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BIOMEDICAL IMAGING AND STRUCTURAL ASSESSMENT OF BONE TISSUE DURING OSSEOINTEGRATION

Olexandra Serdiuk, Nataliia Stelmakh
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
E-mail: alexandraserdyuk1@gmail.com, n.stelmakh@kpi.ua

This paper presents approaches to assessing bone tissue changes before and after application of osseointegrative prosthetics using modern information and measurement technologies. Particular attention is paid to a comprehensive analysis of the state of bone structures at different stages of osseointegration, which allows for a deeper understanding of the processes of tissue remodelling under the influence of implantation.

One of the key research tools is the use of high-resolution computed tomography data. Based on the obtained tomographic slices, three-dimensional (3D) models of bone structures are built using specialised software. These models provide a detailed visualisation of the anatomical features, spatial location of the implant and surrounding tissues, and allow for the analysis of morphological changes resulting from the osseointegration process.

In addition to the morphological assessment, mechanical testing of the bone tissue is carried out as part of the work. Loading methods are used to determine physical and mechanical characteristics such as strength, stiffness and elastic properties of the bone in the area of contact with the implant. This allows not only to detect structural changes but also to assess their impact on the functional capacity of the musculoskeletal system after prosthetics.

The results are combined into a single data set for comprehensive analysis. This approach allows us to objectively assess the effectiveness of the osseointegration process, identify potential risk areas for implant stability, and formulate recommendations for individualising prosthetic planning for each patient.

An important feature of the applied methodology is the possibility of early detection of pathological changes or unsatisfactory implant integration by monitoring the dynamics of morphometric and mechanical parameters in the postoperative period. This opens up prospects for improving the overall success of osseointegrative prosthetics and reducing the number of complications associated with implant instability or rejection.

Thus, the developed approach demonstrates high informative value and practical significance, providing a multilevel assessment of bone tissue condition, which is extremely important for ensuring long-term stability and functionality of osseointegrative prostheses in clinical practice.

Keywords: *osseointegration, computed tomography, 3D modelling, mechanical loads, bone tissue.*

Introduction

Due to the full-scale military operations in Ukraine, the number of people in need of prosthetics is increasing, both among military personnel and civilians. A significant number of combat wounds, explosive and gunshot injuries result in amputations, which leads to a growing need for modern rehabilitation methods. There is a wide range of upper and lower limb prostheses available, but traditional methods of fixation do not always provide sufficient functionality and comfort during use, especially in complex cases [1].

In situations where classical prosthetics does not give the desired results or significantly limits the patient's activity [2], the possibility of osseointegration of the appendicular skeleton is considered. During this operation, a metal implant is directly attached to the residual bone, after which the prosthetic structure is fixed through a special percutaneous connector, through a skin opening [3]. This technology allows for better control over the prosthesis, reduced pain from loading, and improved quality of life.

However, before performing osteointegrative surgery, it is necessary to critically assess the risks and justify the feasibility of its use in each individual case. This requires a thorough analysis of the condition of the residual bone tissue both before and after surgery. For this purpose, digital diagnostics and engineering analysis methods are actively used.

At the stage of preoperative preparation, key parameters are determined [4]: the thickness of the cortical layer of the bone, the length of the limb stump, and the presence or absence of inflammatory processes in the area of future implantation. The time factor is also important - the duration of the period after amputation or previous surgical interventions, which can affect the condition of the bone tissue.

The condition of the residual bone is subject to dynamic monitoring not only at the planning stage, but also during surgery and in the postoperative period. This allows us to detect possible complications in a timely manner and adjust the treatment tactics in a timely manner.

The individual anatomical features of the patient are taken into account when building 3D models, which allows for a personalised approach to prosthetics and significantly increases the effectiveness of treatment. The introduction of digital technologies opens up prospects for optimising the planning process and improving the results of osseointegrative prosthetics.

Analytical review of existing approaches to osseointegration analysis

In the relatively short period of its existence, two-stage osteointegrative limb prosthetics [5] has accumulated an empirical base that includes clinical results, biomechanical testing, in vitro studies, and computer modelling. This data contributes to a deeper understanding of osseointegration processes and improves prosthetic techniques.

Clinical observations of patients who have undergone osseointegration procedures have revealed both the benefits and potential risks of this method. In particular, it was noted that the functionality of prostheses improved and discomfort associated with traditional methods of attachment was reduced. However, there have also been cases of complications [6] such as infections and mechanical damage to implants, which underscores the need for careful patient selection and adherence to postoperative care protocols.

In their paper, Yan Li and Rickard Brånemark investigated the functionality and effectiveness of the Swedish osteointegrated prosthesis system OPRA (Osseointegrated Prostheses for the Rehabilitation of Amputees) [7], which was one of the first standardised solutions in this field. The system involves a two-stage surgical procedure that includes the placement of an intraosseous implant made of titanium, a material that is highly biocompatible and corrosion-resistant (Fig. 1). An important technical solution was the use of implants with a microtextured surface created by sandblasting or anodising. Such a surface increases the area of contact with bone tissue and stimulates osteoblastic activity, accelerating the process of osseointegration.

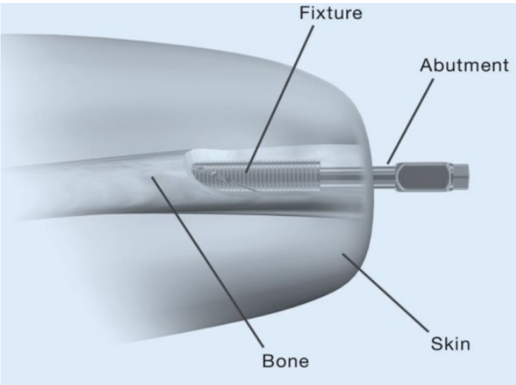

Figure 1. The main components of OPRA osseointegrative, extracted from [7, Fig. 2]

The researchers paid special attention to the mechanical stability of the connection between the implant, abutment and prosthesis, as this area is subject to the greatest stress during the patient's daily activities. They examined the behaviour of the system under axial compression, bending, shearing and torque, as well as under cyclic loading conditions that simulate the process of walking. The implant is fixed inside the tubular bone with a high degree of conformity, which minimises micromovements and reduces the risk of fibrous capsule development. Additionally, a taper lock connection is used between the abutment and the intramedullary part, which ensures tight mechanical fixation and even load distribution [8].

The material of construction - titanium alloy Ti6Al4V - was chosen because of its high strength and elastic modulus, which is close to bone tissue, which avoids local stress concentration at the implant-bone interface. Stresses in the peri-implant area were also analysed, taking into account geometric parameters and bone density. Despite the intensive mechanical use, the swedish single center study involving 51 patients with tranfemoral amputations showed a 92% stable implant engraftment rate over two years [9]. This emphasises not only the biological effectiveness of the design, but also its high reliability in long-term operation.

Thus, the works of Li and Brånemark demonstrates the importance of technical improvement of implants through the synergy of engineering solutions, material science and clinical practice. It has become the basis for further research in the field of biomechanical optimisation of osseointegrated prosthetic systems.

A more detailed biomechanical analysis of osteointegrated prosthetics of the lower extremities is presented in the work of Al Muderis et al. in which [10] the effectiveness of the Osseointegrated Prosthetic Limb (OPL) system was investigated - direct implantation of titanium pins into the femur or tibia with subsequent fixation of the prosthesis through the skin (Fig. 2).

Figure 2. X-ray image of the ILP implant system, extracted from [10, Fig. 1]

The approach is based on an axially oriented implant geometry that ensures direct load transfer along the limb axis, reducing bending moments and the risk of micromovements. The implants were made of titanium or titanium alloys with a porous or textured surface, which improved fixation in the bone bed and contributed to the formation of stable integration.

The study analysed 22 clinical cases in which both functional parameters (mobility scale, subjective pain score on the VAS scale) and technical parameters of implants were assessed, including: stability of fixation according to radiological signs (absence of lumen around the implant), presence or absence of backlash under load, analysis of axial and lateral load capacity, load tolerance during different phases of support during walking.

The authors paid special attention to the formalisation of technical success criteria, including: radiographically confirmed stability of the implant without signs of loosening, absence of backlash during dynamic loading, gradual reduction of pain according to the VAS scale, and preservation or improvement of the patient's ability to fully or partially load the operated limb. The proposed approach provided a comprehensive assessment of the long-term functionality of the implant, not only from a biological but also from an engineering point of view.

These results were an important step towards the formation of technical parameters of osteointegrated systems and confirmed the feasibility of using OPL as a stable and load-efficient structure for direct prosthetics.

A significant contribution to the understanding of the causes of technical failures of osteointegrated systems was made by Robinson et al. who [11] considered a clinical case of early mechanical instability of the implant in a patient with unilateral transfemoral amputation. The aim of the study was to identify the key factors that cause loosening or overloading of the implant in the early stages of operation. To do this, the team used three-dimensional kinematic modelling (3D motion analysis) combined with strain-gauge load monitoring directly on the abutment.

The results showed that in the support phase during the gait cycle, there was a local excess of the maximum permissible loads in the distal part of the implant (Fig. 3). This was especially true for the axial and bending force components, which were excessive in the case of improper distribution of the support moment or imperfect biomechanical alignment of the prosthesis. As a result of the strain gauge analysis, critical stress concentration zones were identified, where the first signs of implant loosening actually occurred..

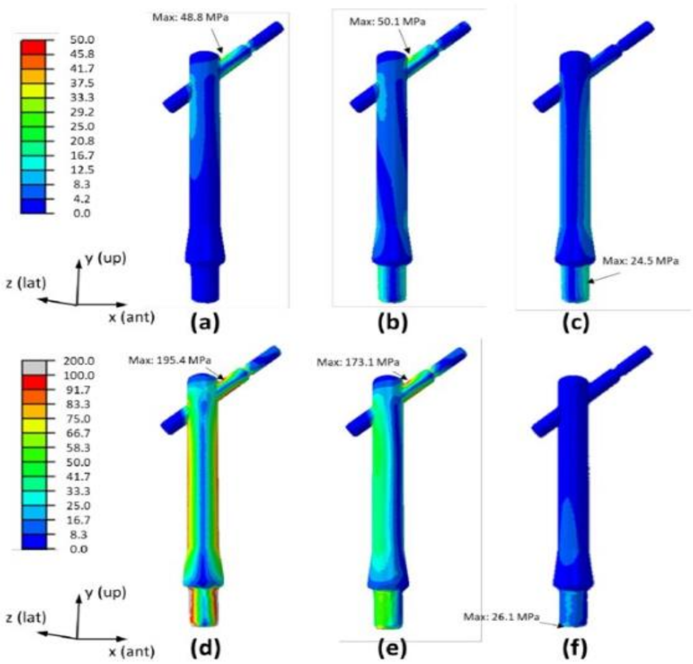

Figure 3. The osseointegrated implant experienced the highest loads at the interface between the intramedullary post and screw and the abutment during walking, extracted from [11, Fig. 5]

The use of computer modelling allowed not only to visualise the stress distribution, but also to predict the direction and degree of bone remodelling around the implant. This made it possible to draw conclusions about the need for an individualised approach to mechanical alignment and consideration of specific gait patterns in patients [12]. The study also demonstrated the value of using objective strain gauge-based sensory systems in real time [13] as a tool for early detection of potential points of mechanical failure.

These results highlighted the importance of monitoring the loading behaviour of osseointegrated implants, especially in the early stages of postoperative adaptation, and can be used as a basis for correcting prosthetic alignment, implant design, and developing adaptive walking training protocols

In the area of laboratory evaluation of implant stability, Galteri et al. proposed [14] a reliable in vitro methodology that allows quantifying the primary mechanical stability of osseointegrated implants at the implantation stage. The study was conducted on synthetic anatomically correct femoral models in which titanium pins were pre-implanted to simulate real clinical conditions. The implanted structures were subjected to cyclic vertical and axial loads in the range of 500-1000 N at a frequency of 1 Hz, which simulates typical loads during slow walking or standing (Fig. 4) .

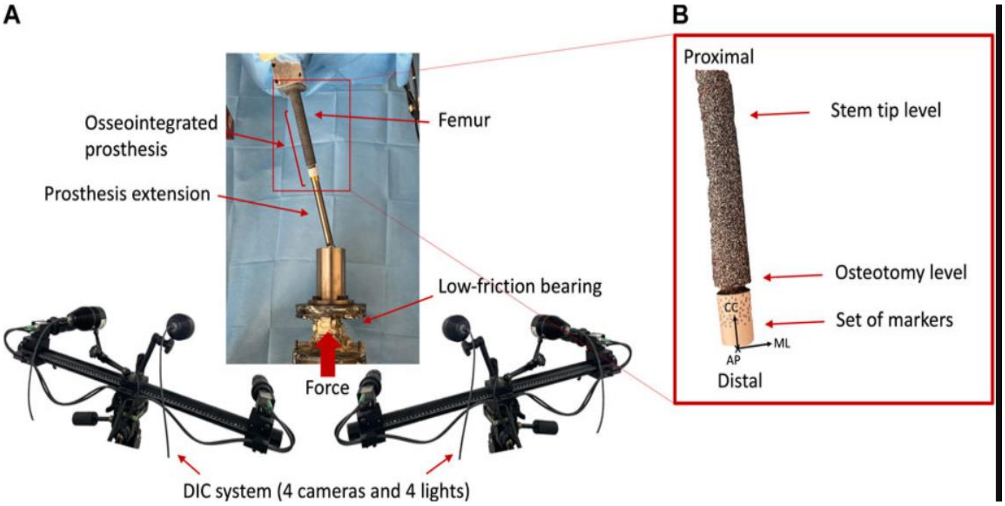

Figure 4. Primary stability assessment system, extracted from [14, Fig. 3]

A key element of the experiment was the use of the Digital Image Correlation (DIC) method, an optical technique that allows for non-contact measurement of microdeformations and displacements with a spatial resolution of up to 10 microns. This ensured extremely high accuracy in determining the level of micromovements between the implant and the bone bed, which is a critical indicator of primary fixation. Micromovements of more than 150 microns are considered clinically undesirable due to the risk of fibrous tissue formation instead of full integration.

The obtained results demonstrated high repeatability and stability of measurements, which allows the proposed approach to be used as a standardised tool for preliminary assessment of the stability of various implant designs prior to their clinical use. Accurate mapping of micromotion concentration zones allows for the improvement of implant geometry, including optimisation of surface properties or actual contact shapes. The methodology creates an engineering-based platform for testing osseointegrated structures that combines high accuracy with practical adaptability to different types of loading and can be effectively applied in basic research and at the stage of preclinical selection of prosthetic solutions.

For their part, El-Sheikh et al. used the Finite Element Analysis (FEA) method to study the biomechanics of the hip joint [15] under both static and dynamic loading, in particular in the stumbling phase, a situation that simulates short-term overload of the joint during loss of balance. To do this, the authors built a three-dimensional model of a hip joint with an implant based on computed tomography and implemented the simulation in Abaqus, one of the leading packages for nonlinear mechanical analysis (Fig. 5).

Particular attention was paid to the distribution of stresses in the articular surfaces at variable loading rates, reflecting different phases of movement - from slow movement to sharp impulsive changes characteristic of loss of balance. The model took into account the moments of inertia, mass-centre characteristics of the lower limb, as well as contact mechanics between the implant and bone tissue, which allowed for a more accurate assessment of the peak load zones. In particular, during stumbling, an increase in axial compression and bending moments in the root part of the implant was observed, which may be a key factor in mechanical failure or tissue remodelling.

A comparative analysis between static and dynamic models showed that dynamic loading significantly changes the location and amplitude of stresses, which is underestimated in traditional approaches. The authors' conclusions demonstrate the advantage of the dynamic approach to modelling osteointegrated structures, as it better reproduces real loading scenarios during patients' daily activities.

The functional load of osteointegrated implants was the subject of a study by Frossard et al. who conducted a quantitative analysis of the distribution of forces at the prosthesis attachment site in patients with transfemoral amputation during typical everyday activities such as walking [16], stair climbing, body weight bearing [17], and even falling [18]. For this purpose, strain gauges built into prosthetic components were used, as well as force plates, which allowed for high accuracy recording of the vertical and horizontal components of the support reaction force in real time.

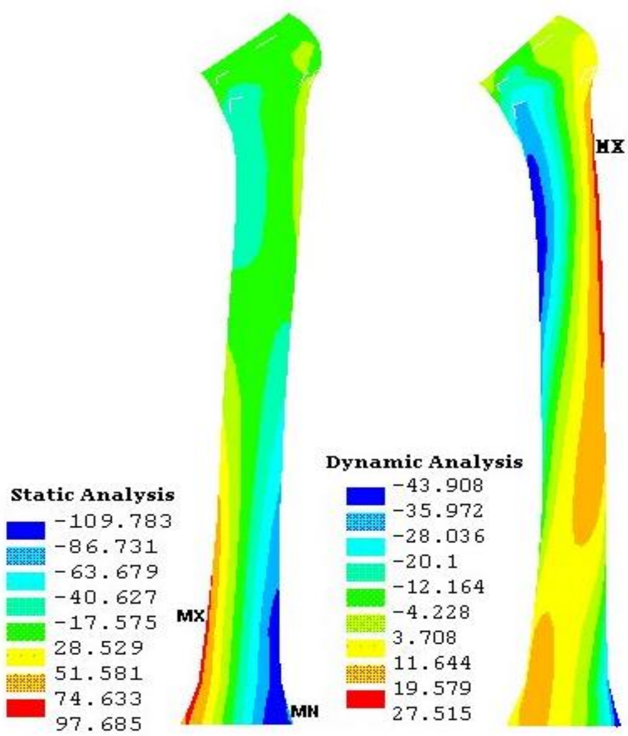

Figure 5. Estimation of the peak load of the femur during tripping, extracted from [15, Fig. 6]

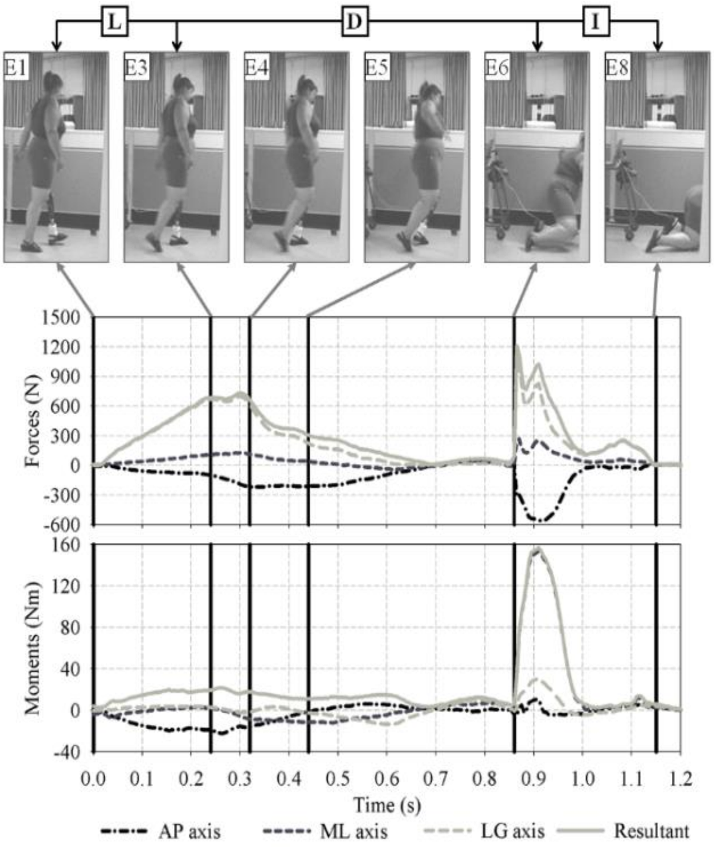

Figure 6. Overview of the resultant force (R) and the three components of forces and moments along the antero-posterior (AP), medio-lateral (ML) and longitudinal (LG) axes of fixation during the loading (L), descent (D) and impact (I) phases of a forward fall, defined according to the sequence of events, extracted from [19]

The authors analysed (Fig. 6) in detail the load dynamics in different phases of the gait cycle, which includes five main moments: the beginning of contact (heel strike), the transition to full support (midstance), the stabilisation period (terminal stance), toe-off and foot transfer (swing phase). At the beginning of the contact, the implant is subjected to a pulsed vertical impact load accompanied by a short-term force peak. In the full support phase, a stable axial load with a small bending moment occurs. During the stabilisation period, there is a gradual increase in the repulsive force, which turns into a sharp load at finger separation, when the horizontal component dominates. The transfer phase carries a minimal load, but is accompanied by moments of inertia, which can be critical in case of asymmetric gait or loss of balance.

It was found that the load on the implant is not uniform and fluctuates significantly during the cycle, with peak values in the root part of the implant during the transition from the middle support phase to the push phase. Such peak loads, especially in combination with bending moments, can create conditions for bone fatigue or osseointegration disorders.

The use of objective data on load distribution allowed the authors not only to describe the biomechanics of movement in patients with prostheses, but also to suggest areas for improving the geometry of implants, in particular: strengthening the root zone, modifying the shape of the implant neck to reduce bending moment, and adapting the contact area with bone tissue for better load distribution.

This approach emphasises the importance of taking into account real functional loads when designing osseointegrated systems and confirms the feasibility of integrating biomechanical monitoring into the process of clinical adaptation and technical improvement of implants.

Against the backdrop of studies that have already been conducted that confirm the effectiveness of the osseointegrative approach and outline the main methods for assessing implant stability, the clinical application of these approaches in the context of individual patient analysis is of particular importance. Given the variability of the course of osseointegration, the next stage of the study was the evaluation of a specific clinical case to identify the features of bone remodelling and adaptation of the implant to the patient's anatomy [20].

The results of the action-oriented research

As part of the practice-oriented analysis, the subject of the study was a patient who was at the stage of preparation for osseointegrative prosthetics after the completion of primary amputation, as well as after the second stage of implantation, the aim was to assess the structural adaptation of bone tissue to the implant in the dynamics, taking into account real clinical conditions.

The study was based on a sequential analysis of the patient's CT data (Fig. 7), which covered several time points - before implantation, immediately after it, and during the medium-term follow-up period. Particular attention was paid to morphometric and densitometric parameters: cortical layer thickness, spongy substance density, structural integrity of trabecular architecture and the presence of remodelling foci. Separately, signs of inflammatory or lytic changes that may indicate a complicated course of osseointegration were assessed.

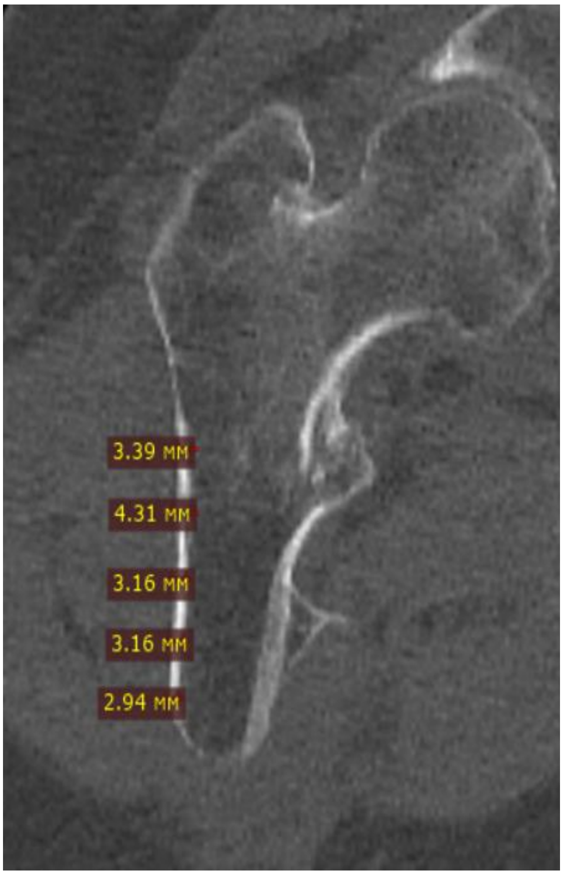

Figure 7. Assessment of the thickness of the cortical layer of the femoral stump at 1 cm intervals

The study revealed clinically significant signs of positive bone adaptation, in particular: increased osteogenesis in the area of contact with the implant, stabilisation of the spongy tissue structure and redistribution of the load, which is manifested in a change in the geometry of the supporting areas. These changes allow not only to record the fact of successful osseointegration, but also to predict the long-term stability of fixation.

To improve the accuracy of the analysis, modern digital modelling tools were used: 3D Slicer software environment for three-dimensional reconstruction of tomographic sections and segmentation of anatomical structures, ANSYS for numerical modelling of the stress-strain state in the implant root zone, as well as other visualisation tools for dynamic monitoring of tissue morphology changes.

Thus, it is obvious that an individual approach to patients increases the prognostic value of the assessment, allows for optimised planning of the load on the prosthesis and forms a more informed tactic for further treatment.

At the same time, it takes into account that the anatomical characteristics of the skeleton, tissue density, and the patient's clinical history can vary significantly, making each case unique. Therefore, effective treatment of a patient requires a thorough, personalised analysis of all morphological and functional parameters, without generalisations or simplified solutions.

Prospects for further development

Personalisation of approaches to osteo-integrative prosthetics, taking into account individual anatomical and functional characteristics of patients, is a key vector for further research. Standardised prosthetic techniques do not always achieve optimal results due to a wide range of variations in the morphology of limb stumps, bone tissue condition and functional capabilities of patients. Therefore, further development in this area is aimed at creating individualised protocols for diagnosis, modelling and planning of treatment and subsequent rehabilitation [21].

Conclusions

The development of osteointegrative prosthetics is an important component of modern medical rehabilitation, which requires the integration of accurate methods for assessing the condition of bone tissue at all stages of treatment. An integrated approach that combines the results of computed tomography, mechanical testing and numerical modelling allows for an objective analysis of the morphological and functional characteristics of bone, which is key to ensuring successful osseointegration.

The study highlights the importance of a systematic assessment of the quality of the residual bone before surgery, which includes both determining the density and thickness of bone tissue and identifying potential pathological processes in the implantation area. The use of digital technologies and engineering solutions can significantly expand diagnostic capabilities, improve planning accuracy and reduce the risk of complications in the postoperative period.

At the same time, the issue of further standardisation of diagnostic procedures and optimisation of methods for integrating data from various sources to create unified protocols for assessing and monitoring bone health remains relevant. Another important task is to ensure the availability of high-tech approaches in clinical practice and their adaptation to the conditions of the real medical environment.

Thus, the formation of a modern concept of bone tissue assessment before osteointegrative prosthetics requires further evolution of methods, their verification and widespread implementation in clinical practice to achieve the most effective and safe treatment results.

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Олександра Сердюк, Наталія Стельмах

Національного технічного університету України «Київський політехнічний інститут імені Ігоря Сікорського» Київ, Україна

БІОМЕДИЧНА ВІЗУАЛІЗАЦІЯ ТА СТРУКТУРНА ОЦІНКА КІСТКОВОЇ ТКАНИНИ ПРИ ОСТЕОІНТЕГРАЦІЇ

У даній роботі представлено підходи до оцінки змін кісткової тканини до та після остеоінтегративного протезування із застосуванням сучасних інформаційно-вимірювальних технологій. Особлива увага приділена комплексному аналізу стану кісткових структур на різних етапах остеоінтеграції, що дозволяє глибше зрозуміти процеси ремоделювання тканин під впливом імплантації.

Одним із ключових інструментів дослідження є використання даних комп'ютерної томографії високої роздільної здатності. На основі отриманих томографічних зрізів проводиться побудова тривимірних (3D) моделей кісткових структур із залученням спеціалізованого програмного забезпечення. Ці моделі забезпечують можливість детальної візуалізації анатомічних особливостей, просторового розташування імпланта та навколишніх тканин, а також дають змогу аналізувати морфологічні зміни, що виникають у результаті процесів остеоінтеграції.

Крім морфологічної оцінки, у рамках роботи здійснюються механічні випробування кісткової тканини. Застосовуються методи навантаження для визначення фізико-механічних характеристик, таких як міцність, жорсткість і пружні властивості кістки в ділянці контакту з імплантатом. Це дозволяє не лише виявити структурні зміни, але й оцінити їхній вплив на функціональну спроможність опорно-рухового апарату після протезування.

Отримані результати об'єднуються у єдиний масив даних для проведення комплексного аналізу. Такий підхід дозволяє об'єктивно оцінити ефективність процесу остеоінтеграції, виявити потенційні зони ризику порушення стабільності імпланта, а також сформувати рекомендації щодо індивідуалізації планування протезування для кожного пацієнта. Важливою особливістю застосованої методики є можливість раннього виявлення патологічних змін або незадовільної інтеграції імпланта шляхом моніторингу динаміки морфометричних і механічних параметрів у післяопераційний період. Це відкриває перспективи для підвищення загальної успішності остеоінтегративного протезування та зменшення кількості ускладнень, пов’язаних із нестабільністю або відторгненням імплантів.

Таким чином, розроблений підхід демонструє високу інформативність і практичну значущість, забезпечуючи багаторівневу оцінку стану кісткової тканини, що є надзвичайно важливою для забезпечення довгострокової стабільності та функціональності протезів у клінічній практиці.

Ключові слова: остеоінтеграція; комп’ютерна томографія; 3D-моделювання; механічні навантаження; кісткова тканина.

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