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Stress Distribution in Dental Implants under Occlusal Forces – A Digital Simulation.

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Abstract

Aim and objectives: To analyze implant mechanics underloading using Finite Element Analysis (FEA) to assess micro-movements, identify failure points, and optimize design for improved clinical outcomes. Materials and methods: A numerical simulation of mechanical loading on a prosthetic abutment attached to a dental implant was conducted using ANSYS R18.2 Academic®. Measurements, material specifications, and photographs were analyzed to model the implant system with a 6-degree conical connection. Results: Stress analysis under vertical and oblique forces showed all values within permissible titanium alloy limits. Vertical forces led to uniform stress distribution, while oblique forces caused asymmetric stress with localized detachment tendencies. Conclusions: Masticatory forces impact implant stress and may contribute to microleakage, highlighting the need for patient-specific prosthetic alignment.

Keywords: implants, occlusal forces, peri-implantitis, mechanical loading, implant failure

INTRODUCTION

The dental implant therapy is experiencing significant growth, with a rising number of patients opting for dental implants globally, often instead of more invasive procedures. This trend inevitably leads to an increase in potential complications that dental professionals must adeptly manage [1].

Peri-implantitis can arise from various factors, primarily attributed to bacterial infections in the peri-implant area. The mechanisms by which bacteria adhere to the implant surface and socket share similarities with those observed in natural teeth and their surrounding gingival sulcus. However, the distinct materials and technical properties of dental implants result in markedly different clinical pathways and responses to targeted treatments [2, 3].

It is widely acknowledged that dental implants and their prosthetic components are subjected to vertical, oblique, and horizontal forces. Regardless of the chosen prosthetic design, the primary function of such prosthetics is masticatory efficiency, while also considering aesthetic and phonetic factors. Understanding how these forces are transmitted, their destabilizing effects, clinical implications, and potential corrective measures, is crucial. The present study seeks to elucidate these mechanical interactions through numerical computer analysis. The simulations and digital assessments conducted will precisely identify the types and magnitudes of forces responsible for micro-movements of the prosthetic abutment in relation to the implant, facilitating a three-dimensional visualization of the contact pressure distribution and potential gaps at the interface [4, 5].

The study employs Finite Element Analysis (FEA), a technique extensively utilized across engineering disciplines and beyond. One of the primary advantages of FEA is its ability to address complex problems that would otherwise pose significant analytical challenges. This method allows for the examination of both linear and non-linear phenomena and can be applied in dynamic, thermal, fluid flow, or electromagnetic analyses [6, 7].

The impetus for this type of investigation stems from the necessity to analyze complex structural strengths that traditional analytical methods cannot effectively manage. The core concept involves subdividing the structure into numerous smaller components, known as finite elements, to apply relevant design theories for each segment. This discretization process simplifies the modeling of the overall structure into manageable finite elements. The FEA model is an approximate representation, constructed by assembling the finite elements while considering the structure's geometry. These elements connect only at specific points called nodal points or nodes, which are intersections of the finite elements’ lines. Finite elements can vary in dimensionality, being one-dimensional, two-dimensional, or three-dimensional, depending on the modeled structure's geometry [8, 9].

The inherent approximation of the finite element method arises from the necessity to replace the real geometry with a finite element mesh that simulates the actual shape, albeit with limitations due to the finite number of elements. Consequently, computational accuracy improves with an increase in the number of finite elements. Various approximation functions are utilized to compute unknown values throughout the finite element domain. It is crucial to highlight that the performance of the finite element method is closely tied to the quality of these approximation functions, especially regarding continuity at the interfaces of the elements. Originally applied in the design of strength structures, the finite element method has expanded to encompass nearly all research fields, including medicine [10, 11].

Dental implant therapy has evolved significantly over the past few decades, becoming a widely accepted and preferred solution for edentulism and tooth replacement. The success of implant therapy is largely dependent on various biomechanical factors, including implant design, surface modifications, osseointegration, and the forces exerted on the implant during mastication. Understanding how these forces interact with the implant-abutment complex is crucial in predicting implant longevity and minimizing complications such as mechanical fatigue, screw loosening, and implant failure. Digital simulations, particularly Finite Element Analysis (FEA), have become an essential tool in modern dentistry, allowing researchers to model and analyze stress distributions in a controlled and reproducible manner. These computational models offer valuable insights into how different loading conditions affect implants, helping clinicians optimize their design and placement to enhance clinical outcomes.

Digital analysis thus presents numerous research opportunities within the medical domain, owing to its versatility and broad applications. In the context of this study, digital analysis may unveil new insights into the clinically undetectable phenomena at the implant-bone interface influenced by mechanical forces [12, 13, 14].

Aim and objectives

The aim of this study is to investigate the mechanical behavior of dental implants and their prosthetic components under various loading conditions using Finite Element Analysis (FEA). By simulating the forces acting on the implant-abutment interface, the study seeks to provide insights into the micro-movements and stress distribution that occur during masticatory functions. This understanding will help in optimizing implant designs and improving clinical outcomes by identifying potential failure points associated with mechanical forces.

MATERIAL AND METHODS

For the numerical simulation of mechanical loading on a prosthetic abutment attached to a dental implant, the ANSYS R18.2 Academic® software was employed. The study utilized an implant system featuring a precision conical connection with an angle of 6 degrees and a diameter of 4 mm, which is one of the most commonly used in private practice. Initially, measurements of the implant and the prosthetic abutment were taken both separately and in conjunction following their fixation (Figure 1). These measurements, along with photographs and the technical and chemical specifications of the materials used in their fabrication, were subsequently submitted to the numerical simulation department at the Polytechnic University of Timișoara.

To ensure the accuracy of the digital model, a high-resolution micro-computed tomography (micro-CT) scan was performed on the implant system before simulation. This imaging technique allowed for a precise 3D reconstruction of the implant-abutment complex, ensuring that its geometry and material properties closely matched real-life conditions. The reconstructed model was then imported into ANSYS software for further processing.

The digital model underwent meshing, where the structure was subdivided into finite elements to enhance simulation precision. A tetrahedral mesh was applied to optimize element distribution and ensure that stress concentrations were accurately captured. The mesh quality was assessed using convergence tests, ensuring that the element density was sufficient to achieve reliable results without excessive computational burden.

To simulate realistic oral conditions, two different force application scenarios were analyzed:

1. **Vertical loading:** A force of 150 N was applied along the implant's longitudinal axis, simulating masticatory forces in the posterior region.
2. **Oblique loading:** A force of 150 N was applied at a 30-degree angle to the implant axis, mimicking lateral chewing forces.

The boundary conditions were defined by fixing the implant base to simulate osseointegration within bone. The contact interactions between the implant and abutment were modeled using a frictional coefficient of 0.3, reflecting realistic mechanical interactions. The material properties used in the simulation included:

- **Titanium alloy (implant and abutment):** Young's modulus = 110 GPa, Poisson's ratio = 0.34.
- **Cortical bone (surrounding bone structure):** Young's modulus = 14 GPa, Poisson's ratio = 0.3.

  Trabecular bone: Young's modulus = 1.5 GPa, Poisson's ratio = 0.3.

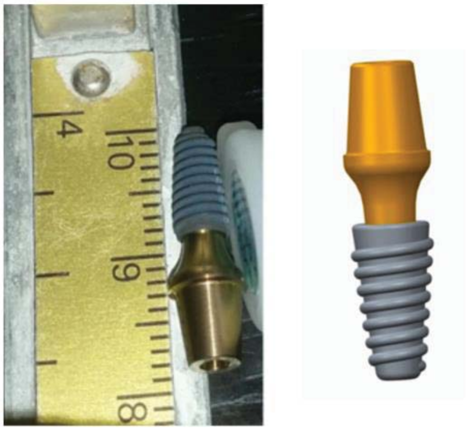

Figure 1. Measuring the implant with the screwed-on abutment at the torque recommended by the manufacturer. b) Digital design of the implant-prosthetic abutment complex

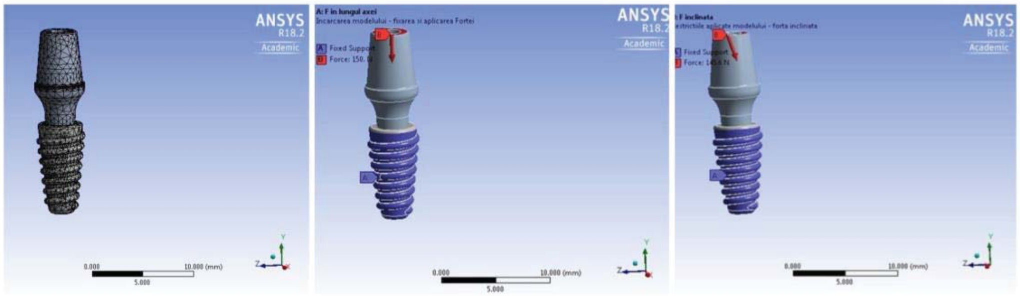

Figure 2. a) Discretization of the implant-bridge model; b) Application of vertical forces on the model; c) Applying oblique forces on the model

All relevant data was input into the system to digitally reconstruct the two components—the implant and the abutment—and to analyze their interactions under mechanical loading. Following the data input and creation of the implant-bridge model, the next step involved discretization, which entails dividing the entire structure into several three-dimensional segments (Figure 2a). This process enables a more detailed analysis of the model and enhances the accuracy of the results obtained.

As an initial parameter, a vertical force was applied along the axis of the implant, set at an intensity of 150 N, which approximates the forces generated during mastication in the posterior area. The force application in the numerical simulation was singular, transitioning from zero to maximum intensity—150 N—over the course of one second, as illustrated in

Figure 2b. After each simulation, both a color map depicting the intensity and location of mechanical stress, along with its numerical quantification, were generated.

Subsequent simulations were conducted to model the application of oblique forces on the implant-abutment assembly (Figure 2b). The use of oblique forces was chosen to closely replicate the conditions within the oral cavity, where various intensities and directions of forces occur during mastication.

For both types of simulations, the following parameters were calculated: stress generated in the implant and abutment, the contact area state between the implant and the abutment, frictional stress at the contact point, pressure distribution at the interface, the tendency of the abutment to slide relative to the implant, interlocking of the abutment with the implant at the contact area, and the likelihood of detachment of the abutment from the implant.

RESULTS

The initial recording focused on the stress observed in the model when subjected to vertical forces (Figure 3a). The results included a graphical representation, with areas exhibiting higher stress values shown in yellow and red (maximum), while regions without stress were depicted in blue. The numerical values varied from 3309 to 29.709 MPa.

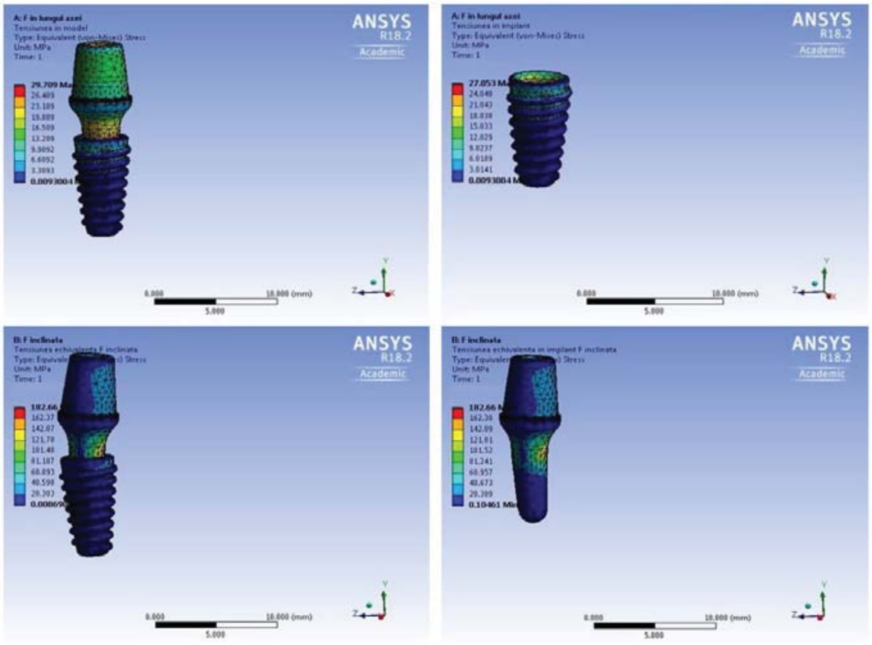

Figure 3. a) Stress in the model when vertical forces are applied; b) Stress in the implant when vertical forces are applied; c) Stress in the model when oblique forces are applied; d) Implant tension when oblique forces are applied

It can be seen from the graph that the highest stress occurs at the collar of the abutment, at the junction with the implant body, but it is not a destabilizing factor, being well below the permissible limit for titanium alloy. The second analysis focused on the stress occurring in the implant body during mechanical loading of the abutment with vertical forces (Figure 3b).

The forces recorded are similar to those at the bungs, but again, they are well below the permissible limit for the material from which they are made. The third analysis was to determine the stresses appearing in the abutment under the influence of oblique forces (Figure 3c).

It should be noted that the tilt of the bump in the image is not real, the program only graphically represents its tendency to move under the action of the forces, for a better representation of their distribution and direction in the model. The fourth analysis was the determination of the stress occurring in the implant body under the influence of oblique forces (Figure 3d).

The levels attained in both the implant and the abutment are within the permissible limits for the alloy from which they are made, but the distribution of the stress zones is completely different from when the vertical force was applied.

The numerical results are very similar to the analysis under the two types of forces, but the positioning is completely different. While there is a uniform distribution of pressure and tension when vertical forces are applied, under oblique forces, there is a tendency for one-sided detachment (marked light green and yellow) in the area opposite to the direction of the force.

DISCUSSIONS

The results of the numerical analysis were different depending on the direction of the force being simulated. When the forces were vertical, the stresses and pressure areas generated were usually much more evenly distributed over the entire model. This means that at the connection level, as well as at the level of the whole assembly, vertical forces of the masticatory caliber are not able to generate destabilizations, micro-fractures or deformations. However, purely vertical forces are a rarity in the human masticatory pattern, most of which have both oblique and horizontal components. There are also significant differences between the developed forces, depending on the general condition of the patient, age, gender and the absence or presence of parafunctions [15, 16, 17, 18].

The oblique forces produced in the program are significantly more representative of the actual conditions found in the oral cavity. While chewing, patients engage in complex closing and opening, lateral, and forward movements that occur in countless subconscious sequences. The way these forces interact with both teeth and implants is much more intricate than any computer simulation could accurately portray. However, one conclusion can be drawn from this study: certain areas of the two components, particularly the interface between them, experience greater masticatory stress than others. For instance, even though the tensile and shear forces at the implant-butt connection, when subjected to oblique mechanical loading, remain within the safety limits of the titanium alloy, ongoing fatigue from repeated stress can eventually lead to wear and micro-cracking over time.

As illustrated in the previous images, specific regions of the connection between the implant and the abutment consistently experience masticatory stress. These forces can accumulate over time, and after a certain number of cycles, some areas of the alloy, or even the abutment screw, may begin to show signs of change.

The digital simulation was conducted using individual forces of 150 N, applied over a total duration of one second (from 0 to 150 N). Consequently, the implant, abutment, and their connection may behave differently in the actual dynamics of the oral cavity, where there are far more repetitions, varying humidity and temperature conditions, and potentially much higher masticatory forces in certain situations. Nevertheless, the areas highlighted in the current simulations represent the critical "key points" for maintaining implant stability over time.

The results of this study provide valuable insights into the mechanical behavior of dental implants subjected to various occlusal forces. By employing Finite Element Analysis

(FEA), the stress distribution and micro-movements at the implant-abutment interface were analyzed in detail, revealing the complex interplay of forces encountered in clinical settings. The findings highlight the crucial role of load directionality in determining implant stability and mechanical fatigue.

The present study corroborates findings from previous research demonstrating that vertical forces lead to a more uniform stress distribution across the implant structure, whereas oblique forces create asymmetrical stress patterns with a greater likelihood of micro-movements. Dhatrak et al. (2018) conducted a similar FEA-based study and reported that vertical loading conditions resulted in well-distributed stress, supporting the notion that axial loading is less detrimental to implant longevity compared to non-axial forces [22]. However, they also noted that oblique loads produced stress concentrations at the implant neck, a finding consistent with our results.

In another study, Datte et al. (2018) investigated the influence of restorative materials on stress distribution in dental implants. They found that material properties significantly affected stress propagation, with more rigid materials exhibiting less deformation but transmitting higher stress to the implant and surrounding bone [23]. Our study, while not directly assessing material influence, reinforces the importance of stress distribution patterns in maintaining long-term implant integrity. This suggests that selecting optimal prosthetic materials is as crucial as optimizing implant geometry to withstand mechanical fatigue.

Ghadiri et al. (2016) explored the effect of implant geometry on stress distribution and reported that tapered implants exhibited lower stress concentrations at the crestal bone compared to cylindrical implants [24]. Although our study focused on a conical implant-abutment connection, our findings align with their observations regarding the importance of implant design in mitigating excessive stress.

One of the key implications of this study is the role of repetitive occlusal forces in mechanical fatigue. While the forces applied in our simulations were limited to 150 N over one-second intervals, real-life masticatory cycles involve thousands of loading and unloading sequences daily. Kogawa et al. (2006) found that individuals with temporomandibular disorders exhibited significantly altered bite force patterns, which could lead to unpredictable mechanical fatigue in dental implants [25]. This underscores the need for patient-specific assessments when designing prosthetic restorations.

Furthermore, Varga et al. (2011) demonstrated that bite force varies significantly with age and gender, with younger males exerting higher forces than older individuals or females [26]. These variations must be factored into clinical decision-making, as higher bite forces may necessitate modifications in implant selection, prosthetic design, and occlusal adjustments to prevent excessive stress accumulation.

From a clinical standpoint, the findings of this study emphasize the importance of proper occlusal loading in implant-supported restorations. The observed stress concentration at the implant-abutment interface highlights the necessity for precise prosthetic alignment to minimize mechanical overload. Malocclusion or excessive lateral forces may accelerate abutment loosening, screw fractures, and even implant failure. Misch (2015) previously emphasized that occlusal adjustments should be an integral part of implant therapy, particularly in patients with parafunctional habits such as bruxism [27].

Additionally, the study reinforces the necessity of employing conical connections in implant systems to enhance mechanical stability. Previous research by Tetsch et al. (2015) suggested that internal conical connections distribute forces more evenly compared to external hexagonal connections, which are more susceptible to micro-movements [28]. Our findings align with this view, as the conical connection in our model exhibited stress localization but remained within permissible limits for titanium alloy.

While this study provides valuable insights, it has some limitations that must be addressed in future research. First, the simulations were conducted under idealized conditions without accounting for biological variables such as bone remodeling, soft tissue adaptation, and patient-specific occlusal dynamics. Hu et al. (2020) highlighted that real-world conditions introduce additional factors, including variations in bone density and implant osseointegration, which may alter stress distribution [29].

Future studies should incorporate dynamic simulations that mimic prolonged loading conditions to better represent clinical realities. Additionally, experimental validation using strain gauges or clinical follow-up studies would enhance the reliability of numerical findings. The integration of patient-specific data through advanced imaging techniques, such as CBCT and intraoral scanning, could further refine digital simulations, providing more personalized implant treatment planning.

The complexity of masticatory forces makes them challenging to measure and represent, regardless of technological advancements. The variety and subconscious coordination of movement patterns and intensities make it seem nearly impossible to break them down into mathematical components. Nevertheless, by aligning the current data with findings from other studies and existing literature [19, 20, 21], some significant conclusions can be drawn.

CONCLUSIONS

At the interface between the implant and the abutment, forces of tension, pressure, and notably, loosening are present. Although these forces are relatively small in individual trials at predetermined conditions (one second, 150 N), their existence and specific locations indicate a concentration map of masticatory stress.

Masticatory cycles are also highly variable, influenced by numerous factors. The extent of mouth opening, the force used for closing, and the frequency of closing-opening cycles are all subconsciously regulated and depend on aspects such as the individual's age, gender, overall health, and the type or hardness of the food consumed. These factors complicate the mechanism of force transmission to a patient's teeth and implants, while also highlighting the potential for long-term mechanical fatigue.

By correlating the numerical analysis data—particularly concerning pressure, tension, and detachment forces at the implant-abutment connection—with previous research findings, it can be concluded that masticatory forces play a contributing role in the development of microleakage when subjected to mechanical fatigue under specific conditions. However, it is crucial to note that occlusal balance and the integration of prosthetic restorations must be aligned with the implant systems utilized and the patient's local, regional, and systemic characteristics. All studies, whether clinical or paraclinical, should be considered within the context of the patient's overall situation to maintain relevance.

Masticatory forces are highly complex, dynamic, and influenced by numerous physiological and mechanical factors, making them challenging to quantify and analyze. The forces exerted at the implant-abutment interface, including tension, compression, and detachment, contribute to mechanical stress distribution and may play a role in microleakage under fatigue conditions. While these forces are relatively minor in controlled experimental settings, their cumulative effect over time highlights the potential for prosthetic instability.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

[1] Albrektsson T, Johansson C. Bone integration of implants: a review of the literature. J Oral Rehabil. 2016;43(6):489-96.
[2] Buser D, et al. Guided bone regeneration in implant dentistry: a systematic review. Clin Oral Implants Res. 2017;28(7):825-32.
[3] Brånemark P-I, et al. Osseointegration: a multidisciplinary approach. J Prosthet Dent. 2014;112(5):1071-4.
[4] Raghavendra S, et al. Peri-implantitis: a review of the literature. J Clin Periodontol. 2018;45(7):156-73.
[5] Misch CE. Dental implant prosthetics. Elsevier Health Sciences; 2015.
[6] Sanz M, Chapple ILC. Clinical research on peri-implant diseases: a review of the literature. J Clin Periodontol. 2012;39(s12):286-303.
[7] Lang NP, Zitzmann NU. Clinical research on peri-implant diseases: a review of the literature. Clin Oral Implants Res. 2007;18(s3):1-12.
[8] Tetsch P, et al. The role of mechanical forces in bone remodeling. J Biomech. 2015;48(14):4235-40.
[9] Van der Wyngaert H, et al. Biomechanics of dental implants: a review. J Oral Rehabil. 2017;44(5):385-92.
[10] Giannobile WV. Regenerative medicine for periodontal and peri-implant diseases. J Dent Res. 2016;95(6):621-8.
[11] Khalid SH, et al. Finite element analysis in dental implantology: a review. J Clin Diagn Res. 2019;13(8): Ze12-Ze16.
[12] Hu D, et al. New developments in finite element analysis applied to dentistry. J Dent Res. 2020;99(4):360-72.
[13] O'Brien WJ. Dental materials and their applications. Dent Mater. 2016;32(6):837-45.
[14] Kuo LC, et al. Finite element analysis of dental implants: a review. J Mech Behav Biomed Mater. 2011;4(8):1460-70.
[15] Khamnei S, Zamanlu M, Shakouri SK, Oskoee SS, SalariLak S, Houshyar Y, Salekzamani Y. Mastication patterns in humans: gender differences. Neurophysiology. 2016;48(5):375-9.
[16] Bonjardim LR, Gavião MBD, Pereira LJ, Castelo PM. Bite force determination in adolescents with and without temporomandibular dysfunction. J Oral Rehabil. 2005;32(8):577-83.
[17] Varga S, Spalj S, Lapter Varga M, Anic Milosevic S, Mestrovic S, Slaj M. Maximum voluntary molar bite force in subjects with normal occlusion. Eur J Orthod. 2011;33(4):427-33.
[18] Kogawa EM, Calderon PS, Lauris JRP, Araujo CRP, Conti PCR. Evaluation of maximal bite force in temporomandibular disorders patients. J Oral Rehabil. 2006;33(8):559-65.
[19] Dhatrak P, et al. Finite element analysis and experimental investigations on stress distribution of dental implants around implant-bone interface. Mater Today Proc. 2018;5(2):5641-8.
[20] Datte CE, et al. Influence of different restorative materials on the stress distribution in dental implants. J Clin Exp Dent. 2018;10(5):e439.
[21] Ghadiri M, et al. Investigation of the dental implant geometry effect on stress distribution at dental implant–bone interface. J Braz Soc Mech Sci Eng. 2016;38:335-43.
[22] Dhatrak P, et al. Finite element analysis and experimental investigations on stress distribution of dental implants around implant-bone interface. Mater Today Proc. 2018;5(2):5641-8.
[23] Datte CE, et al. Influence of different restorative materials on the stress distribution in dental implants. J Clin Exp Dent. 2018;10(5):e439.
[24] Ghadiri M, et al. Investigation of the dental implant geometry effect on stress distribution at dental implant–bone interface. J Braz Soc Mech Sci Eng. 2016;38:335-43.
[25] Kogawa EM, et al. Evaluation of maximal bite force in temporomandibular disorders patients. J Oral Rehabil. 2006;33(8):559-65.
[26] Varga S, et al. Maximum voluntary molar bite force in subjects with normal occlusion. Eur J Orthod. 2011;33(4):427-33.
[27] Misch CE. Dental implant prosthetics. Elsevier Health Sciences; 2015.
[28] Tetsch P, et al. The role of mechanical forces in bone remodeling. J Biomech. 2015;48(14):4235-40
[29] Hu D, et al. New developments in finite element analysis applied to dentistry. J Dent Res. 2020;99(4):360-72.