American Journal of Medicine and Medical Sciences 2025, 15(10): 3649-3654
DOI: 10.5923/j.ajmms.20251510.78

Role of Biomechanical Influencing Factors During Dental Implantation

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Abstract For this purpose, various methods of reconstructive interventions are used, the result of which should be an increased or restored bone volume necessary for optimal positioning and full functioning of the implants, based on their number and size, as well as the possibility of correcting the condition of mobile and immobile soft tissues in the implantation area. This article is devoted to a critical analysis of modern methods of implantological treatment in complex anatomical conditions that have developed due to significant bone atrophy.

Keywords Atrophy, Dental implantation, Osteoplastic materials, Resorption, Subcostal implants

1. Introduction

Dental implantation is the most popular and optimal method of treating adentia and has various variations of clinical protocols and design designs that have a specific field of application. Along with the wide variability in the use of this method of eliminating dental defects, dental implantation is a rather complex process, the final result of which depends on a number of factors. These factors have been studied for several decades and have become the basis for various concepts and protocols. The structural features of dental implants have a direct impact on the success of implantological treatment in terms of ensuring effective distribution of the chewing load from the orthopedic structure to the bone. With the advent of methods for modeling the implant–bone system and the creation of mathematical models reflecting stress-strain states, the process of studying the physical and biomechanical characteristics of implants of various designs has become simpler and more efficient in terms of the accuracy of the results obtained [1,3,4]. This review of the scientific literature is devoted to the analysis of biomechanical factors determining the success of dental implantation, as well as various concepts for their study. The review material includes journal articles from clinical and experimental studies of scientific databases Scopus, Web of Science, elibrary, etc., devoted to the study of the above-mentioned issues of dental implantation. Biological factors will include the biocompatibility of the material, the condition of the bone tissue in the field of implantation, and the high professional level of surgical techniques. The group of biomechanical factors includes the design of the implant, the quality of the implant surface, and the operating load conditions. A complex complex of interrelated processes occurring at the interface between the implant surface and bone tissue requires an approach that takes into account a set of indicators [2,5]. Considerable attention was paid to the search for structural elements of the implant that would mitigate the load on the bone. This effect has been used in a number of designs, for example, in IMZ implants-intramobile elements as a shock absorber, the effectiveness of which has been confirmed in clinical studies and experimental modeling of various other elastic compounds and structures with "shape memory" made of titanium nickelide, imitating periodontitis [6]. However, in real conditions, only the functioning of the implant as part of a single biomechanical system with surrounding bone tissue provides an effective result as a supporting element of the dentition with minimal risk of pathological bone resorption [7,9,20]. The principle of a multimodal approach to implant selection, laid down by L. Linkow and G. Muratori in the 80s of the twentieth century, set the task of improving various implant designs, increasing their functional and biological properties. The nature of the implant integration depends on the processes occurring at the implant–bone interface during the entire duration of the implant's functioning [5,10].

The condition 4-6 months after loading of the implant is called functional osseointegration and fibroosteointegration. In the case of the application of traumatic forces exceeding the endurance limit of bone tissue, loss of integration occurs. M. Quirynen identified excessive stress as a fundamental factor leading to bone resorption and implant loss. J.V. Brunsky identified a group of factors affecting the result of dental implantation: magnitude; direction and point of application of the load; number, tilt and position of teeth; geometry of implants, type and material of the prosthesis; the

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Received: Sep. 29, 2025; Accepted: Oct. 23, 2025; Published: Oct. 31, 2025

nature of the implant – bone tissue coupling; properties of bone tissue. Along with the influence of many systemic and local factors on the reparative processes in bone tissue, the biomechanical effect of loads is fundamental. There are 3 components that determine the development of bone morphology: the genetic program, hormonal activity, and stress conditions [8]. When the force is applied within the average value typical for this type of bone, the process of bone formation and resorption will proceed evenly. The bone tissue surrounding the implant undergoes repeated remodeling to a lamellar configuration, providing support for the implant throughout its entire life. Extreme loads cause bone resorption [2]. There is a certain level of mechanical stress, which is physiological for the structural units of the bone. It provides a controlling effect and is the basis of vital activity of bone tissue and bone organ. A decrease in mechanical stress in bone tissue causes its atrophy and osteoporosis; an increase leads to disruption of the process of physiological regeneration of bone, resulting in its destruction. Thus, a decrease and increase in mechanical stress in bone tissue relative to physiological stress are disturbing effects that can initiate irreversible pathological changes in the bone organ and lead to its regressive transformation. The analysis of bone tissue architectonics allows not only to predict the results of implantation, but also to plan the choice of an implant and the procedure of surgery, taking into account the nature of the adentia and the intended design of the prosthesis. Preferably, the implant is surrounded by viable bone with a thickness of 1.0 mm. The main requirements for the shape of the implant are: convenience during installation at the surgical stage and ensuring the necessary strength and aesthetics during prosthetics. At the same time, the intraosseous part of the implant should contribute to the uniform transfer of acting loads to the bone, eliminating the concentration of stress stresses in the interface [11]. An implant located in the bone tissue and exposed to cyclic chewing loads will cause deformation and, consequently, stress in the surrounding bone tissue. Bone tissue, like any material body, has certain strength and elastic properties. It is known that the modulus of elasticity (Young's modulus) of compact bone is 1.5-104 N/mm2, the Poisson's ratio is 0.3, and the spongy tissue is 1.5-10 N/mm2 and 0.3, respectively. The ultimate strength (maximum possible developing stresses) of a compact bone is 10 N/mm2, and that of a spongy bone is 5 N/mm2. Thus, the strength and modulus of elasticity of the compact bone layer are significantly higher than the similar parameters of the spongy layer. Therefore, the stress levels in the bone layers surrounding the implant will vary. According to V.A. Zagorsky (2013), obtained during a mathematical experiment, the maximum destructive stress value for a cortical plate does not exceed 40-80 MPa, for a spongy layer – 3-15 MPa, for a titanium implant – 400-600 MPa [3]. The successful functioning of dental implants largely depends on the type of occlusal surface of the structure, the biomechanical compatibility of the material from which the implant is made with the tissues of the body, and the degree of its primary stabilization in the bone. In the case of irrational treatment of dental row defects using dental implants, the stress in the bone surrounding the implant may exceed that in the area of natural teeth, which contributes not only to bone resorption around the implant, but can also provoke fracture of bone structural units at a stress value above their strength limit. It is possible to conditionally distinguish two stages or phases of transfer and distribution of functional load during the functioning of an orthopedic structure based on an intraosseous implant. At the first stage, the chewing load is transferred through the denture structure to the dental implant. The second stage is the transfer and distribution of forces through the implant to the surrounding bone tissue. Exceeding the permissible stress limits at the second stage leads to the destruction of the supporting biological tissues surrounding the implant and, as a result, to a violation of the chewing function. To ensure a dynamically balanced biomechanical situation and create the most favorable conditions for the functioning of the implantation and prosthetic structure, it is necessary to study in detail the stress-strain state of the supporting tissues of the dental implant insertion zone [2,3]. Increasing the functional load optimizes the amount of bioelectric potentials of bone, enhances the hydrodynamic effect of elastic deformations of bone structural units on microcirculation and trophism of endosteal tissues. Static-dynamic loads on the bone are usually accompanied by activation of perio- and endosteal bone formation.

Structural restructuring of the bone with an increase in functional load is compensatory osteogenesis; if the increased load on the bone alternates with sufficient rest, it manages to rebuild and adapt to new conditions. However, the bone, like any other organ of the human body, has the maximum limit of its functional capabilities. With an increase in the permissible level of physical activity (more than 3,000 cycles of microstrain of structural units per day), the elements of bone tissue are subjected to excessive stress, resulting in resorption. At the moments of an obvious discrepancy between the magnitude of the local load and the anatomical structure and degree of development of the structural units of the bone, pathological restructuring may begin, which is essentially a disease of breakdown, temporary insufficiency, and decompensation of the bone. A key factor in the pathological restructuring is a violation of blood circulation and microcirculation in the area of excessive mechanical stress. Bone tissue is unable to withstand such physiological loads, which leads to bone resorption and the occurrence of peri-implantitis. According to scientific sources, currently the number of periimplantations, including traumatic ones caused by overload, reaches 15%. The greatest risk of peri-implantitis occurs during the loading period of the implant. Moreover, low-density bone is more at risk of resorption, therefore, when using a two-stage implantation technique, this moment falls on stage 2. According to Hansson S. (2011), a dental implant should be modeled in such a way that the bone can receive positive mechanical stimulation. Currently, the search for the optimal implant design is primarily carried out analytically. For this purpose, computer programs for two- and three-dimensional mathematical modeling are used. Such studies, taking into account the biomechanical characteristics of the bone, implant, and prosthetic structure, make it possible to reproduce various situations and obtain data to compare stress levels, compression, and grip forces inside and around the implant. Therefore, when designing the structure, the main attention is paid to the geometry of the intraosseous part: the base should be of the correct shape for ease of installation and the most accurate match to the profile of the bone bed, with ledges and other surface macrodesign elements that increase the area of the contact surface; and the holes should be sufficient for bone tissue to germinate. Of no small importance in the design of dental implants is the surface structure, which directly affects the ability of the elements of the biotechnical system "denture – implant – bone tissue" to interact. An analysis of the conducted studies has shown that for the optimal course of the osseointegration process, the surface must be microstructural, and in the form of hemispherical surface pores with a depth of 1.5 to 4 microns in diameter. Porous implants combined with a textured surface provide the most resistance when performing a twist test. The reliability of primary fixation is one of the fundamental factors for the success of implantation. However, studies show that with a smooth neck, there is a risk of underloading the bone and high stresses in the cortical layer. Therefore, in systems of intraosseous screw implants, it is advisable to create micro-threads in the neck area, which promotes good retention in the bone in combination with high axial strength and bearing capacity, and also relieves stress in the cortical bone; at the same time, a coarser apical thread provides good primary stability. This idea is implemented in the implants of the AstraTech system [12]. Artificial restoration of the dentition using a non-removable prosthesis supported by implants functionally suits the patient and gives sensations close to those in the oral cavity in the presence of an intact dentition. At the same time, the problem of maintaining a stable balance in the "prosthesis–implant – bone tissue" system remains relevant. Studying the effects of stress on bone through implants helps to solve many problems in prosthetics of patients. The main task of planning treatment using intraosseous implants is to determine the implant size. The type and size of the implant is usually selected based on an analysis of the thickness and height of the alveolar processes. There is a formula for calculating the number of cylindrical implants required to repair dental defects without using teeth bordering the defect as denture supports: (X – 1 mm): 7 = N, where X is the width of the defect, and N is the number of implants. It is also quite justified in a clinical situation to use the principle of "implantation isotopy" – the number of implants should be equal to the number of missing teeth. The geometric rules of implant placement must be taken into account.: - if the load on the bone tissue surrounding two implants installed and located at the edges of a bridge-like prosthesis consisting of two premolars and one molar is taken as 100%, then increasing the number of implants to three reduces the pressure on the bone to 67%; - when installing implants in the shape of a triangle, the resistance of the structure to transversal loads increases and the pressure on the jaw bone tissue decreases to 33%; - the presence of a cantilever element in the structure increases the pressure by 100% [13,15]. At the same time, in order to predict the results of treatment, it is also necessary to take into account the bone architecture, which is one of the most significant factors determining the effectiveness of implantation. Of particular interest for the study is the correspondence of the type of bone tissue to the units of density on the Hounsfield scale, determined using computed tomography. For successful functioning, a prosthesis as a biomechanical system must ensure that the chewing load is redistributed to the supporting tissues of the oral cavity in such a way as to maintain their normal function. Prevention of the occurrence of areas of increased stress in the tissues of the prosthetic bed is essential for predicting the results of prosthetics. Biomechanical research involves the stages of mathematical modeling of the bone structure in the area of implants of the selected type and determining the amount of physiological stress in the areas of the denture supports [14]. A mathematical model of the functioning of a prosthesis based on implants and oral tissues makes it possible to determine the necessary types of implants and their number for each individual patient by calculations, taking into account the anatomical and topographic structure of the implantation zone and its biomechanical characteristics. The use of mathematical modeling makes it possible, when using implants and dentures, to analyze the magnitude and direction of the acting force, biomechanical compatibility, and determine the concentration of stresses arising from stress in the surrounding bone tissue. Numerous studies have established the necessary requirements for intraosseous implants – the surface of the implant must be rough or microporous. The roughness creates a connection between the tissue and the implant and prevents rejection. Implants with a rough surface strengthen better in the bone and are less affected by the forces acting on it. Examination of the intraosseous part of an implant with a porous surface using the finite element method on a flat model showed that the correct choice of material properties plays an important role in the uniform distribution of stresses in the periimplant tissue, and in the case of bone germination into the pores of the intraosseous part of the implant, the physiological stress distribution is determined. Primary stability is increased by increasing friction during the installation of the structure, therefore, the design of the implant surface is currently developing along the path of increasing its area and texture. As the implant functions, the bone structures are reorganized into structures with haverslike channels under the influence of functional load.

With an increase in the area of contact between the bone and the implant, the biomechanical parameters of the bone–implant system improve. Bone tissue has elastic-plastic properties, and the long-term functioning of the implant depends on the physical and mechanical properties of the material from which it is made, as well as the shape of the intraosseous part of the implant. Implants that are similar in shape to a cylinder and have a porous surface best distribute functional loads on adjacent bone tissue. The stress distribution in the bone, according to photoelastic modeling, around such implants is characterized by optimal uniformity and magnitude. Due to the different malleability of the surrounding tissues in the area of intraosseous implants and natural teeth, it can be argued that most of the load is transferred to the implant. On the bone of the alveoli surrounding the tooth, the load is distributed more evenly due to the shock-absorbing property of the periodontium. At the same time, the load is transmitted rigidly in the implant insertion area, which can cause bone overload and subsequent bone resorption. Evidence has been obtained that due to the lack of a periodontal shock-absorbing function, occlusive forces acting on the head of the intraosseous implant are transmitted directly to the bone bed. Mathematical modeling and analysis of the stress-strain state make it possible to compare the processes in the "prosthesis – implant – bone tissue" system with the natural dentition. When considering the load on a non-removable bridge-like prosthesis with implant supports, it was found that the greatest stress values in the bone tissue are observed in the lateral supports, whereas in the intact dentition they occur directly in the area of application of the load. The maximum stress values in the model of the natural dentition are determined in the spongy bone, and in the case of prosthetics on implants – in the cortical, and the stress values in the model with a prosthetic structure are twice as high as in the intact dentition. The dependence of stress fields on the size of the compact bone layer has been studied for two models with constant loads and elastic bone parameters. It was planned to reduce the thickness of the compact bone layer from 1.5 mm to 0.75 mm. In this case, the permissible vertical force decreased slightly. The main changes concerned the amount of permissible horizontal force. Even the minimum length of the implant significantly exceeds the thickness of the cortical bone layer, through which the main load from the implant is transferred to the bone tissue. For this reason, increasing the length of the implant did not lead to such a noticeable decrease in stress levels. The thickness of the cortical layer, the geometry of the layer, and the integral density of bone tissue have a more significant effect on the amount of permissible load. When choosing the length of the implant, first of all, data on the structure and distribution of bone density should be taken into account. Developments are underway to create a new generation of implants, for example, with a through, porous structure that allows bone to "grow" into implants, and the keratinized mucous membrane in the cervical part of the abutment to form an artificial circular ligament, the so-called periimplant cuff [16,17,19].

Subcostal implants were used for non-removable orthopedic rehabilitation of patients with partial adentia and severe bone loss. The use of periosteal implants, first used by Dahl in the 40s of the last century, has recently expanded with the development of imaging and manufacturing technologies. Today, they are being developed digitally and produced by 3D laser milling, which ensures fast and effective treatment of patients with severe bone deficiency. Due to their structural features, subosseous implants exhibit different biomechanical properties and the process of studying them requires a radically different approach. Modern manufacturing technologies ensure biocompatibility with bone, and stability is enhanced by installing screws and fixing under local anesthesia. In the process of studying the scientific literature, a number of experimental and clinical studies on this issue were analyzed [18]. The study by Abdulsamet Kundakcioglu and Mustafa Ayhan (2024) determined the minimum thickness of the periosteal implants capable of withstanding physiological stress. The authors created a digital averaged bone structure based on real patient data and developed various subcostal implants with a material thickness of 1, 1.5 and 2 mm for this digital model. The developed implant models were subjected to a force of 250 N, and the load, its transmission mechanism, and mechanical strength were studied using finite element analysis, taking into account the physical parameters of the implant material and bone. The results demonstrated that, with certain design parameters, the 1 mm thick structure could not withstand the load due to exceeding the yield strength of 415 MPa at a value of 495.44 MPa. The thinnest implant showed plastic deformation and transmitted excessive forces, which can cause bone resorption due to residual stress [15]. The study measured the residual forces and Von Mises force on implants at an occlusal load of 250 N, the amount of displacement and residual stresses in the bone. The equivalent stress value of 415 MPa was exceeded for a 1 mm thick implant, which indicates that the 1 mm thick implant will undergo plastic deformation under the influence of occlusal forces. It is assumed that the geometry of the 1.0 mm thick implants may cause problems with plastic deformation. 1.5 mm and 2 mm thick implants are safe from the point of view of plastic deformation, since their pressure remains below 415 MPa. It was found that the most intense movement occurs in the occlusal region of the 1 mm thick implant, and the displacement value was 1.4 mm. When a 2 mm thick implant was inserted, there was little movement in the same area. The displacement value was 0.42 mm. With intraoral application, such minimal movements are acceptable. More movements can lead to increased stress on the implant, fracture of the prosthesis and bone resorption. One significant disadvantage of periosteal implants is their direct contact with the periosteum, which can lead to gum recession, exposure, or even infection of the implant. It is believed that one of the reasons for this complication is the thickness of the metal of the implants. To ensure the possibility of installing implants under local anesthesia, they should be installed in the area of the zygomatic protrusion and pear-shaped opening, without requiring large flap mobilization. Many different designs of periosteal implants have been proposed in the literature. In the old designs, some implants were designed to support the pear-shaped opening, the zygomatic protrusion and the palatine dome, as well as the entire occlusal surface. Thus, the purpose of such modeling of the implant design is to ensure that the implant receives maximum bone support and is resistant to lateral movement. Using 3D visualization and manufacturing techniques, structures are created virtually. One of the significant advantages of this method is the ability to identify screw fixation sites to increase stabilization. This ensures that the volume of the implants is reduced and the load is reduced. During the first tests of this method, the implants were pre-made from resin on a 3D printer and then cast from metal in a dental laboratory. In the laser sintering method, which was later used, the implant is manufactured from metal directly on a 3D printer. This method is important from the point of view of preventing errors that may occur at laboratory stages.

Stress on the bone is one of the causes of bone resorption, and using a subcostal implant of proper thickness can help avoid this resorption. Taking into account the von Mises loads on implants, the largest load is on implants with a thickness of 1 mm, and the smallest is with a thickness of 2 mm. The zones of maximum stress on implants of different thicknesses also differ. The stresses that occur at the joints of the implants with the bone demonstrate that the screw hole in the pear-shaped aperture area, located below the 2 mm thick implant, experiences maximum stress. In 1.5 mm and 1 mm thick implants, the maximum screw tension is observed in the lower part of the zygomatic protrusion. As we know from surgical experience, the bone quality in the area of the zygomatic protrusion is higher than in the area of the piriformis. For this reason, it should be preferred that the area where maximum stress is required is the zygomatic region. From the point of view of studying the stress zones on the implant, the studies revealed the absence of significant stresses in the area of the abutment junction. This is also important because it is possible to narrow the connecting protrusions for the abutment, which subsequently prevents the retraction of soft tissues around the implant. In addition, thin and narrow connective protrusions allow the soft tissues to cover the implant faster and more tightly after its fixation. Thus, the contact area of the metal with the bone is reduced, the risk of exposure is reduced, and the implant, accordingly, becomes lighter in weight.

2. Conclusions

Thus, considering that in approximately 30% of cases, due to unfavorable anatomical conditions, basic, standard techniques are used only in certain modifications, "multi-stage" treatment options due to their duration (prosthetics are postponed for 6 months-1.5 years), physical and psychological trauma, high cost and in some cases necessarythe rate of hospitalization of patients remains unacceptable for a significant number of patients, There is a tendency to minimize invasive manipulations due to an increase in bone volume and the presence of an unresolved issue of choosing an implant design in conditions of bone deficiency and features of biomechanical interaction in the prosthesis–implant–bone system, it seems promising to develop a new dental implant design used in conditions of jaw bone deficiency.

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