATE. COMPUTER MODELING BY THE FINITE ELEMENT METHOD

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Abstract

Introduction. Proximal humerus fractures (PHF) are the third most common fractures after fractures of the femoral neck and distal metaepiphysis of the radius. PHF are most often found in the elderly and old people. Despite the availability of a large number of surgical treatment methods, a large number of complications are still observed, such as secondary displacement, screw eruption and aseptic necrosis. In this study computer modeling was carried out to determine the biomechanical characteristics of osteosynthesis of a PHF with a new device, and the immediate results of the operation on a patient are given as a clinical example.

Research objective. Comparative study using the finite element method of computer models of the humerus, which fixed by the developed device and a standard bone plate.

Materials and methods. A new device for proximal humerus fractures fixing has been developed and manufactured. Based on a CT scan of the shoulder joint of a middle-aged man, a 3D model of the humerus was developed. On the humerus models was applied simulation of 500 N compression loads along the axis and axial sharing with 20^0, rotational loads with a force of 200 N. The results of biomechanical experiments obtained during computer modeling, the distribution points of the maximum von Mises stress, and the restoration of shoulder joint function in the early postoperative period were studied.

Results. The results of computer modeling using the finite element method showed that the von Mises stress distribution was smaller in the humerus model fixed by the new device than in the model fixed by the standard plate. In the humerus model with the standard plate, the displacement of bone fragments was greater. The patient who underwent surgery had good recovery of the shoulder joint function, with a Constant Murley (Score) score of 85%.

Conclusion. Osteosynthesis of the proximal humerus fracture by the new device increases fracture stability, prevents secondary displacement of bone fragments and promotes early restoration of movement in the shoulder joint.

Key words. *Proximal humerus fracture, computer modeling by finite elements, newly designed device, osteosynthesis, bone-plate models.*

Резюме

БИОМЕХАНИЧЕСКОЕ ИССЛЕДОВАНИЕ СТАБИЛЬНОСТИ ОСТЕОСИНТЕЗА ПЕРЕЛОМА ПРОКСИМАЛЬНОГО ОТДЕЛА ПЛЕЧЕВОЙ КОСТИ РАЗРАБОТАННЫМ УСТРОЙСТВОМ В СРАВНЕНИИ СО СТАНДАРТНОЙ НАКОСТНОЙ БЛОКИРУЕМОЙ ПЛАСТИНОЙ. КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ МЕТОДОМ КОНЕЧНЫХ ЭЛЕМЕНТОВ

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Введение. Переломы проксимального отдела плечевой кости по частоте встречаемости занимают третье место после переломов шейки бедренной кости и дистального метаэпифиза лучевой кости. Чаще всего встречается у пожилых и людей старческого возраста. Несмотря на наличие большого количества методов хирургического лечения, до сих пор наблюдается большое количество осложнений, таких как вторичное смещение, прорезывание винтов и асептический некроз. В исследований было проведено компьютерное моделирование для определения биомеханических характеристик остеосинтеза перелома проксимального отдела плечевой кости новым устройством, а так же в качестве клинического примера приведены ближайщие результаты операции на пациенте.

Цель исследования. Сравнительное исследование методом конечных элементов компьютерных моделей плечевой кости фиксированных разработанным устройством и стандартной накостной пластиной.

Материалы и методы. Разработано и изготовлено устройство нового образца для фиксации переломов проксимального отдела плечевой кости. На основе компьютерной томограммы плечевого сустава мужчины средних лет была разработана 3D – модель плечевой кости. На модели плечевой кости были симулированы нагрузки в 500 Н на сжатие по оси и с наклоном 20^0, вращательные нагрузки с силой в 200 Н. Были изучены результаты биомеханических экспериментов, полученных при компьютерном моделировании, точки распространения максимального напряжения фон Мизеса, а так же восстановление функции плечевого сустава в раннем послеоперационном периоде.

Результаты. Результаты компьютерного моделирования методом конечных элементов показали, что распределение напряжения фон Мизеса было меньше в модели плечевой кости, фиксированной новым устройством, чем в модели, фиксированной стандартной пластиной. В модели плечевой кости со стандартной пластиной смещения костных отломков было больше. У прооперированного больного функция плечевого сустава восстановилась хорошо, по шкале Constant Murley (Score) вышло 85%.

Выводы. Остеосинтез перелома проксимальной части плечевой кости новым устройством повышает стабильность перелома, предотвращает вторичное смещение костных отломков и способствует раннему восстановлению движений в плечевом суставе.

Ключевые слова. *Перелом проксимального отдела плечевой кости, компьютерное моделирование методом конечных элементов, устройство нового образца, остеосинтез, модели кость-пластина.*

Түйіндеме

ИЫҚ СҮЙЕГІНІҢ ПРОКСИМАЛЬДЫ БӨЛІГІНІҢ СЫНЫҒЫН ӘЗІРЛЕНГЕН ҚҰРЫЛҒЫМЕН ЖӘНЕ СТАНДАРТТЫ СҮЙЕКҮСТІЛІК ҚҰЛЫПТАУШЫ ПЛАСТИНАМЕН ОСТЕОСИНТЕЗІНІҢ ТҰРАҚТЫЛЫҒЫН САЛЫСТЫРМАЛЫ ТҮРДЕ БИОМЕХАНИКАЛЫҚ ЗЕРТТЕУІ. СОҢҒЫ ЭЛЕМЕНТТЕР ӘДІСІМЕН КОМПЬЮТЕРЛІК МОДЕЛЬДЕУ.

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Өзектілігі. Иық сүйегінің проксимальды бөлігінің сынықтары кездесу жиілігі бойынша сан сүйегінің мойыны мен кәрі жілік сүйегінің дистальды метаэпифизінің сынықтарынан кейінгі үшінші орынды алады. Көбінесе егде жастағы адамдар мен қарттарда кездеседі. Хирургиялық емінің көптеген әдістерінің болуына қарамастан, әлі күнге дейін екіншілік ығысу, винттардың шығып кетуі және асептикалық некроз секілді асқынулары көп кездеседі. Зерттеуде иық сүйегінің проксимальды бөлімінің сынығын жаңа құрылғымен остеосинтезінің биомеханикалық қасиеттерін анықтау үшін компьютерлік модельдеу жасалынып, клиникалық мысал ретінде науқасқа жасалған отанын жақын нәтижелері көрсетілді.

Зерттеудің мақсаты. Ойлап тапқан жаңа құрылғымен және стандартты сүйекүстілік пластинамен бекітілген иық сүйегінің компьютерлік модельдерін соңғы элементтер әдісімен салыстырмалы түрде зерттеу.

Материалдар мен әдістер. Иық сүйегінің проксимальды бөлігінің сынықтарын бекітуге арналған жаңа үлгідегі құрылғы жасап шығарылды. Орта жастағы ер адамнын иық буынының компьютерлік томограммасы негізінде иық сүйегінің 3D – моделі жасалынды. Иық сүйегінің модельдеріне 500 Н күшпен осі бойынша қысу, 20^0 қиғашынан қысу және 200 Н күшпен айналмалы жүктемелер симуляцияланды. Компьютерлік модельдеу кезінде алынған биомеханикалық эксперименттердің нәтижелері, фон Мизестің максималды кернеуінің таралу нүктелері, отадан кейінгі ерте кезеңдегі иық буынынын қызметінің қалпына келуі зерттелді.

Нәтижелер. Соңғы элементтер әдісімен компьютерлік модельдеудің нәтижелері фон Мизес кернеуінің таралуы жаңа құрылғымен бекітілген иық сүйегінін моделінде, стандартты пластинамен бекітілген модельге қарағанда аздау болғанын көрсетті. Сынық бөліктерінін ығысуы стандартты пластинамен бекітілген иық сүйегінің моделінде көбірек болды. Ота жасалған науқаста иық буынының қызметі жақсы қалпына келді, Constant Murley (Score) шкаласы бойынша 85%-ды құрады.

Тұжырым. Иық сүйегінің проксимальды бөлігінің сынығын жаңа құрылғымен остеосинтезі сынық орнынын тұрақтылығын арттырады, сынық бөліктерінің екіншілік ығысуынын алдын алып, иық буынындағы қимыл-қозғалыстың ерте қалпына келуіне септігін тигізеді.

Түйінді сөздер: *иық сүйегінің проксимальды бөлігінің сынығы, соңғы элементтер әдісімен компьютерлік модельдеу, жаңа үлгідегі құрылғы, остеосинтез, сүйек-пластина модельдері.*

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Introduction

Fractures of the proximal humerus account for 5–10% of all musculoskeletal fractures and 26% of humeral fractures [1,2]. In the elderly, especially in people with osteoporosis, fractures of the proximal humerus are the third most common after common distal radius fractures and femoral neck fractures [3]. 80% of the above fractures are stable and can be treated conservatively, while the remaining 20% are multifragmented, displaced fractures, which require surgical treatment [4,5].

Various methods and implants are used for surgical fixation of fractures of the proximal humerus. To date, the "gold standard" of surgical fixation has not been established, the complications of the currently known methods are high, and there is a heated debate among orthopedic scientists about which type of surgery is best [6,7,8]. The anatomical features of the shoulder joint and the complexity of proximal humeral fractures make it difficult to perform stable functional osteosynthesis [9]. The most commonly used surgical treatments today are: intraosseous locking osteosynthesis, supraosseous osteosynthesis, combined osteosynthesis, and partial and complete shoulder joint arthroplasty [10]. Despite the existence of several types of osteosynthesis, none of them can be used equally for all types of fractures [11]. Among the above surgical methods, open reduction and plate fixation for complex multifragmentary fractures of the proximal humerus and shoulder joint arthroplasty in elderly patients are often used [12].

After the invention of plates with screw holes, the number of surgical treatments for proximal humeral fractures has increased significantly [13]. The locking technology provides a stronger fixation of the screws in the bone tissue, thereby preventing secondary displacement and allowing for an earlier start of movements in the shoulder joint [14,15]. Despite the above-mentioned achievements, the frequency of complications after fixation with a locking plate is still high, reaching from 18% to 37% in international scientific data [16]. In this regard, further improvement of the supraosseous locking method and the invention of new types of implants are an urgent issue. Currently, orthopedic scientists from different countries of the world are engaged in the development of this method, the following inventions have been proposed: the use of carbon fiber reinforced polyester ketone instead of titanium, screw fixation with bone cement, new sutures of the rotator cuff, etc. [17,18,19].

Despite the above-mentioned innovations and treatment results, this method still requires improvement and new innovative developments. With this in mind, we developed a new design of locking plate to achieve stable osteosynthesis of proximal humeral fractures. The results of computer simulations and a clinical example using the new device are presented in this article.

Materials and methods.

A new device for fixing fractures of the proximal humerus has been developed at the Department of Traumatology and Pediatric Surgery of the Semey Medical University. This device is an orthopedic implant, a new design of a locking plate. The plate is characterized by holes in the upper part for locking screws with a diameter of 3.5 mm and 8 holes in two rows for small fixing screws with a diameter of 2.0 mm. An arcuate, curved, narrow plate-like element with screw holes is attached to these holes, through which screws are inserted into the humeral head in a different direction (Figure 1). The device was manufactured from VT6 (Grade 5) titanium at the Smart Engineering Competence Center of the D. Serikbayev East Kazakhstan Technical University.

Computer modeling.

A computer modeling using the finite element method was performed to determine the stability of osteosynthesis of a proximal humerus fracture with a new device. First, a three-dimensional geometry of the proximal humerus was created based on a computed tomography of the shoulder joint of a 56-year-old healthy man. The new plate and the ChM plate, which are commonly used in the department, were scanned using a ZG RigelScan Plus (ZG Technology Co., Ltd., Wuhan, China) 3D scanner and three-dimensional models were created. A 10 mm image was made on the humerus model, and the surgical neck fracture was formed and fixed with a plate (Figure 2).

Finite element analysis of bone-plate structures was performed using the commercial software ANSYS 2023 R1 (ANSYS, Inc., Canonsburg, Pennsylvania, USA). Materialize mimics 21.0 software was used to characterize the mechanical properties of the cortical and soft layers of the humerus. The humerus model was given elastic and isotropic mechanical properties, the elastic modulus of the implants was set to 111.2 GPa, and the Poisson's ratio was set to 0.3 for all materials. The coefficient of surface friction between the various components of the models was taken to be 0.42. Three different loads were simulated on the humeral head. The first load was applied vertically to the humeral head, and the second was applied at an angle of 200, both with a force of 500 N (Newton). The first simulated the load on the humerus when a person is standing upright, and the last simulated the load when a person is standing up from a chair with their hands or using crutches. The third load was rotational, with a force of 200 N (Figure 3).

Figure 1. Picture of a new device for fixation of proximal humerus fractures.

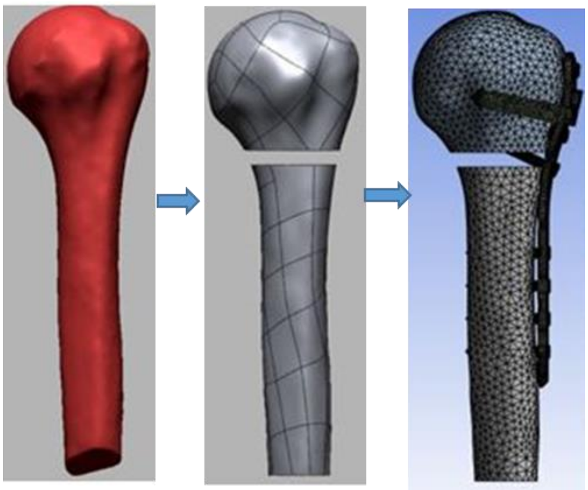

Figure 2. Creation of a 3D model of the humerus fixed with a new device.

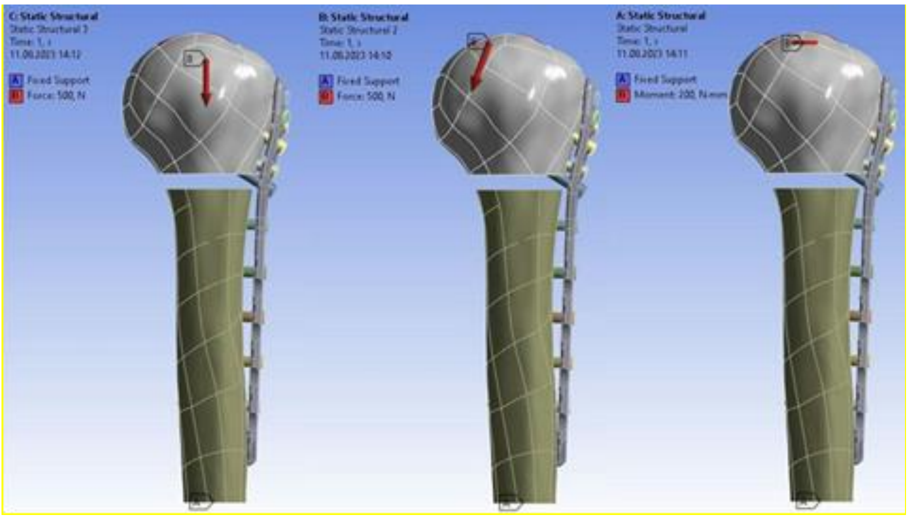

Figure 3. Computer – simulated loads on the plate-bone models.
A: Axial compression force; B: Axial force on 20^0 inclinations; C: Torsion with a rotational force.

Clinical example. Patient I., 44 years old, was urgently admitted to the Polytrauma Center of the "Emergency Medical Care Hospital" of the Semey city of the Military Hospital of the Armed Forces of the Kyrgyz Republic. Diagnosis: closed displaced fracture of the anatomical neck of the left humerus. After the patient's soft tissue swelling subsided, osteosynthesis of the humerus was performed 1 week later with a new device.

Stages of the operation: Endotracheal anesthesia was administered. After the surgical field was treated with an antiseptic, a 12.0 cm long skin and subcutaneous fat layer were cut in the shoulder joint area. The fracture area was opened with a delto-pectoral approach, reduction was performed, and the fracture fragments were temporarily fixed with spokes. A plate was installed on the lateral surface of the humerus and the bone was drilled through the holes in the plate with a drill. Locking screws were inserted through the holes and the fracture fragments were fixed. Then, through a small hole in the upper part of the plate, an arcuate, curved, narrow plate-like element with screw holes was fixed. Through the holes of this plate, screws were inserted into the head of the humerus in an anterior-posterior direction, and the fracture fragments were additionally fixed. X-ray control was performed. The wound was treated with antiseptic, sutured with a layer, and a drainage tube was left. 3 days after the operation, passive movements of the shoulder joint were started using the "arthromot" device. The operated arm was hung around the neck with a soft towel, and active movements were allowed after 3 weeks (Figure 4).

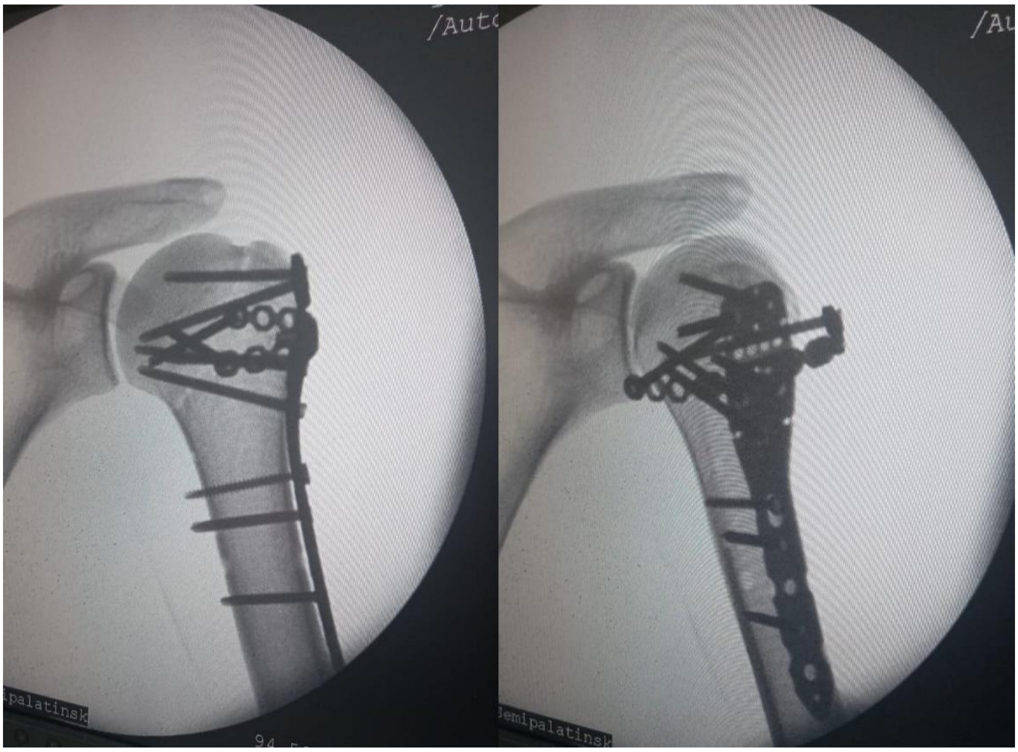

Figure 4. X-ray of the patient's shoulder joint after osteosynthesis with a new device.

Results

A finite element computer simulation was performed to compare the biomechanical properties of the ChM plate and the newly developed device for fixation of the upper humerus fracture. Six simulations were performed using ANSYS 2023 R1 (ANSYS, Inc., Canonsburg, Pennsylvania, USA) software, yielding 18 values. The following results were obtained from the computer simulation:

The maximum von Mises stress on the plate surface during compression with a force of 500 N along the axis of the humerus was 1260.6 MPa for the ChM plate and 1018.6 MPa for the newly developed plate. The maximum shear stress at the location of the locking screw attachment to the cortical bone was 41.416 MPa for the newly developed plate and 29.911 MPa for the ChM plate. The maximum von Mises stress in the locking screws was 1188.2 MPa for the new plate and 1323.6 MPa for the ChM plate.

When a compressive force was applied at an angle of 200 to the bevel, the following results were obtained: the maximum von Mises stress on the plate surface was 1586 MPa for the new plate and 1973.2 MPa for the ChM plate. The maximum shear stress at the location of the locking screw attachment to the cortical bone was 108.47 MPa for the new plate and 44.49 MPa for the ChM plate. The maximum von Mises stress determined from the locking screws was 2166.9 MPa for the new plate and 2560.1 MPa for the ChM plate.

When simulating a rotational load of 200 N on the humeral head, the maximum von Mises stress was 20.931 MPa for the new plate and 14.757 MPa for the ChM plate. The maximum shear stress at the attachment of the plate screws to the bone was 1.4372 MPa (new plate) and 0.63956 MPa (ChM plate), respectively. The maximum von Mises stress at the locking screws was 24.713 MPa for the new plate and 29.669 MPa for the ChM plate.

When axially loaded on the humerus, the displacement of the bone fragments at the fracture site was greater in the model fixed with the ChM plate. When subjected to rotational loading, the secondary displacement was less in our model of the humerus fixed with the plate. The maximum von Mises stress was located around the hole through which the calcar screw passed through the plate during the loads applied with a compressive force of 200 along the axis of the bone and obliquely (Table 1).

Table 1.

Comparative results of calculations of the stress-strain state of the bone-fixator systems.

No.	Indicators	New device			Bone locking plate		
		Rotational load, 200 N*mm	Axial load from 20 degree inclination, 500 N	Axial load 500 N	Rotational load, 200 N*mm	Axial load from 20 degree inclination, 500 N	Axial load 500 N
1	Maximum equivalent stress according to Mises, MPa	20.931	1586	1018.6	14,757	1973,2	1260,6
2	Maximum displacement, mm	0,1463	6,2965	3,0361	0,1066	9,8439	5,0497
3	Minimum safety factor, MPa	5103,5	68,8	107,2	7535,4	56,4	88,2

The patient was examined 1.5 months after surgery with a newly manufactured plate for the anatomical neck of the humerus. The function of the shoulder joint was assessed using the Constant Murley (Score) scale, the result was 85%.

Discussion.

To determine the strength of osteosynthesis of the proximal humerus fracture with the ChM plate and the newly manufactured plate, a computer simulation was performed using the finite element method to compare the biomechanical properties. The peculiarity of our plate is that it fixes the proximal humerus not only in the lateral direction, but also in the anterior and posterior directions, thereby increasing the stability of the fracture site. As shown in the results, the maximum von Mises stress in the ChM plate under pressure applied along the axis of the humerus was 1260.6 MPa, and in the newly manufactured plate was 1018.6 MPa. Under the influence of the compressive force at an angle of 200 from the oblique, the maximum von Mises stress in our plate was 1586 MPa, which is much lower than that of the Chm plate. All maximum stresses occurred in the vicinity of the hole for the "calcar" screw and in the “calcar” screws themselves. These are the most likely places of failure after internal fixation and withstand the highest loads.

Overall, the developed plate showed better stress distribution in the applied loads than the ChM plate. In our opinion, this is explained by the fact that the locking screws are inserted into the humeral head in different directions, which leads to a more even distribution of stress in the locking screws and reduces the load on the “calcar” screws. The calcar screws provide an important medial support in the proximal part of the humerus. The reduction in the load on this structure indicates that the medial support function is partially replaced by screws inserted into the humeral head from the anterior and posterior directions.

Another feature of our plate is that the angle of flexion of the proximal part is greater than that of standard plates, corresponding to the angle of lateral flexion of the proximal humerus and better fitting to the bone surface. Based on the above data, it can be concluded that the newly developed plate provides increased medial support, thereby reducing the risk of secondary varus displacement of the fracture fragments and allowing for an earlier start of shoulder joint rehabilitation. An example of this is the satisfactory recovery of shoulder joint mobility in the patient after surgery.

Our study has the following limitations. First, 3D data from only one patient were used to create the computer model, and the results obtained cannot be generalized to the general population. However, we collected data from a human humerus and used the finite element method, thus observing the real effects that can be applied in a clinical setting. Second, only three types of loads were applied to the humerus, and further studies that include different biomechanical conditions are needed in the future. Third, the finite element models were developed based only on bones and joints, and the effects of muscles and ligaments were not taken into account. However, other studies similar to ours have not taken their effects into account and have not been shown to have a significant impact on the modeling results. Fourth, the forces of the loads used in the modeling were very high, considering the values often used in previous studies [20,21]. For example, a force of 500 N can be applied to the humerus only when a person weighing more than 100 kg is supporting himself with his hands from a chair. This is a very rare situation in everyday life, given the average weight and body composition of people in the Republic of Kazakhstan. These issues can be resolved by calibrating the experimental conditions based on weight data according to age group. Fifth, so far, only one patient has been monitored for postoperative clinical outcomes, and long-term results have not yet been obtained. This issue can be resolved by increasing the number of patients and extending the follow-up period. In this article, we have discussed the biomechanical properties determined mainly using the finite element method. Despite the above-mentioned shortcomings, the results of the study proved that osteosynthesis with the developed plate is robust and functionally stable.

Conclusion.

The results of the study, conducted using computer modeling, showed that osteosynthesis of the proximal humerus fracture with a new plate achieved good biomechanical performance and stability under axial compression, axial shear, and rotational loads. Thus, the results of the study showed that fixation of the fracture site with a new plate is very stable, which helps to reduce the incidence of curved fusion and secondary displacement of bone fragments.

Conflict of interest.

The authors declare no conflict of interest.

Contributions of the authors.

Mussabekov A.S. – writing the basis of the article, conducting computer modeling, discussing the results.

Zhunussov Ye.T., Zhanaspayev M.A. – the main idea and supervision, writing the final version of the article.

Tlemisov A.S., Prokazyuk A.A., Aubakirova S.K. – analysis of the results obtained, collecting information, examining the patient, assisting in writing the article.

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