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FINITE ELEMENT MODELING OF COMPOSITE BIOMECHANICAL STRUCTURES: ANALYSIS OF THE LUMBO-PELVIS AND CRANIAL-MAXILLOFACIAL COMPLEXES

The object of this study is human biomechanical systems in both normal and pathological conditions, focusing on the lumbo-pelvic and craniofacial complexes, including restorative structures such as miniplates, screws, and dental implants. The military actions caused by Russian aggression against Ukraine have prompted the development of more effective methods for injury treatment and rehabilitation.

This research proposes novel digital modelling methods for biomechanical systems that incorporate individual mechanical properties of biological tissues and enable a comprehensive stress-strain analysis under normal conditions, pathological changes, and post-reconstructive states. The study utilizes finite element analysis (FEA) and computer simulation, integrated with CT and MRI data, ensuring high accuracy in predicting the functional behaviour of biological tissues. The dominant biomechanical factors that help prevent mechanical overload of tissues and reduce the risk of complications have been identified. The study investigates the kinematic chain "lumbar spine – sacroiliac joint – pelvis", assessing the impact of pathological variations in lumbar lordosis and sacral inclination angle. For the craniofacial complex, the research examines the biomechanical conditions for successful osseointegration of miniplates, screws, and implants in jaw reconstruction.

The practical applications of the obtained results include orthopedics, traumatology, dentistry, and rehabilitation medicine. The proposed methods contribute to improving surgical planning accuracy, optimizing rehabilitation procedures, and developing durable implants adapted to the patient's anatomical features. This will help minimize the risk of complications and accelerate patient recovery.

Keywords: *biomechanical system modelling, finite element analysis, digital simulation, stress-strain state, osseointegration, kinematic analysis, computational biomechanics of biological tissues.*

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1. Introduction

The military actions caused by the Russian aggression against Ukraine prompted the creation of a perfect system of treatment of injuries to biological tissues of various human biomechanical systems with the diversity and complexity in geometric and physical terms as their most important feature. Modelling of biomechanical systems in different states allows to predict the functioning of biological tissues in the normal state and in the event of pathological changes and injuries, as well as to formulate recommendations for prescribing treatment, performing preventive measures and postoperative rehabilitation of patients. Biomechanical systems have a complex internal structure and shape, which greatly complicates experimental research and their analytical description. The materials of these systems – biological tissues – are complex composite heterogeneous structures with anisotropic properties, which are much more pronounced than for many traditional materials used in engineering. The study of the mechanical properties of biological tissues is much more difficult than the properties of traditional structural materials. In addition to mechanical factors, biological functions. should also be taken into account when testing biological specimens. In addition, experimental studies of specimens removed from the body (in vitro) allow to evaluate only the passive mechanical behavior, not the functional effect of the tissue in the body (in vivo). The uncertainty of diagnostic criteria for destruction of biological tissues leads to low efficiency of their rehabilitation with persistent pain syndrome, accompanied by prolonged disability and a decrease in the quality of life and social maladjustment of patients. One of the solutions to the problem of restoring pathologically altered bone tissue is to replace it with a biologically compatible reconstructive structure. The solution of these problems with a complex set of clinical and biological factors allows for an individual choice of reconstructive structure. The need to take into account the specific anatomical features of patients further deepens the significance of the problem, which is the need to create a favorable stress-strain state in both damaged tissues and adjacent tissues, as well as in restorative structures. All of the above determines the relevance of the field of biomechanics, dealing with the development of a methodology for simulating the stress-strain state and fracture of composite structures of human biomechanical systems, which will allow predicting the behavior of these systems during treatment and formulating practical recommendations for planning of the appropriate rehabilitation procedures.

The sacroiliac joints play an important role in the kinematic chain of the supporting skeleton "lumbar spine – sacrum – pelvis". About 85 %

of chronic lumbopelvic pain is associated with mechanical causes [1]. One of them is inadequate posture, which causes chronic harmful effects of overload and leads to adaptive changes in the system "lumbar spine – sacrum – pelvis". In the kinematic chain of the supporting skeleton, the sacrum, the sacroiliac joints and the surrounding ligaments are important links that transfer loads from the spine to the pelvis. Authors noted dysfunction of sacroiliac joints as a cause of pain in 30–50 % of cases [2]. The sacroiliac joint has a rotational mobility of approximately 4°. This allows optimizing the transfer of loads in the kinematic chain "spine – sacrum – pelvis". There are many papers devoted to studying the stress-strain state of the lumbar spine, the sacrum as a link in the structure of the pelvic ring, certain muscle groups and ligaments in the "lumbar spine – pelvis" stabilization system. The aim of study [3] was to investigate the biomechanical alterations of the lumbar spine segment under various loads by simulating six different lumbar spine movements. The stress analysis revealed a localized concentration pattern, predominantly located on the concave side of the scoliosis. Among the different loads, the intervertebral disc experienced higher stress levels during rotational movements compared to other load types, suggesting that the intervertebral disc is more susceptible to injury when exposed to rotational loads. However, the study is based on a single-patient model, which limits the generalizability of the results. The paper [4] provided a novel approach for the comprehensive validation of a lumbar finite element model. However, this study is limited to comparisons with in vitro data, which does not fully account for the complex in vivo loading conditions and the influence of ligaments characteristic of real patients. The paper [5] was focused on the validation of the base model under pure-moment, pure-compression and combined-compression-and-moment loadings. However, this study is limited to nominal geometry without accounting for patient-specific anatomical variations, which may affect the accuracy of biomechanical predictions in clinical applications. The authors of [6] developed five finite element models of the human lumbar spine. The modelling method introduced in this study can be used in modelling dysfunctional lumber spines such as disc degeneration and scoliosis. However, despite the development and validation of a finite element model of the lumbar spine for healthy subjects, the study does not account for inter-subject variations in tissue mechanical properties and does not test the model under pathological conditions, limiting its applicability in clinical scenarios. The aim of study [7] was to develop a discrete element model of the mechanical behavior of the L_4–L_5 spinal motion segment, which covered all the degeneration grades from healthy intervertebral disc to its severe degeneration. The modelling results indicate that during the early phases of degenerative changes, there is an observable increase in both the magnitude and extent of maximum compressive stresses within the disc. Conversely, during the later stages of disc degradation, a decline in intradiscal pressure and a repositioning of the maximum compressive stresses towards the dorsal direction are noted. However, the study does not account for the influence of adjacent spinal segments and the muscle-ligament apparatus, which may affect the accuracy of biomechanical predictions in real clinical conditions. The paper [8] compares spinal stability after two different minimally invasive techniques, the lateral lumbar interbody fusion and the transforaminal lumbar interbody fusion approaches. Two nonlinear three-dimensional finite element models of the L_4–L_5 functional spinal unit are subjected to the loads that usually act on the lumbar spine. However, it does not account for variations in the physiological condition of patients, such as degenerative disc changes, which may affect the accuracy of the predicted mechanical responses post-surgery. The paper [9] compares the differences in the biomechanical behavior between the healthy lumbar spine and different spine fixation at L_4–L_5 level. However, while the study combines finite element modeling with clinical follow-up to assess the biomechanical behavior of the lumbar spine after dynamic fixation, it does not account for the long-term effects of loading and potential changes in tissue structure, which may impact the accuracy of predicting implant effectiveness.

In contemporary maxillofacial traumatology, there is a tendency to increase the proportion of injuries of the maxillofacial region (from 3 to 8 %). Of these, 61–70 % occur in the mandible [10]. Fractures of the mandible are the most common, accounting for up to 80 % of all injuries to the bones of the facial skeleton, as this bone is more vulnerable one [11]. In case of trauma to the mandible, bone fragments are displaced. The displacement of bone fragments depends not only on the force of the traumatic factor and the vector of force application, but also on the force of contraction and the direction of traction of the muscles attached to the fragments [12]. Therefore, reliable fixation of the fragments with observance of the anatomical shape of the bone and taking into account the biomechanics of the musculoskeletal apparatus of the mandible is urgently needed. Modern medicine uses a huge arsenal of systems for osteosynthesis in the form of miniplates and screws made of titanium, which makes it possible to perform repositioning and fixation of bones of the skull of almost any complexity [13]. At the same time, the fixation system should provide both the necessary stiffness and strength and the natural distribution of stresses and deformations in the bone tissue, since the bone structure significantly depends on the mechanical loading conditions in which it is placed. In recent years, as opposed to the empirical approach, simulation computer modelling has been used to solve the problems related to the calculation of fixation systems in traumatology and maxillofacial surgery [14]. The aim of study [15] was to compare the stress distribution of magnesium alloy and titanium fracture fixation plates using different designs of fixation plates. The displacement of the fixation plates for all designs was less than 1 mm. The von Mises stress values for circular bar showed less stresses acting within the prosthesis compared to the straight plate with interval, and straight plate without interval. However, while the study employs three-dimensional finite element analysis to evaluate the mechanical behavior of magnesium and titanium plates, the model does not account for the complex anatomical variability of bone structures among patients, which may affect the accuracy of biomechanical predictions. The study presented in [16] focuses on the simulation of fractures occurring in various anatomical structures, including the human mandibular body, the sheep mandibular body, and the sheep mandibular diastema, all stabilized using clinically validated titanium miniplates and screws. The assumptions incorporated into the modeling process, including the simplification of anatomical structures may influence the accuracy of the predicted biomechanical conditions. These constraints highlight the necessity for additional validation of the model and a more comprehensive consideration of the variability in biological tissue properties. The objective of the research conducted in [17] was to evaluate and compare the stability of fracture fragments in the treatment of bilateral parasymphysis mandible fractures using miniplate fixation versus reconstruction plate fixation. The findings indicated that the miniplate fixation approach resulted in a comparatively smaller gap between bone fragments than the reconstruction plate, suggesting improved stabilization and enhanced conditions for the healing process. However, while the study employs finite element analysis to compare the stability of two types of plates in the fixation of bilateral parasymphysis mandible fractures, the model does not account for variations in the biomechanical properties of bone tissue among patients or the potential influence of different types of masticatory loading, which may affect the accuracy of the obtained results. The paper [18] presented a new approach for the design of a flexible miniplate for mandibular fractures, which combined simultaneous fracture reduction and fixation. The results indicate that the proposed design can support the fracture while inducing limited fracture displacement.

Dental implantation is one of the topical tasks of contemporary dentistry. The use of implants as artificial dental supports allows solving numerous problems of prosthetics for patients with partial and complete absence of teeth, thus improving the quality of life of patients [19]. Despite the close attention of clinicians to the problems of dental implantation, many questions remain open to date. In the field of dental dentistry, there has been a notable increase in the number of publications focused on investigating the stress-strain behavior of both prostheses and bone tissues in the context of their fixation [20]. This growth can be attributed to advancements in the tools that facilitate the tomographic monitoring of bone tissues, as well as the development of software packages for three-dimensional modelling of loaded bodies using the finite element method [21, 22]. The contemporary advancements in this research field focus on the examination of bone material models [23]. These studies analyze the impact of different material types on the stress-strain behavior of bones and prostheses [24]. Additionally, they investigate the shape of implants [25, 26] and explore new materials for manufacturing implants [27]. These objectives align with the requirement of ensuring the uniform stress-strain behavior in bone tissues [23], which is crucial for the primary stability of implants. Minimization of the load on bones provides favorable conditions for the rapid development of new bone tissue around the implant. Furthermore, analysis of the reviewed papers reveals a key condition for successful prosthetics: the maximum intensity of stresses in bone tissues should not surpass the ultimate strength of the bone tissue, which is influenced by its quality [23, 28]. Despite the significant amount of research in the field of biomechanical system modeling, most existing studies focus on general principles and results without adequately considering individual variations in the mechanical properties of tissues, which complicates model validation and their clinical application.

The application of computational modeling for stress-strain analysis has proven to be effective in various engineering domains, for example [29–31]. The adaptation of these methods to biomechanics allows for an accurate prediction of tissue behavior and implant performance [32]. Recent advancements in finite element modeling have demonstrated its effectiveness in analyzing the biomechanics systems [33, 34]. These studies emphasize the importance of integrating numerical simulations into medical research to enhance surgical planning and improve patient outcomes.

The aim of the study is to develop an effective computer-integrated technology for establishing individual patterns of behaviour of biological tissues and restorative structures of human biomechanical systems in normal and pathological changes based on simulation modelling, which will allow predicting the results of exposure to these systems during treatment and formulating practical recommendations for planning of the appropriate rehabilitation procedures.

To achieve this aim, the following objectives are accomplished:
– to develop methods for modeling human biomechanical systems, including the spine, sacroiliac joints, pelvis, and craniofacial system, using modern finite element analysis techniques;
– to analyze the distribution of stresses and strains in biological tissues and restorative structures under normal and pathological conditions;
– to identify biomechanical factors influencing the stabilization of biomechanical systems, including the spine and craniofacial region, to minimize mechanical overload of tissues.

2. Materials and Methods

To create the geometric model of the biomechanical system, data from computed tomography (CT) and magnetic resonance imaging (MRI) were used. CT scanning was performed using a Philips Brilliance 64 scanner (120 kV, 400 mA, slice thickness – 0.5 mm, matrix – 512×512 pixels), ensuring high-detail visualization of bone structures. MRI scanning was conducted to assess the condition of soft tissues and ligaments using a Siemens Magnetom Aera 1.5T scanner (T1- and T2-weighted imaging protocol, isotropic resolution – 0.8 mm). After image processing in the 3D Slicer software environment, the obtained models were exported in STL format for further segmentation.

The study examined two biomechanical systems: the kinematic system encompassing the "lumbar spine – sacroiliac joints – pelvis" and the "craniofacial system".

A computational model of the "lumbar spine – sacroiliac joints – pelvis", incorporating major ligaments, was developed based on CT and MRI scans from 20 and 10 patients, respectively. To construct a geometric representation of the sacroiliac joint, individual models of the vertebrae (L_I–L_V), sacrum (S_I–S_V) with the coccyx, and pelvic wings were first generated [35]. These models were derived from segmented slices of computed tomography scans of actual biomechanical structures. Intervertebral discs and articular cartilage were represented by disc-shaped elements positioned between the vertebrae and articular processes to replicate their physiological function. The cartilaginous tissue and the joint connecting the pelvic wing to the sacrum were modeled by incorporating a geometric structure that ensured the appropriate degrees of freedom for sacral movement relative to the pelvis (Fig. 1).

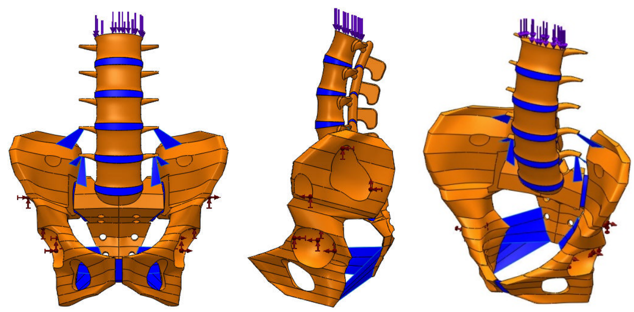


Fig. 1. Views of the generated loaded and fixed model of the lumbosacral region and sacroiliac joint including major ligaments in normal (SS=60°)

The simulation accounted for key ligaments responsible for rotational stabilization of the sacroiliac joint and the positional integrity of the lower lumbar segments and sacrum concerning the pelvis. These included the anterior sacroiliac, interosseous sacroiliac, posterior sacroiliac, sacrotuberous, and sacrospinous ligaments. Table 1 shows the accepted physical and mechanical characteristics of biological tissues [36].

Table 1

Mechanical characteristics of system "lumbar spine – sacroiliac joints – pelvis"

Biological tissues	Modulus of elasticity, MPa	Poisson's ratio
Cancellous bone	690	0.35
Cortical bone	6900	0.32
Intervertebral disc	50	0.35
Cartilage	50	0.35

The modeling process was conducted in several stages. During model construction, three variations of the cranial sacral slope (SS) were defined: SS=30°, SS=60°, and SS=85°, with corresponding lumbar lordosis values taken into account. The model was subjected to a compressive vertical force along the spinal axis at the upper vertebra (L_I), representing the weight of the body segment located above vertebra L_V (Fig. 1). According to [37], this load was set at 50 % of the total body weight.

To simulate realistic boundary conditions, the model was rigidly constrained at the surfaces of the pelvic wings, preventing any displacement. Two distinct loading conditions were considered for the lumbosacral region, based on an average human body weight of 80 kg: a 400 N and a 2,000 N force in the cranio-caudal direction, accounting for the pelvis's ability to absorb forces 5 to 10 times the body weight during walking. The model was firmly fixed at the pelvic wing surfaces to eliminate any unintended movement.

The morphology of the second biomechanical system, representing a restored mandible following a fracture, was analyzed using CT scans of an anonymized patient. Based on these scans, a simplified mandibular model was developed, reflecting the average anatomical dimensions of a human mandible. To ensure biomechanical accuracy, the fracture was assessed following AO guidelines and Champy's principles of osteosynthesis, which enabled the identification of ideal lines of osteosynthesis for internal fixation [38].

In this study, fracture stabilization was achieved using a titanium miniplate with a thickness of 1.25 mm (Fig. 2). The selected miniplate had a length of 27 mm between the axes of its outer holes and a width of 2.5 mm. A four-hole titanium miniplate was positioned on the superior aspect of the fracture, 4 mm from the alveolar crest, and secured using 2 mm screws. A second four-hole miniplate was attached to the lower border of the mandible with 10 mm screws. To maintain anatomical alignment and prevent occlusal disturbances, the miniplates were precisely adapted to the bone surface, ensuring perfect contact and preventing any displacement at the bone-implant interface. Load-sharing osteosynthesis was considered, with a firm fixation between the miniplates, screws, and bone, allowing for an accurate assessment of stress distribution along the bone and fixation system. The fracture line was modeled as an irregular surface without deep serrations to mimic real-world conditions.

Prior studies [17] indicate that the maximum bite force in healthy adult ranges between 300 and 400 N, though it significantly decreases during the fracture healing period. The bite force varies across different dental regions, with molar teeth experiencing the highest forces, while the incisor region bears the lowest. After six weeks of post-fracture healing, the expected bite forces are 57 N in the incisor region and 119 N in the molar region. In this study, a 120 N load was applied to the molar region to simulate functional conditions. The mandibular condyle was constrained in all three spatial directions to replicate the reaction forces at the temporomandibular joint, in accordance with prior studies [15, 17].

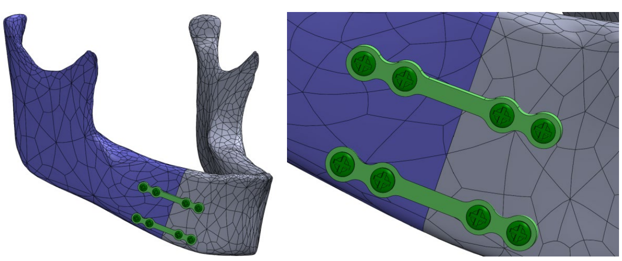


Fig. 2. Generated model of the mandible restored with miniplate

The interactions between the screws and the mandible, as well as between the screws and miniplates, were simulated as contact interfaces. Due to the presence of threads on the screws and the pretension applied during tightening, these contact interactions were deemed mechanically justified. Additionally, frictional contacts were defined between the fractured bone segments and between the miniplates and the mandible, with a coefficient of friction set at 0.3 to account for realistic mechanical constraints.

The study was conducted under the assumption of elastic material behavior for both the implant components and biological tissues. For computational simplicity, bone tissues were modeled as isotropic and homogeneous materials. The miniplates and osteosynthesis screws were composed of titanium, with their mechanical properties characterized by two fundamental material constants: Young's modulus and Poisson's ratio. The material property values used in the analysis were derived from established literature sources [39] and are presented in Table 2.

Table 2

Mechanical characteristics of the biological system "Mandible restored with miniplate"

Materials	Young modulus, GPa	Poisson's ratio
Cortical bone	13.70	0.30
Cancellous bone	1.37	0.30
Titanium	104.47	0.36

In the process of determination of parameters of the third biomechanical system, i. e. "screw implant – mandible segment", the data of computer-aided tomography were used as well. The dental implant serving as a support for the dental prosthesis consists of an artificial root made of medical titanium (supporting screw part) and an abutment connecting the support and crown part of the tooth (Fig. 3). The study with regard to regulation of the geometric parameters of implants is based on the open data of implant manufacturers; the geometric characteristics are shown in Table 3.

The maximum occlusal load in the study was taken equal to 300 N; the load was evenly applied over the upper part of the abutment. Based on the initial data, a finite element model describing the biomechanical system under consideration is synthesized (Fig. 3) [40].

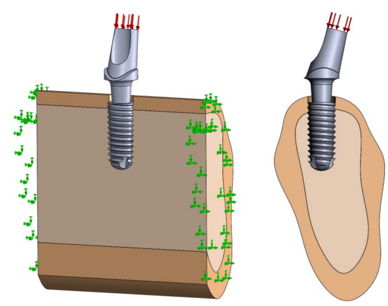
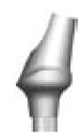


Fig. 3. Generated model of "screw implant – mandible segment" biomechanical system

Table 3

Adopted implant configurations

Threaded area (supporting part)			Abutment (upper part)			
Titanium implant	Diameter, mm	Length, mm	Aesthetic titanium abutment	Diameter of orthopedic profile, mm	Gum height	Crown slope angle
	3.4	10		5	3.5	0°
	4					
	4.6					15°
	4	8				
		10				23°
		12				

Numerical analysis of bone-implant models was conducted using FE software Solidworks Simulation (Dassault Systèmes SolidWorks Corporation, Waltham, MA, USA). The finite element mesh was generated using 10-node tetrahedral solid elements and 3-node triangular shell elements, which account for both bending and membrane properties. To evaluate the stress state of the bone, von Mises equivalent stress was selected as the primary measure, as it is widely used in biomechanical models to predict material behavior under complex loading conditions. To ensure modeling accuracy, a mesh convergence analysis was performed. The initial element size ranged from 3.0 mm to 0.05 mm, and the refinement process continued until the maximum von Mises equivalent stress variation remained within a 5 % threshold across all elements. The final mesh size ranged from 1.0 mm to 0.05 mm, allowing for detailed representation of critical stress regions.

Average size of the finite element mesh of the mandible restored with miniplate was set to 0.4 mm for cortical bone, 0.2 mm for screws and plates, 0.8 mm for cancellous bone and 0.1 mm on the surface of the holes. The total number of finite elements varied from 5,947,441 to 7,000,652, with node counts ranging from 8,470,111 to 10,695,410. A quality assessment of the finite element mesh revealed no critical errors, ensuring its reliability and accuracy for further analysis. The distribution patterns of equivalent strains and linear resultant displacements were used to analyze the deformability of the systems.

3. Results and Discussion

The visualization of von Mises equivalent stress and strain distribution within the lumbosacral region and sacroiliac joint model, incorporating key ligaments, is presented in Fig. 4–6. The non-deformed state of the model is depicted in translucent color, providing a clear contrast between the initial and stress-induced deformations. These illustrations highlight the localized stress concentrations and strain variations under different loading conditions, offering insights into the biomechanical response of the system.

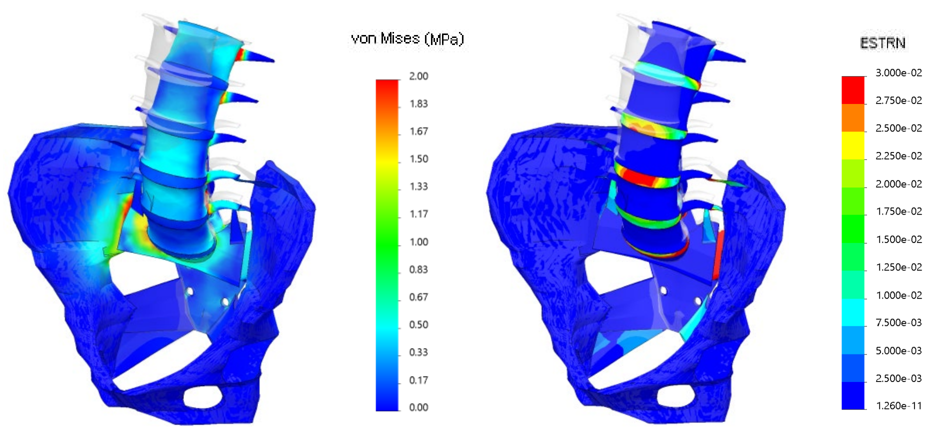
The findings indicate that the anterior sacroiliac, interosseous sacroiliac, posterior sacroiliac, sacrotuberous, and sacrospinous ligaments play a crucial role in restricting rotational movement within the sacroiliac joint across all tested sacral inclination angles. These ligaments effectively reduce strain and displacement throughout the "lumbar spine – sacrum – pelvis" system by facilitating load redistribution.

Under conditions of a physiological sacral inclination angle and normal lumbar lordosis, a uniform distribution of tensile stress was observed across all ligaments. However, as the vertical load increased, significant rises in tensile stress were noted within the iliolumbar ligaments, emphasizing their critical role in stress redistribution under physiological alignment conditions.

When the sacrum was in a vertical position with smoothed lordosis, the highest tensile stress concentrations were localized in both the cranial and caudal regions of the anterior sacroiliac ligaments and iliolumbar ligaments, regardless of the applied load. A similar stress distribution pattern persisted with increased loading.

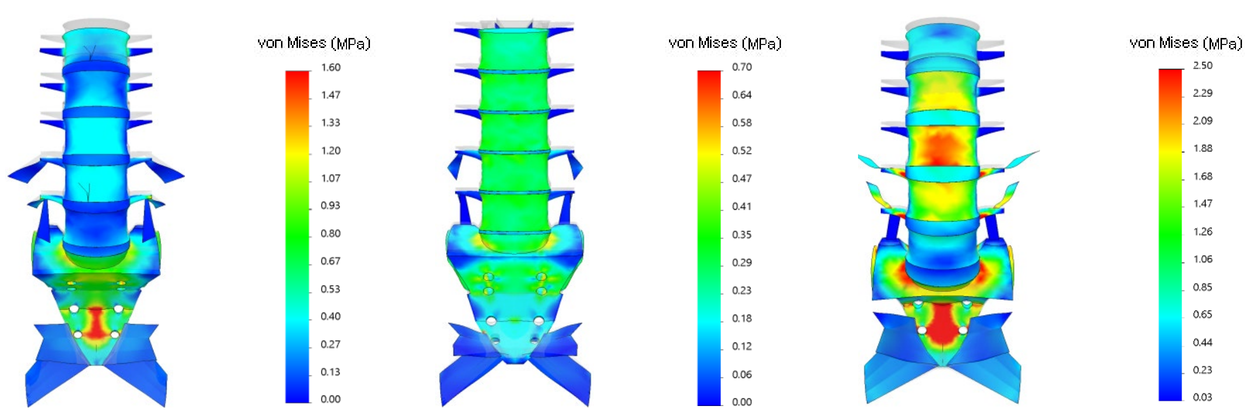
Conversely, in the horizontal sacral position associated with hyperlordosis, peak tensile stresses were primarily observed in the cranial portions of the ventral and dorsal sacroiliac ligaments, as well as within the iliolumbar and interosseous sacroiliac ligaments [35]. These results highlight the biomechanical significance of ligamentous structures in maintaining sacroiliac joint stability and mitigating excessive mechanical strain under varying spinal alignments.

For the second biomechanical system, representing the mandible restored after fracture, the findings demonstrated that the osteosynthesis system technology created optimal conditions for mandibular ridge healing under controlled functional loading. The analysis revealed that micromovements within the fixation system remained within a safe threshold, not exceeding 150 micrometers (Fig. 7). This threshold aligns with the criteria established by Perren [41], which define the limits of safe displacements necessary to facilitate effective bone healing while preventing excessive motion that could impair the regeneration process. These results confirm the stabilizing effectiveness of the fixation system in promoting successful post-fracture recovery under physiological loading conditions.



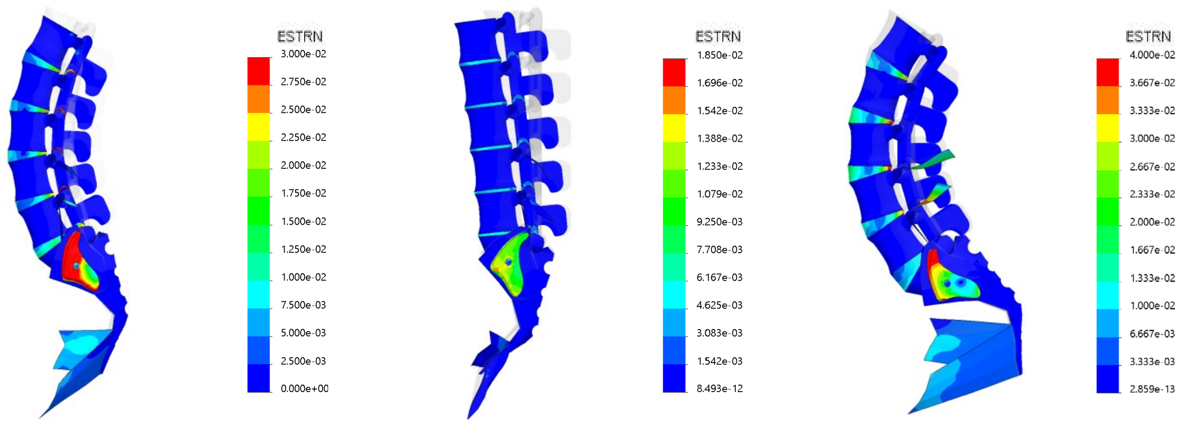
a *b*

Fig. 4. Illustration of von Mises equivalent stress and strains localization in the model of the lumbosacral region and sacroiliac joint in the presence of ligaments of SS=60°: *a* – von Mises; *b* – ESTRN



a *b* *c*

Fig. 5. Illustration of von Mises equivalent stress localization in cartilages of the sacroiliac-iliac joint of the model of the latter with the lumbar section with ligaments under the load P=400 N: *a* – physiological value of SS=60° normal physiological value of lumbar lordosis; *b* – vertical sacrum (SS=30° and smoothed lordosis); *c* – horizontal sacrum (SS=85° and hyperlordosis)



a *b* *c*

Fig. 6. Illustration of equivalent strain localization in cartilages of the sacroiliac-iliac joint of the model of the latter with the lumbar section with ligaments under the load P=400 N: *a* – physiological value of SS=60° normal physiological value of lumbar lordosis; *b* – vertical sacrum (SS=30° and smoothed lordosis); *c* – horizontal sacrum (SS=85° and hyperlordosis)

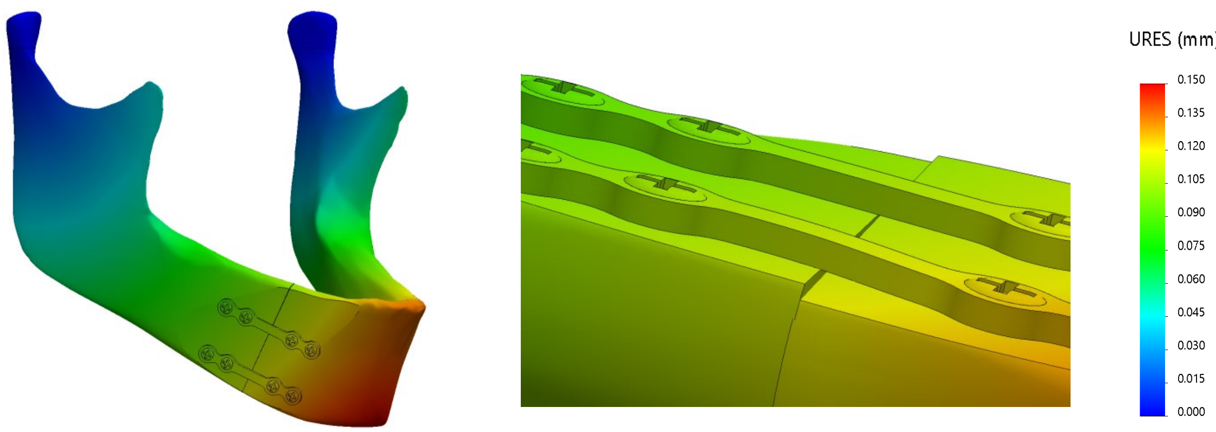


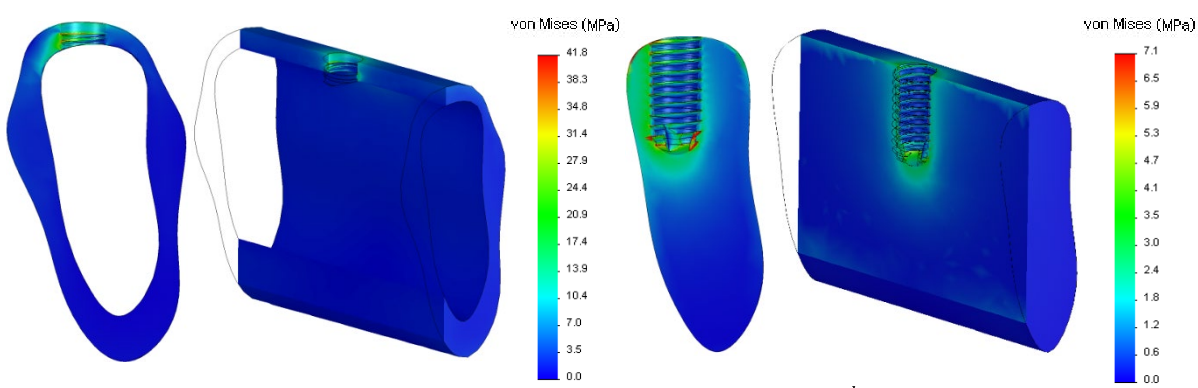
Fig. 7. Illustration of resulting displacement distribution of the mandible restored after fracture

The simulation results for the third biomechanical system ("screw implant – mandible segment") are illustrated in Fig. 8 and Table 4.

As a result of stress-state analysis, it is found that the most stressed element of the biomechanical system is the cancellous bone. For the considered implant configurations, the maximum equivalent stresses in this tissue correspond to the implant diameter of 4 mm, length of 8 mm and the angle of inclination of the aesthetic abutment 15°.

The study demonstrates the utility of simulation modeling and finite element analysis in advancing our understanding of the biomechanics of human systems under both normal and pathological conditions. The approach enabled precise predictions regarding stress-strain behavior, which is critical for optimizing the design of restorative structures and rehabilitation strategies.

The findings for the "lumbar spine – sacroiliac joint – pelvis" biomechanical system highlight the pivotal role of sacroiliac ligaments in load redistribution and stabilization. Notably, stress distribution patterns suggest that physiological lumbar lordosis provides a balanced tension in ligaments, whereas deviations from this alignment, such as hyperlordosis or smoothed lordosis, result in stress concentrations. These insights align with previous studies indicating that altered sacral angles exacerbate mechanical stress, increasing the risk of pain and dysfunction in the lumbopelvic region. These results underscore the importance of maintaining physiological lordosis during rehabilitation or surgical interventions.



a *b*

Fig. 8. Illustration of von Mises equivalent stress localization in:
a – cortical and *b* – cancellous bones of the model of "screw implant – mandible segment" biomechanical system

Table 4

Parameters of stress-strain state of the model of "screw implant – mandible segment" biomechanical system for the different geometrical parameters of the implant and abutment

Titanium implant		Abutment	Maximum von Mises equivalent stress, MPa		Maximum linear resultant displacements, mm
Diameter, mm	Length, mm	Crown slope angle	Cortical bone	Cancellous bone	
3.4	10	15°	62.6	8.2	0.0271
4.0			41.8	7.1	0.0279
4.6			29.7	6.0	0.0296
4.0	8	15°	42.2	9.0	0.0286
	10		41.8	7.1	0.0279
	12		42.6	7.5	0.0275
4.0	10	0°	35.7	7.7	0.0156
		15°	41.8	7.1	0.0279
		23°	61.2	7.0	0.0187

In the second biomechanical system, the study validated the performance of titanium mini-plate systems for mandibular fracture fixation. The safe micromotions observed during healing indicate that the osteosynthesis technique supports effective bone regeneration while avoiding excessive strain that might impede recovery. The findings resonate with the established thresholds of micromotion for successful fracture healing, as highlighted in previous literature. Moreover, the uniform stress distribution in miniplates and surrounding bone tissues under functional loads confirms their biomechanical suitability for clinical application.

For the "screw implant – mandible segment" system, variations in implant geometry demonstrated significant effects on stress-strain distribution. Implants with a diameter of 4.6 mm and length of 10 mm minimized stress concentrations in cortical and cancellous bone tissues. These configurations ensure adequate load distribution while maintaining bone integrity, crucial for osseointegration and long-term implant stability. The findings corroborate recent studies on the impact of implant geometry and abutment inclination on stress distribution and highlight the necessity of tailored implant designs for individual patients.

The study confirms the efficacy of integrating individual anatomical and mechanical characteristics into biomechanical models. By leveraging patient-specific data, clinicians can optimize treatment strategies, mitigate mechanical overload, and improve rehabilitation outcomes. Additionally, the findings highlight the role of finite element analysis as a non-invasive tool for pre-surgical planning and post-surgical evaluation.

Despite the obtained results and their alignment with widely accepted biomechanical concepts, this study has certain limitations:

– the numerical results were obtained using finite element analysis; however, they have not been directly verified through laboratory experiments or clinical trials. This limits their direct extrapolation to patients without additional confirmation;

– the study focuses on static or short-term dynamic loading conditions, whereas long-term effects, such as bone resorption or implant adaptation, remain beyond the scope of this analysis.

Considering these limitations, future research should include experimental validation, expansion of model individualization parameters, and investigation of the long-term biomechanical behavior of the studied structures.

Integrating these factors will further enhance the accuracy of biomechanical model predictions and their clinical applicability.

4. Conclusions

New effective methods for designing digital models of the various human biomechanical systems have been developed. The dominant biomechanical factors have been identified, which would help to avoid mechanical overloading of biological tissues and reduce the risk of complications in the treatment and rehabilitation of patients. The following biomechanical systems were considered: kinematic chain "lumbar spine – sacroiliac joint – pelvis" and "craniofacial system". The pathological state of the first biomechanical system was defined as different variants of lumbar lordosis and an angle of inclination of the cranial surface of the sacrum. Biomechanical conditions for successful individual osseointegration of such restorative elements as splints and screws in case of jaw fracture, as well as dental implants to support dentures with adjacent bone tissue, were studied on the example of the second system. An important advantage of the presented approach to solving the problem of rapid restoration of patients' health is the possibility of using individual mechanical properties of biological tissues in the numerical analysis of stress-strain of restored human biological tissues.

The results of this study confirm that the application of finite element analysis methods enables the assessment of biomechanical stability and identification of key parameters influencing treatment success.

1. Lumbo-Pelvic Complex:

– It was found that a sacral slope angle of >40° contributes to load redistribution, potentially increasing the risk of degenerative changes in the lumbar spine.

– The optimal range of lumbar lordosis for maintaining stability is 30–50°; values <30° lead to increased stress on intervertebral discs.

– In cases of pathological changes (e. g., hyperlordosis or lordosis flattening), pelvic positioning adjustments are crucial for even load distribution.

2. Craniofacial Complex:

– Biomechanical analysis revealed that a miniplate fixation angle within 20–30° ensures optimal stress distribution and minimizes the risk of screw instability.

– For mandibular reconstruction, using plates with a thickness of ≥2 mm significantly improves mechanical stability, particularly under masticatory forces >120 N.

– The axes of integrated implants should deviate no more than 15° from the orthogonal position to ensure even load distribution.

3. Practical Significance**:**

– The proposed approach allows for predicting the effects of anatomical and biomechanical parameter variations, which can be used for personalized planning of orthopedic, trauma, and dental interventions.

– The use of accurate numerical models in clinical practice will help reduce the risk of mechanical overload on implants and corrective structures, thereby improving rehabilitation success.

The obtained results may serve as a foundation for future studies focusing on model validation and the development of new clinical application guidelines.

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Conflict of interest

The author declares that he has no conflict of interest in relation to this research, whether financial, personal, author-ship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the current work.

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