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Biomechanical behavior of an implant system of carbon fiber-reinforced polyether ether ketone (PEEK) bars with different designs: finite elements analysis

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ABSTRACT

We used finite elements analysis to assess the biomechanical behavior of lower protocol bars made of Polyether Ether Ketone (PEEK) reinforced by carbon fiber, with different designs on All-on-four® system, subjected to physiological occlusal loads. The models were built to have an I-shaped or an inverse T-shaped section. We also assessed the stress distribution on the peri implant bone, implants, prosthetic intermediates, prosthetic intermediate screws, and prosthetic screws. In the simulations, strength peaks were similar for both inverse T and I shaped models; however, the I-shaped bars showed larger resistance in comparison with the inverse T shape. Since it is a new material in dentistry, further research is necessary for a better assessment of PEEK's mechanical and clinical performance.

Keywords: Polymers; Dental Implants; Prosthesis Design; Finite Element Analysis; Mandibular Prosthesis.

INTRODUCTION

Osseointegrated implants used in restorations of total edentulous patients was reported by Branemark in the 1960's. This method presents a high success rate and has been modified several times according to the application [1].

In 2003, Maló et al. [2] presented the concept All-on-four® that uses four implants - distal implants tilted to reduce cantilever and to distribute stress on the implant system. Authors have shown a high success rate for the technique [1,3]. The prosthesis is usually manufactured using a metal bar; however, due to aesthetical requirements, new materials have been proposed as alternative to metals, offering optical characteristics similar to that of the dental substrate [4]. Among those, Polyether ether ketone (PEEK), a high performance thermoplastic polymer [5,6].

PEEK is not only biocompatible but it is also advantageous regarding weight, lack of corrosion, minimum water absorbance, radiotransparency, and is non-allergenic. It is, thus, a new material with excellent characteristics that has been shown to offer excellent results in prosthesis over implant structures [7,8].

This work aims to assess, using finite elements analysis, the implant system's biomechanical behavior using carbon fiber reinforced PEEK bars with different designs for All-on-four® system protocol.

MATERIAL AND METHODS

A total lower prosthesis and a jawbone (Nacional Ossos, Jau, São Paulo, Brazil) were scanned using a laser 3D scanner (Nextengine HD, Santa Monica, USA).

The jawbone model was primed with talc and the prosthesis model with matte white acrylic paint (Suvinil, Basf Brasil SA, São Paulo, Brazil), spray painted to avoid laser reflection.

For the virtual model construction, 16 circular scans were taken at intervals of 22.5° for each model. The models were stored in STL format (3D Systems, Rock Hill, USA).

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Following the scans, the 3D virtual models were exported to a CAD-like software Solidworks 2016 (Dassault Systemes, Solidworks Corps, USA) for edition and NURBS (Non Uniform Rational Basis Splines) parametrization.

The cortical and medullary bone representation was considered type-III and measured 2.0mm thick [9]. Mandibular muscle insertion was also represented in order to stabilize the system when loads are applied. Computational models of the implants and prosthetic components were acquired from the manufacturer (SIN - Sistemas de Implantes, São Paulo, Brazil).

After that, the scanned models were combined with the implant component obtained with the manufacturer and edited to represent implant-supported fixed total prostheses with the following characteristics:

a) Implants measuring 3.75 x 13 mm (Strong Sw HE, SIN – Sistemas de implantes, São Paulo, Brazil). The platform was placed at the crestal level, with two anterior implants parallel and perpendicular to the crest and two posterior implants tilted 30° relative to the long axis of the anterior implants and 3mm anterior to the mental foramen;

b) Intermediates of 4 mm, anterior implants upright and posteriors tilted in 30°;

c) Titanium screws;

d) PEEK bars with 15 mm cantilever and variable geometry;

e) Acrylic gingiva and acrylic resin stock teeth;

g) Saucerization of 1.5 mm

h) Structured to emulate the occlusal contact of the antagonist teeth on the posterior axial load. On teeth 14, 15 e 16, circular contact points with 1 mm of diameter. A food bolus was modeled with approximate thickness of 5 mm;

i) Resin structures to standardize the posterior oblique load, placed on the lingual edge of the vestibular cusps of teeth 14, 15 e 16.

The two emulated models were:

• **MI Model:** Prosthesis with I-shaped section of the infrastructure;

• **MT Model:** Prosthesis with inverse T-shaped section of the infrastructure.

The models were exported from Solidworks to the finite elements simulation software Ansys Workbench V17.2 (Ansys Inc., Canonsburg, PA, USA) using Ansys import supplement.

To emulate the contacts between the implants, components and infrastructure, non-linear frictional-type contacts with friction coefficient of 0.2 were used to resemble saliva-lubricated surfaces [10]. Two load patterns were simulated for each model.

A vector perpendicular to the occlusal plane and on the upper part of the structure emulating the antagonist teeth was applied for the posterior axial unilateral load. For the posterior oblique unilateral load, a vector was applied on the vestibular palatal direction, at an angle of 45° with the occlusal plane. The respective antagonist structures were used to standardize the load area.

Masticatory loads were simulated as 150N [11]. Rigid supports were added to the area where the maxilla would connect to the skull.

All models were then processed using Windows 10 64 bits, on a Intel I7 6800k processor with 112 Gb of RAM.

RESULTS

We used the Mohr-Couloumb criterion for the peri implant bone analysis. Calculation considered a tensile yield strength of 82.8 MPa and a compressive yield strength of 133.6 MPa [12] (figures 1 and 2). M1 model was defined as control.

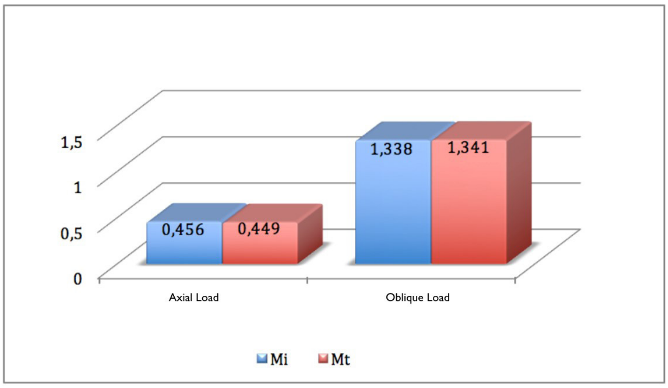

Figure 1. Peaks on the peri implant bone according Mohr Coulomb criterion (in MPa).

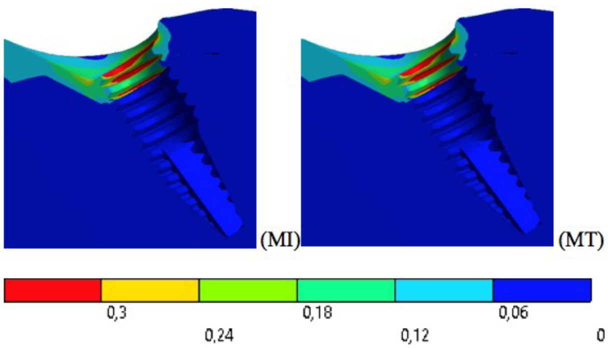

Figure 2. Results for peri implant bone under oblique load.

Implants were analyzed by von Mises criterion. Results were considered relative to titanium grade 4 yield of 550 MPa [13] (figures 3 and 4).

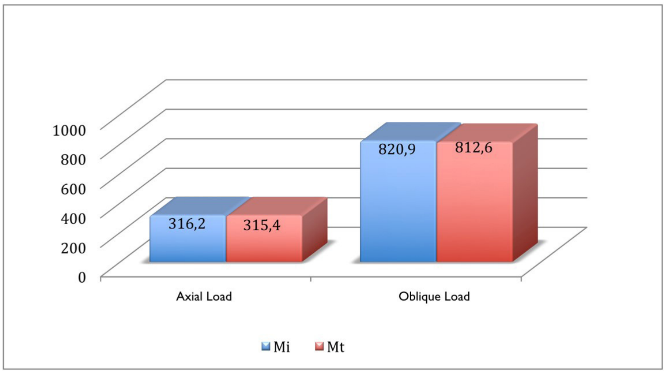

Figure 3. Peak strength on the implants according to von Mises criterion (in MPa).

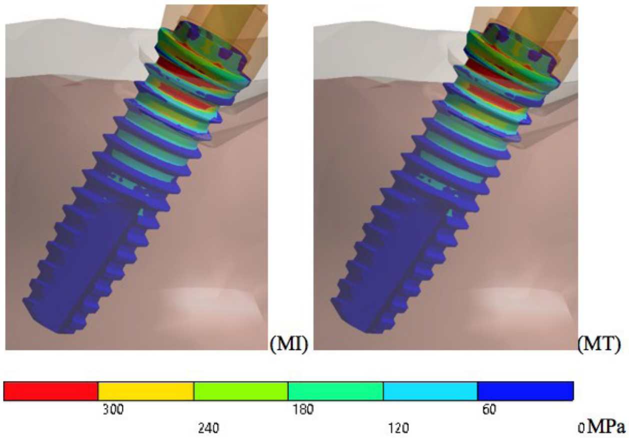

Figure 4. Results for the posterior implant under oblique load.

Intermediate, intermediate screws and prostheses screws were analyzed according to von Mises criterion. Results were considered relative to titanium grade 5 yield of 880 MPa [13] (figure 5).

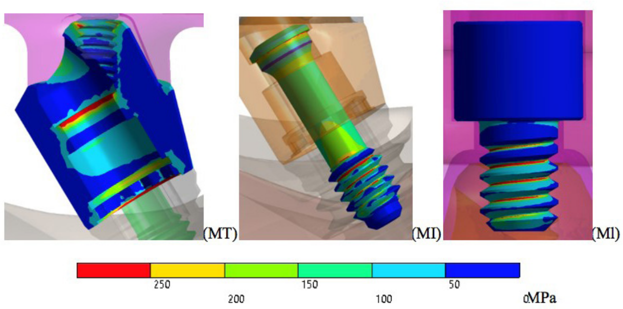

Figure 5. Results for the intermediates, intermediate screws, and posterior prostheses under oblique load.

The bars were analyzed according to Rankine criterion [14]. Results were considered relative to carbon fiber-reinforced PEEK's tensile yield strength of 210 MPa [10] (figures 6 and 7).

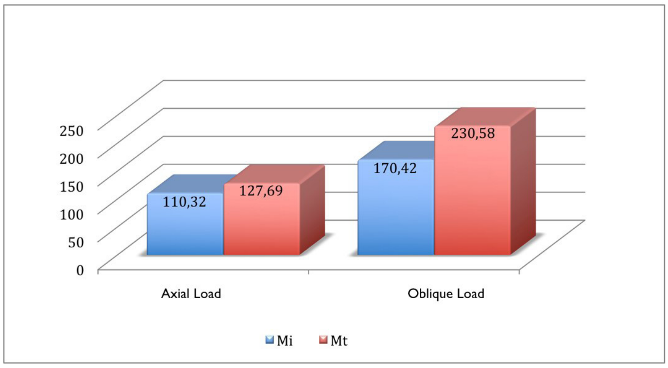

Figure 6. Peak strength on the bars according to Rankine criterion (in MPa).

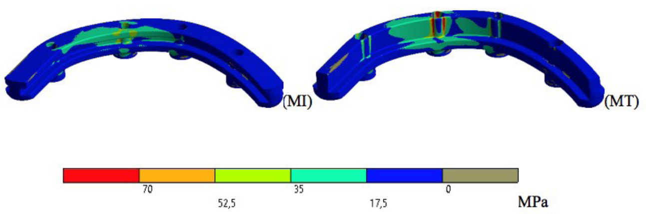

Figure 7. Results for prosthesis bar under oblique load.

DISCUSSION

Protocol bars are usually made of metallic materials. However, hypersensitivity cases [15,16] casting issues, porosity [17], and aesthetic impairment have motivated the search for alternative materials [18].

Polyether ether ketone (PEEK) is a new material that presents promising mechanical properties associated to its huge versatility. This biomaterial has been studied in the medical field since the 1990's [4,19]. The best results have been reported in orthopedics, especially in spine surgery [20,21]. These advances are attributed to its elasticity modulus similar to that of the bone, particularly the carbon fiber-reinforced PEEK [22]. This is why this is the material of choice for this study.

An adequate distribution of forces on the implant system is essential for the rehabilitation longevity. Finite elements method is a valuable tool to analyze stress accumulation on each implant system component and, thus, to evaluate its consequences [23].

In the bone, mechanical stimuli may lead to remodeling processes [24]. This remodeling may, in turn, influence the load distribution after the implant has been put to function.[7] Results obtained with bone simulations showed peaks on the bone crest region and on the vestibular and distal regions of the implant possibly because most of the occlusal contacts occur slightly towards the vestibular region and the implant is tilted distally, causing the accumulation of stress distally [14,25]. These results differ from the dissipation of forces on the bone associated to natural biradicular teeth where, under axially applied forces, peaks are predominant on the furcation due to the tendency of roots intrusion. Under oblique load, stress peaks are observed on the vestibular cervical region of the alveolus in natural teeth [26].

Quantitative results of peri implant bone under axial and oblique loads were very similar for both bar designs. Under oblique load, according to Mohr Coulomb criterion, there is an indication of bone fracture. For this reason, the possibility of fracture should be carefully evaluated, keeping in mind that the larger the result, the higher the risk of bone resorption [12]. Qualitatively, peaks were also observed on the cervical and vestibular regions, probably due to the direction of load, from lingual to vestibular. On the distal bone implants under oblique load, we observe a flexural tendency towards the posterior region and a flexural towards vestibular, favoring the accumulation of stress on the bone cervical region, reducing stress on the apical region.

Regarding bone results, it is not possible to determine if a given treatment or condition will fail in the clinical environment. However, the preservation of the vertical bone surrounding implant is key for success of implant rehabilitation, observing all factors likely related to bone loss [27].

Under axial load, peaks occurred on the posterior and lingual region of the outer surface of the left posterior implants first thread. Quantitatively, the difference had little significance on most implants. Because bone is less rigid than implants, it is more easily deformable and the deformation of more rigid structures is minimized [28]. Under oblique load, peaks were showed on the first thread of the implants' vestibular region. This behavior can be minimized with an intermediate with smaller belt [29]. Oblique loads led to higher levels of stress on the peri implant bone compared to axial loads, in agreement with other authors [7]. We can also observe a tendency of stress accumulation on the implant's neck [14].

Under axial and oblique load, intermediates showed peaks on the angles between the implant's screw laying surface and the thread canal. Both loads showed similar behavior in all models.

On the intermediate screws, a pre-stress was applied to simulate initial stress [30]. Both under axial and oblique loads, peaks were observed on the screw's first thread. Difference between models was small, corroborating previous results [27,29].

Prosthesis screws were under considerable amount of stress and peaks occurred on the same regions of the intermediate's screw for both loads, corroborating previous studies [28]. Under oblique load, peaks were observed on the screw first thread. This performance can be reduced with the reduction of the pre-stress and of the intermediate, with an increase of the prosthesis. Further studies are necessary to assess these conditions [14].

Under axial load, bars showed peaks adjacent to the surface of contact between the left posterior implant's intermediate and the bar, since this is where most compression and, consequently, tensile stress are applied [1,25]. In clinical conditions, results were very different from those of PEEK's tensile strength, which indicates a long lifecycle and reasonable performance of the bars. Under oblique or axial load, MI model showed peaks on the same region for the same reason. However, the MT model showed peaks on the upper lingual region of the left anterior screw canal. This difference is due to the smaller material volume on the upper region of the inverse T bar. Under oblique load, the bar showed significant difference between results (15%), considering material's tensile strength, corroborating Carvalho et al. [31].

CONCLUSION

Given the conditions used in this study, regarding the behavior of carbon fiber-reinforced PEEK bars, as well as that of the implant system, we conclude that:

• I-shaped infrasctructure was more resistant in comparison with the inverse T shape;

• On implants, strength peaks were shown at the inner threads on both models;

• On prosthetic intermediates, strength peaks were shown at the inner threads on both models;

• On the prosthetic and intermediate screws, peaks were shown at the screws' first thread on both models;

• On the peri implant bone, strengths converged at the crestal, vestibular and distal regions, on both models.

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