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Results of biomechanical studies of the effectiveness of osteosynthesis of unstable fractures of the clavicle with a compression rod

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Objective. To study the effectiveness of osteosynthesis of unstable clavicle fractures of type 15.2AB using a compressive rod based on biomechanical studies. Methods. Biomechanical studies analysed the results of computer experimental studies, as well as finite element method data. In the conditions of modelling osteosynthesis of unstable clavicle fractures 15.2AB, the strength characteristics of the compression rod were taken into account in comparison with the traditional intramedullary Bogdanov rod. Computer modelling analysed studies that used clavicle models created using the finite element method (FEM). These models made it possible to assess the distribution of stresses and deformations in the clavicle and fixing elements under different types of loads. Parameters such as maximum stress in the implant and bone, as well as interfragmentary displacement, were measured. Results. Biomechanical studies of osteosynthesis modelling of unstable clavicle fractures OTA 15.2AB showed the advantages of a compression rod compared to the traditional Bogdanov intramedullary rod in terms of the maximum load required for deformation, implant failure, as well as creating greater stability of clavicle osteosynthesis during its torsion and bending. Thus, the bending stiffness of the compression rod was 1.3-1.4 times higher, and the torsional stiffness was 1.3 times higher ($p < 0.05$). The load to deformation and destruction of the compressive rod was also 1.3–1.6 times higher ($p < 0.05$). The maximum displacement of clavicle fragments with the compressive rod was 0.7–0.8 times less compared to the Bogdanov rod. Conclusions. After osteosynthesis of unstable clavicle body fractures 15.2AB with a compressive rod, its strength characteristics have advantages over Bogdanov's rod in terms of deformation, implant destruction, and higher stability of clavicle fragments during bending and torsion due to a more uniform pressure distribution.

Мета. Вивчити ефективність остеосинтезу нестабільних переломів тіла ключиці типу 15.2AB компресійним стрижнем на основі біомеханічних досліджень. Методи. У межах комп'ютерного експерименту застосовано метод скінченних елементів (МСЕ). В умовах моделювання остеосинтезу нестабільних переломів тіла ключиці 15.2AB ураховувалися міцнісні характеристики компресійного стрижня порівняно з традиційним інтрамедулярним стрижнем Богданова. Тривимірні моделі ключиці й імплантатів, створені за допомогою цього методу, дали змогу проаналізувати розподіл внутрішніх напружень, деформацій, а також величину міжфрагментарного зміщення за різних типів навантажень. Результати. Біомеханічні дослідження моделювання остеосинтезу нестабільних переломів тіла ключиці OTA 15.2AB показали переваги компресійного стрижня порівняно з традиційним інтрамедулярним стрижнем Богданова в аспекті максимального навантаження, необхідного для деформації, руйнування імплантатів, а також створення більшої стабільності остеосинтезу ключиці в разі її торсії та вигину. Так, жорсткість на вигин компресійного стрижня була в 1,3–1,4 раза вищою, торсійна жорсткість — у 1,3 ($p < 0,05$). Навантаження до деформації і руйнування компресійного стрижня були також у 1,3–1,6 раза вищими ($p < 0,05$). Максимальне зміщення фрагментів ключиці в разі використання компресійного стрижня в 0,7–0,8 раза менше порівняно зі стрижнем Богданова. Висновки. Після остеосинтезу нестабільних переломів тіла ключиці 15.2AB компресійним стрижнем його міцнісні характеристики мають переваги над стрижнем Богданова щодо деформації, руйнування імплантата, також вищу стабільність фрагментів ключиці в разі вигину, торсії завдяки більш рівномірному розподілу тиску. Ключові слова. Біомеханічні дослідження, нестабільні переломи тіла ключиці, інтрамедулярні стрижні.

Keywords. Biomechanical studies, unstable clavicle fractures, intramedullary rods

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Introduction

The relevance of biomechanical studies evaluating the effectiveness of metal osteosynthesis (MOS) for unstable clavicular shaft fractures (UCSFs) is explained, on the one hand, by their high incidence, accounting for 70–80 % of all clavicular fractures [1], and, on the other hand, by the wide variety of available osteosynthesis techniques, including Kirschner wires, intramedullary nails, plates, screws, and external fixation devices. In recent years, surgical treatment of UCSFs has favored either plate osteosynthesis using a precontoured locking compression plate (LCP) or intramedullary fixation with nails of various designs [2, 3]. The choice of osteosynthesis technique is undoubtedly influenced by the fracture pattern itself. It is generally accepted that both methods can be successfully used for type 15.2AB fractures according to the AO/ASIF classification. However, in type 15.2C injuries (comminuted fractures), plate fixation is considered the preferred option [4].

Over the past five decades, various intramedullary nails have been used for the osteosynthesis of unstable clavicular shaft fractures, differing in their cross-sectional geometry: the Bogdanov nail with a rounded rectangular cross-section, the Kuntscher nail with a cloverleaf cross-section, the Rockwood compression nail with a round cross-section, the Rush nail with a hexagonal cross-section, and the Knowles compression nail with a rounded rectangular cross-section [5]. Elastic Stable Intramedullary Nailing (ESIN) with a titanium elastic nail has also become a widely used technique. This method can be performed as a minimally invasive closed osteosynthesis procedure, resulting in minimal trauma to both the soft tissues and the periosteum [6]. The most common complications of intramedullary osteosynthesis for unstable clavicular shaft fractures include skin perforation or irritation caused by the implant tip, implant migration, implant breakage, and subsequent impairment of the clavicle's reparative regeneration processes [7, 8].

The study of clavicular biomechanics is important both under physiological conditions and in the presence of fractures, as it provides insight into injury mechanisms and facilitates the development of effective surgical treatment methods, including the use of implants [9]. Biomechanically, intramedullary osteosynthesis is characterized by a load-sharing mechanism in which the nail transfers mechanical loads to the clavicle through contact with the endosteum. Maximum stresses occur at the endosteal surface, at the nail entry and exit points, near its ends, and potentially at the fracture site. Under axial loading, the maximum stresses in the clavicle may reach approximately 30–40 MPa, whereas stresses within the nail may reach approximately 250–300 MPa [10]. Therefore, the critical load-bearing capacity of the clavicle is an important parameter to consider during intramedullary osteosynthesis of unstable clavicular shaft fractures.

The *purpose* of this study was to evaluate, based on biomechanical investigations, the effectiveness of our newly developed compression intramedullary nail for the osteosynthesis of unstable clavicular shaft fractures of type 15.2AB.

Materials and Methods

Biomechanical analyses were conducted using clavicle computed tomography (CT) data.

In the design of our modified nail, compression between the clavicular fragments was achieved by tightening a compression nut onto the end of the nail protruding from the bone. At the same time, nail migration was prevented by a locking thread located at the opposite end of the nail beyond the drill hole. During biomechanical modeling, both the compression nail and the Bogdanov nail were subjected to different loading conditions, including axial loading (simulating compressive forces) and bending loads (simulating the forces generated during shoulder movement). The following parameters were evaluated: implant stiffness under bending, torsional stiffness, the load required to produce implant deformation, and the load required to cause implant failure.

Within the computer simulation, the finite element method (FEM) was employed. Three-dimensional models of the clavicle and the implants were created to evaluate the distribution of internal stresses (von Mises stress, VMS), strains, and interfragmentary displacement under different loading conditions. A schematic representation of the stages of the computer simulation is shown in Fig. 1.

Loads were applied to the model as forces and/or moments at physiologically relevant locations and in physiologically relevant directions to simulate different loading scenarios, including axial compression (400 and 700 N), three-point bending, torsion (5 Nm), and combined loading. Post-processing included visualization of the distribution of von Mises equivalent stress (σ < sub>vms < /sub>), maximum principal stresses and strains, and nodal displacements. The results obtained for the different clavicular fixation methods (the compression intramedullary nail and the Bogdanov nail) were compared under equivalent loading conditions. When a sufficient

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number of model variants were available, statistical analyses, including correlation and regression analyses, were performed to identify relationships between the applied loads and the resulting stresses and displacements.

Statistical analysis of the obtained data was performed using Student's t-test. The results were processed using the Riosat-4, Statustuen 8.0, and Microsoft Excel 2010 software packages.

Results

Biomechanical investigations of the critical loads acting on the implants (the Bogdanov nail and the compression intramedullary nail) and the clavicle under simulated metal osteosynthesis of unstable clavicular shaft fractures yielded the data presented in the Table.

The data presented in the Table indicate that the compression intramedullary nail demonstrated superior bending stiffness compared with the Bogdanov nail. Its critical bending stiffness ranged from 80 to 95 N/mm, whereas that of the Bogdanov nail ranged from 60 to 70 N/mm, representing a 1.3- to 1.4-fold increase ($p < 0.05$). Similarly, the compression nail exhibited greater torsional stiffness, ranging from 0.20 to 0.25 Nm/degree compared with 0.15 to 0.20 Nm/degree for the Bogdanov nail, corresponding to a 1.3-fold increase ($p < 0.05$). The load required to produce deformation of the compression nail ranged from 250 to 320 N, and the failure load ranged from 550 to 650 N, whereas the corresponding values for the Bogdanov nail were 200–250 N and 350–400 N, respectively, representing increases of 1.3 to 1.6 times ($p < 0.05$). The maximum stress at deformation during bending was 550–650 MPa for the compression nail and 500–600 MPa for the Bogdanov nail; however, this difference was not statistically significant. Under torsional loading, the maximum stress in the compression nail was 450–500 MPa, which was 20–30 % lower than that observed in the Bogdanov nail ($p < 0.05$). The maximum stress in the clavicle during bending was 45–55 MPa with the compression nail and 50–60 MPa with the Bogdanov nail, with no statistically significant difference between the groups. Interfragmentary displacement during bending measured 0.7–0.8 mm with the compression nail and 1.0–1.2 mm with the Bogdanov nail, repre-

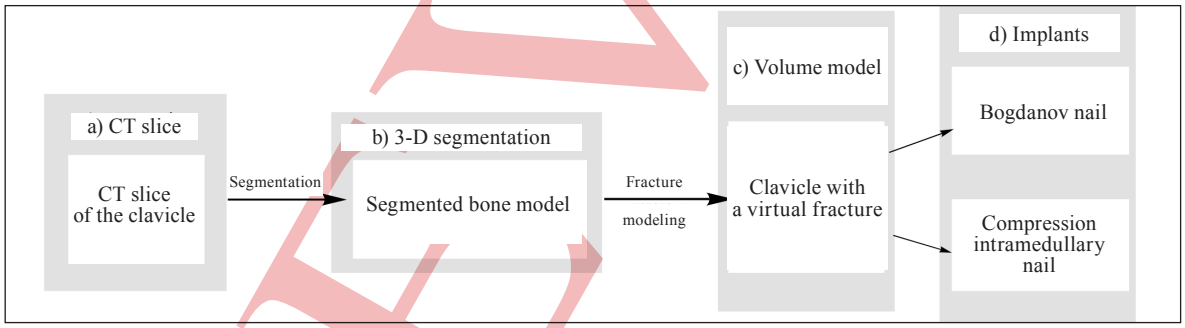


Fig. 1. Schematic representation of the stages of the computer simulation

Table

Biomechanical characteristics of critical loads on the compression intramedullary nail compared with the Bogdanov nail

Parameter	Nail		Ratio	p-value
	Bogdanov	compression intramedullary		
Stiffness – bending; – torsional	~ 60–70 N/mm ~ 0.15–0.20 N•m/degree	~ 80–95 N/mm ~ 0.20–0.25 N•m/degree	~ 1.3–1.4x ~ 1.3 x	< 0.05 < 0.05
Load, N: – to deformation; – to failure	~ 200–250 ~ 350–400	~ 250–320 ~ 550–650	~ 1.3 x ~ 1.6 x	< 0.05 < 0.02
Maximum VMS, MPa: – implant, bending; – implant, torsion; – bone, bending	~ 500–600 ~ 600–700 ~ 50–60	~ 550–650 ~ 450–500 ~ 45–55	~ 1.1 x ~ 0.7–0.8 x ~ 0.9 x	> 0.05 < 0.05 > 0.05
Maximum displacement, mm (bending)	~ 1.0–1.2	~ 0.7–0.8	~ 0.7–0.8 x	< 0.05

Note. The p-value was calculated when comparing loads between the compression intramedullary nail and the Bogdanov nail.

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senting a 20–30 % reduction with the compression nail ($p < 0.05$).

These findings demonstrate that the compression intramedullary nail possesses superior mechanical characteristics in terms of resistance to deformation and failure compared with the conventional Bogdanov nail. Furthermore, fixation with the compression nail provided greater clavicular stability during bending and torsional loading owing to a more uniform distribution of endosteal pressure.

Discussion

The clavicle is subjected to substantial and dynamically changing loads during everyday activities. As demonstrated by biomechanical computer models and in vivo measurements, axial forces in the middle third of the clavicle may reach 91–97 N during movements such as shoulder abduction and flexion. Compressive forces are considerably greater during shoulder abduction than during rotational movements. At rest, loading is substantially lower, ranging from 21 to 39 N, whereas during intense physical activity (in the absence of traumatic impact), axial loads may reach 701–999 N. Individual anatomical characteristics, particularly clavicular curvature (with greater medial curvature in males), also influence load distribution [11].

Determining the strength limit of the clavicle is of considerable importance. Experimental studies evaluating ultimate (failure) loads have demonstrated substantial variability, with the mean failure load under axial compression ranging from 1,524 to 2,800 ± 138 N. This variability is attributable to differences in age, sex, bone mineral density, and testing protocols. The critical load has been reported to range from 1,199 to 1,401 N.

Importantly, the S-shaped anatomy of the clavicle results in a combination of compressive and bending forces even under purely axial loading. This produces tensile stress on the anterosuperior surface and compressive stress on the posteroinferior surface, thereby contributing to the characteristic occurrence of fractures in the middle third of the clavicle.

The experimental biomechanical investigations conducted in this study to evaluate the mechanical properties of implants used for the fixation of unstable clavicular shaft fractures with the conventional Bogdanov nail and the compression intramedullary nail identified characteristic critical loading parameters, including bending and torsional stiffness, loads required to produce deformation and failure, stresses generated during bending and torsion of the implants, as well as the maximum stresses acting on the clavicle and the degree of interfragmentary displacement during bending.

Analysis of the biomechanical findings demonstrated that our modified compression intramedullary nail has advantages over the conventional intramedullary Bogdanov nail with respect to the mechanical properties of fixation for AO/ASIF type 15.2A,B unstable clavicular shaft fractures. Specifically, it withstood higher loads before implant deformation and failure and provided greater stability of the clavicular fragments during bending and torsional loading. Comparison of these biomechanical characteristics with those reported in the literature for precontoured locking compression plates (LCPs) indicates that the compression intramedullary nail provides comparable performance, although in some parameters it remains inferior to plate fixation [13].

Conclusions

Computer-based biomechanical modeling of osteosynthesis for AO/ASIF type 15.2AB unstable clavicular shaft fractures demonstrated that the proposed compression intramedullary nail possesses superior mechanical properties compared with the conventional Bogdanov nail. When the compression nail was used, implant bending stiffness, torsional stiffness, and the loads required to produce deformation and failure were 1.3 to 1.6 times higher ($p < 0.05$).

The design features of the proposed compression intramedullary nail for the osteosynthesis of AO/ASIF type 15.2A,B unstable clavicular shaft fractures, including a threaded drill tip and a compression mechanism, simplify the surgical technique by eliminating the need for reaming the medullary canal, reducing operative time, and allowing osteosynthesis to be performed using either an open or a closed approach. The results of the biomechanical investigations support the clinical use of the proposed compression intramedullary nail.

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Conflict of Interest. The authors declare that they have no conflict of interest.

Future Research. Further studies should focus on the clinical implementation of the proposed compression intramedullary nail for the osteosynthesis of AO/ASIF type 15.2AB unstable clavicular shaft fractures.

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Author Contributions. Hertsen H. I. — developed objectives and methodology of the study, and revised the manuscript and conclusions; Bilonozhkin H.H. — conducted the research and participated in the analysis of the results; Hapon O. M. —

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performed the biomechanical investigations, evaluated long-term outcomes and complications, prepared the manuscript, and conducted the literature review.

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RESULTS OF BIOMECHANICAL STUDIES OF THE EFFECTIVENESS OF OSTEOSYNTHESIS OF UNSTABLE FRACTURES OF THE CLAVICLE WITH A COMPRESSION ROD

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