

3D FINITE ELEMENT NON LINEAR ANALYSIS ON THE STRESS STATE AT BONE-IMPLANT INTERFACE IN DENTAL OSTEOINTEGRATED IMPLANTS

G. SANNINO^A, G. MARRA^B, L. FEO^B, G. VAIRO^C, A. BARLATTANI^A

^aDepartment of Dentistry, University of Rome "Tor Vergata", Rome, Italy

^bDepartment of Civil Engineering, University of Salerno, Italy

^cDepartment of Civil Engineering and Lagrange Laboratory, University of Rome "Tor Vergata", Rome, Italy

SUMMARY

3D finite element non linear analysis on the stress state at bone-implant interface in dental osseointegrated implants.

Purposes. The aim of the study was to assess by means a 3D finite element linear and non-linear analysis mechanical interaction between an implant-supported crown and surrounding tissues.

Materials and methods. A three-dimensional FEM model was developed. Four different material combinations for the abutment and the core were evaluated: Y-TZP - Y-TZP, Y-TZP - microhybrid composite, T - microhybrid composite; T and Y-TZP. 250 N and 450 N loads over a 0,5 mm² areas with different angles (0° and 45°) and locations were applied on the occlusal surface of the framework and the distribution of equivalent von Mises stress was investigated. Using the most critical scenario, the influence of the gradual failure of the cement layer, due to increasing load, on the bone-implant interface, were investigated.

Results. The worst physiological loading condition was the one associated with a horizontal component (45°, 250 N). The 0°, 450 N load (relating to accidental or pathological condition) induced stress concentrations in the cortical bone comparable with those obtained for the tilted load, but with a greater extension to the cancellous bone. Y-TZP prosthetic elements determined minimum values of stress, due to vertical loads at the interface, while the microhybrid composite ones determined minimum stresses due to horizontal loads.

RIASSUNTO

Analisi agli elementi finiti 3D dell'interazione biomeccanica osso-impianto in impianti dentali osseointegrati.

Obiettivo. Nel presente lavoro sono state condotte delle analisi tridimensionali agli elementi finiti, lineari e non lineari, volte a valutare l'interazione meccanica tra osso ed impianto. Sono state infatti stimate le distribuzioni tensionali che sorgono tra una corona supportata da un impianto commerciale ed i tessuti biologici circostanti.

Materiali e metodo. Sono state valutate quattro diverse combinazioni di materiali adottate rispettivamente per l'abutment e il core: Y-TZP - Y-TZP, Y-TZP - composito microibrido, T - composito microibrido; T e Y-TZP. I carichi, agenti su aree di 0.5 mm² disposte sulla superficie occlusale del core per ridurre l'effetto di azione concentrata, sono stati applicati in tre diverse combinazioni. Nella prima il carico previsto pari a 450 N era applicato nella zona centrale del core, nella seconda veniva considerato un carico di 250 N composto da un'azione verticale di 177 N applicata nella stessa zona della prima combinazione e da una orizzontale di 177 N applicata sul margine esterno del core. Infine nella terza combinazione era prevista l'applicazione del carico pari a 450 N applicata in tre punti precisi del core. Dopo aver valutato la combinazione di carico e la configurazione di materiali più critica, analizzando lo stato tensionale di Von Mises, è stata valutata, su quest'ultima, l'influenza della graduale rottura dello strato di cemento, dovuta all'applicazione di carichi crescenti sul core, sullo stato tensionale della zona periimplantare.

Conclusion. Different material combinations for the abutment and the core influenced weakly the stress state at bone-implant interface, with a dependency closely related to the loading mode. The implant – prostheses system stress distribution depended on material choice. Furthermore progressive 45° loads with the gradual failure of the cement layer did not influence Von Mises stresses at bone-implant-interface.

Key words: implant-supported prosthesis, abutment, zirconium, titanium, microhybrid composite, FEM, cement.

Risultati. La condizione fisiologica di carico più gravosa è quella associata alla seconda combinazione (45°, 250 N). L'applicazione di un carico assiale di 450 N (relativa a una condizione accidentale o patologica) determinava delle concentrazioni di stress nell'osso corticale comparabili con quelle ottenute per il carico inclinato, ma con un maggiore coinvolgimento dell'osso spongioso. Gli elementi del sistema impianto-protesi realizzati in Y-TZP. TZP sono associati ai minimi valori di sollecitazioni (tensioni di Von Mises) dovuti a carichi assiali, mentre elementi caratterizzati dall'utilizzo di composito microibrido determinano i minimi valori tensionali per azioni orizzontali.

Conclusioni. Le differenti combinazioni di materiali per l'abutment e il core influenzano debolmente lo stato tensionale all'interfaccia osso-impianto, con una dipendenza strettamente legata alla modalità di carico applicata. All'interno del sistema impianto - protesi invece, la scelta dei materiali consente di ridurre lo stato tensionale tra le superfici a contatto. Inoltre, il progressivo aumento di un carico applicato a 45° con una rottura graduale degli elementi presenti all'interno dello strato di cemento, non influenza la distribuzione degli stress equivalenti di Von Mises all'interfaccia osso-impianto.

Parole chiave: impianti dentali osseointegrati, metodo degli elementi finiti, zirconio, titanio, composito microibrido, cemento.

Introduction

The modern oral implantology offers a reliable and secure solution to replace missing teeth in cases of partial and total edentulism.

This usually occurs by use of screw implants (fixtures) placed in bone, by which tend to integrate by means a process called osseointegration; in this way implants can support the prosthetic element and transfer chewing loads from the prosthesis to the bone.

Several clinical studies have shown that failure of implant rehabilitations is generally not related to mechanical failure of the load-bearing artificial structure (generally titanium based), but it's due to bone weakening or loss at the perimplant region (1-11). Bone resorption is a major problem in prosthetic implantation as it causes loss of stability at the bone – implant interface (12, 13).

A close relationship between bone structures and applied loads has been widely studied and confirmed in the literature (14).

In detail, according to the levels of stress and strain at the bone-implant interface, a process of affixing or resorption may start, and it's called bone remodelling (15, 16), from which depends heavily the risk of failure or the likelihood of long-term success of the implant (17, 18).

Both a stress-shielding (underload) acting on the system and high stresses (overload) is commonly regarded as a reason for bone resorption (19-21).

To analyze the effectiveness and reliability of endosseous implants, revealing possible risks of implant failure, stress analysis of bone - implant mechanical interactions is important.

However, stress and strain fields around osseointegrated dental implants are affected by several biomechanical factors as the load type, material properties of the implant and the prosthesis, the geometry of the implant, the surface structure, quality and quantity of the bone surrounding the fixture, the nature of the bone-implant interface (22-25).

Certainly load is one of the dominant factors, because of its size (26), its dynamic nature (27, 28) and its direction (29) and location (30).

Due to the sophisticated geometry and the involved phenomena, numerical solutions are a proper tool to analyze both the evolution of bone remodelling (31-33), and to evaluate the stress distribution in the per-implant tissues as a result of occlusal loads transferred by the implant. Therefore, the finite element method is a powerful numerical tool that allows to parametrically investigate the influence of the implant and the prosthesis designs, loading intensity and direction, bone and prosthesis mechanical properties, and to simulate various clinical scenarios (34-37).

In order to optimize the stress distribution in the bone tissue, reducing any non-physiological overloading conditions, several clinics have recently proposed the use of innovative materials (zirconium oxide, aluminum oxide, micro-hybrid composite materials and titanium). Their mechanical characteristics are different from those traditionally used (porcelain fused to metal) to manufacture the prosthesis framework (38-40).

The aim of this work was to evaluate, by means finite element analysis, the stress distribution at the bone - implant interface: at first, a linear static analysis was conducted, varying prosthetic materials and load patterns; then, a non-linear dynamic analysis was conducted, considering the most critical scenario among previous results, to assess the influence of the gradual crisis of the cement layer, subjected to increasing loads, on the stress state at the bone-implant interface.

Materials and methods

The geometry for the designs was obtained from 2D drawings of components provided by the implant manufacturer (BTLock srl, Vicenza, Italy). The model consisted of an implant – supported crown placed in the molar zone of the lower jaw (Fig. 1).

The mandibular segment studied was 22 mm long, 24 mm high and maximum 14 mm wide. The cortical bone that surrounds the inside cancellous bone was schematized as a solid annular region of 1.5 mm thick. A fixture 4.50x13-mm (BT-TITE One Line, 45013 BTICV1, BTLock srl, Vicenza, Italy) was selected for this study. It was realized by a revolution along the symmetry axis of a sketch on the plan, the external threads were obtained using a sweep around a spiral propeller on the longitudinal axis of the fixture. The abutment (Abutment Shoulder, 450B BTIPMLS, BTLock srl) was 4.70 mm and 6 mm diameter in the coupling zone with the fixture and the crown respectively, 5.90 mm high and the axial walls had 3° taper. The abutment marginal design adopted was a 1 mm deep slight chamfer (41). A 0,025 mm thick layer of adhesive resin permanent, dual double-paste, cement (RelyX ARC, Dental Laboratory Products, St. Paul, Minnesota, USA) was between abutment and coping. The coping was 0.6 mm thick. All materials used were assumed to be linearly elastic, homogeneous and isotropic. Fur-

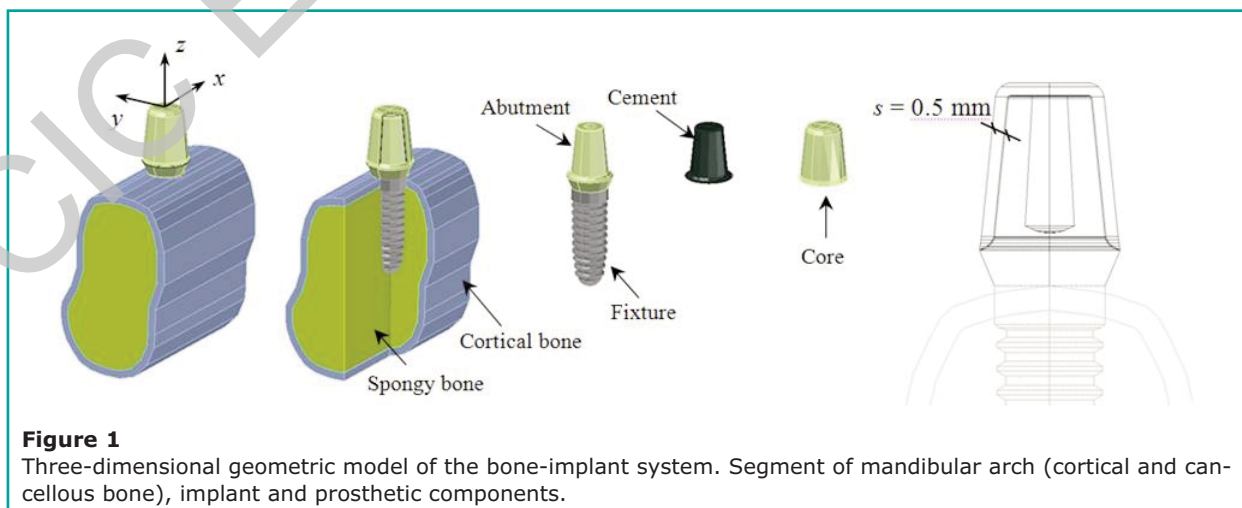


Figure 1

Three-dimensional geometric model of the bone-implant system. Segment of mandibular arch (cortical and cancellous bone), implant and prosthetic components.

Table 1 - Mechanical properties of the materials.

| Material | E [MPa] | ν |
|-----------------------------|--------------|-------|
| Cortical bone [42] | 13700 | 0.30 |
| Cancellous bone [42] | 7930 | 0.30 |
| Titanium [43] | 110000 | 0.34 |
| Zirconium oxide [44] | 210000 | 0.30 |
| Micro hybrid composite [45] | 11240 | 0.30 |
| Cement [46] | 5100 | 0.27 |

thermore, the osseointegration between bone and implant was considered perfect, both in the interfacial spongy and cortical region. All adjacent regions were modelled as perfectly assembled, neglecting any effect of unilateral contact, plain or with friction, any effect of damage and cohesion defect. In order to carry out a comparative analysis, different materials were considered choices for the abutment and the core. The configurations were: Y-TZP for the abutment and the core, Y-TZP and micro hybrid composite for the abutment and the core respectively, T and micro hybrid composite for the abutment and the core respectively, T and Y-TZP for the abutment and the core respectively. In Table 1 mechanical properties of materials are reported. The load combinations considered in the analysis are shown in Figure 2.

In particular, in Combination 1, V , equal to 450 N, was the intrusive axial load applied in the center of occlusal surface of the core. In Combination 2 the tilted 45° load was equal to 250 N, splitted in V and H , with a buccal - lingual direction. In Combination 3, the axial load V was applied in three points of the occlusal surface of the core. The loading area was 1 mm in diameter in order to minimize local high stress concentration.

The load applied can be considered representative of physiological loading conditions in chewing hard foods or relating to accidental/pathological condition.

The numerical analysis was carried out using the software Straus7 of G + D Computing. The entire system was meshed by 300147 tetrahedral elements (or bricks) and 56721 nodes (Fig. 3). The mesh adopted was more dense at the bone-implant interface. In particular, the average size of the elements at the bone-implant interface was 0.5 mm, while 1 mm in the remaining regions. The discrete solution in terms of displacements was constrained to satisfy conditions of continuity in each interface between adjacent regions, as well as the three degrees of freedom for each node located at the end of the mandibular section were suppressed. This assumption, since the remaining part of the jaw does not offer a completely rigid support to the mandibular segment selected, was acceptable for comparative claims of the

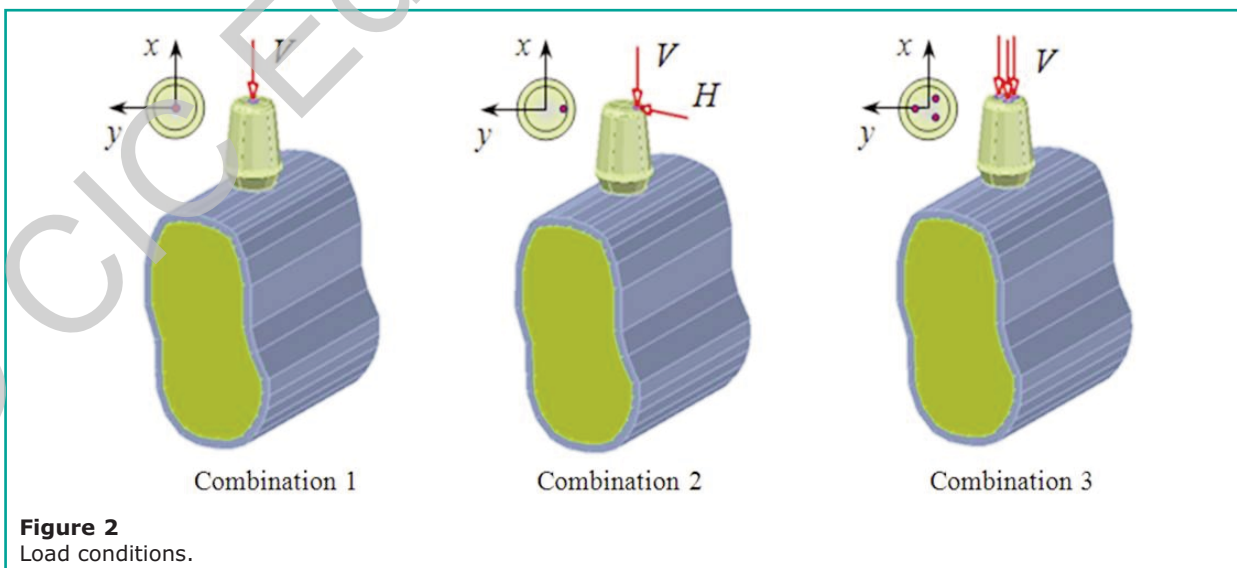


Figure 2
Load conditions.

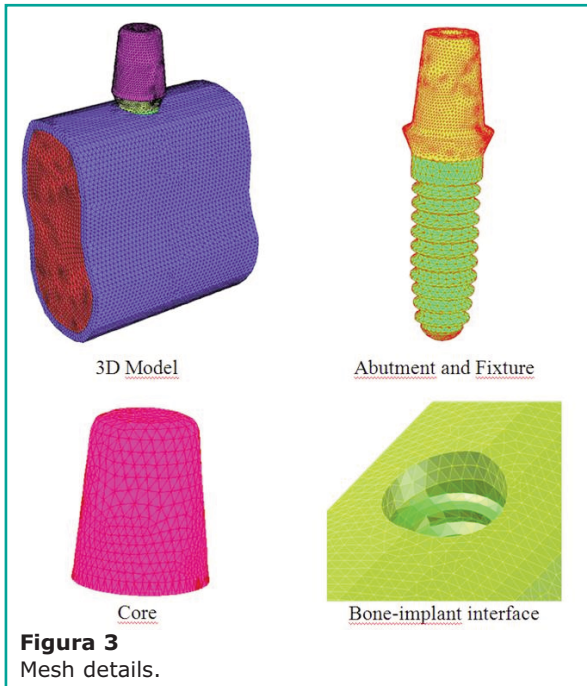


Figure 3
Mesh details.

present study. A further non-linear dynamic analysis was carried out, considering the most critical scenario among obtained results, increasing the loads

and disabling the cement bricks that showed compressive or tensile failure. Many 45° load (H=V) steps were considered: 30N, 60N, 120N, 240N, 500N, 600N, 800N. The compressive and tensile strength of each element were 327.8 MPa and 1 MPa respectively (44). Thus, for each load step, stress state at bone-implant interface was evaluated.

Results

The mechanical interaction between bone and implant was assessed evaluating the tension distribution at the bone - implant interface. According to other recent studies, stress distribution within the elements was expressed in terms of von Mises equivalent stress (14, 19-25).

The von Mises stress distribution for different materials and load patterns applied are shown in Figures 4, 5, 6 and 7. Specifically, the distributions of equivalent tensions are shown at the bone – implant interface and within the implant – prostheses system. Von Mises equivalent stress distributions in the cortical bone around the implant neck are shown in Fi-

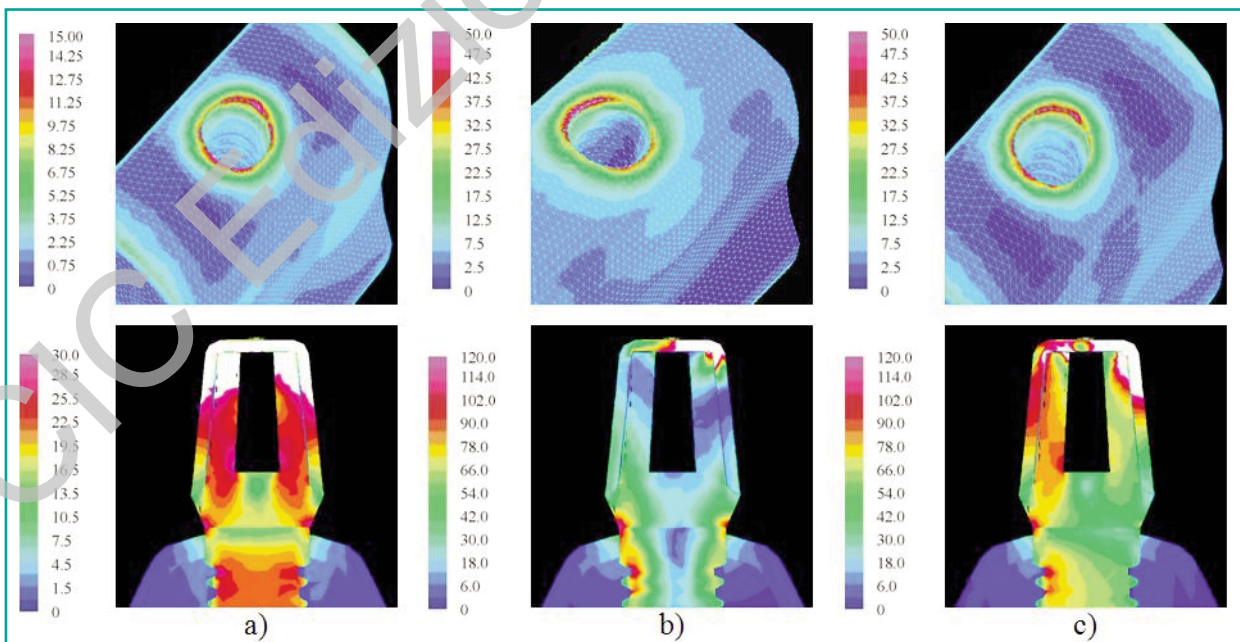


Figure 4
von Mises equivalent stress values (MPa) and distribution at the bone - implant interface - Y-TZP Abutment and core; (a) Load Combination 1, (b) Load Combination 2, (c) Load Combination 3.

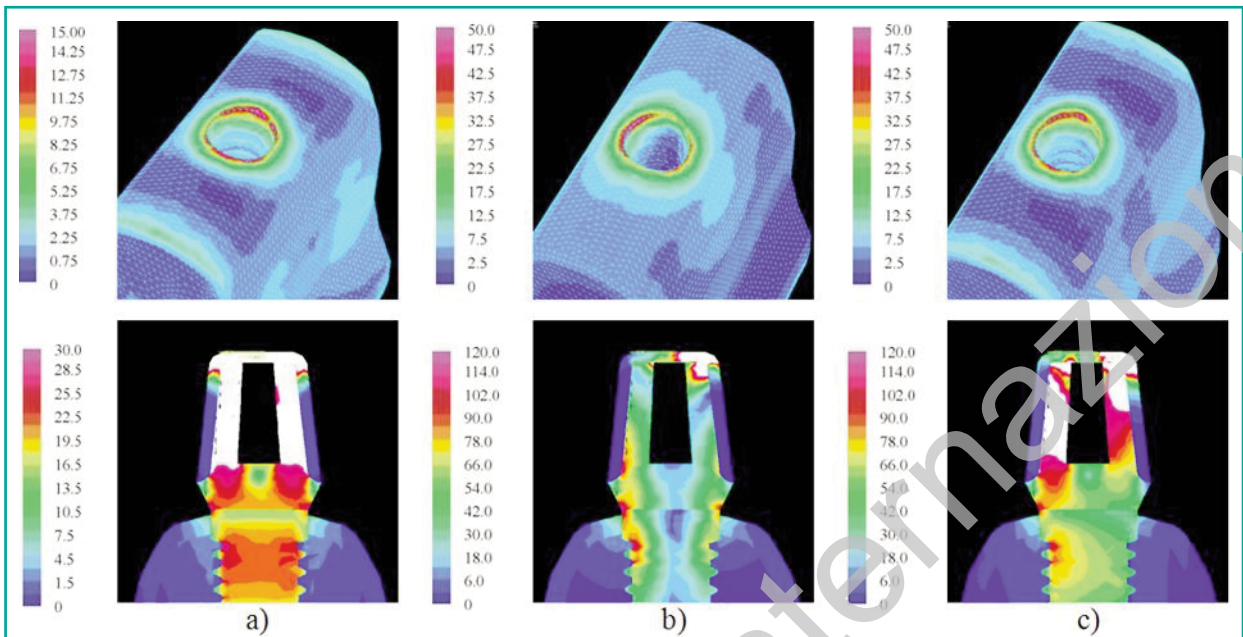


Figure 5 von Mises equivalent stress values (MPa) and distribution at the bone - implant interface - Y-TZP Abutment and micro-hybrid composite core; (a) Load Combination 1, (b) Load Combination 2, (c) Load Combination 3.

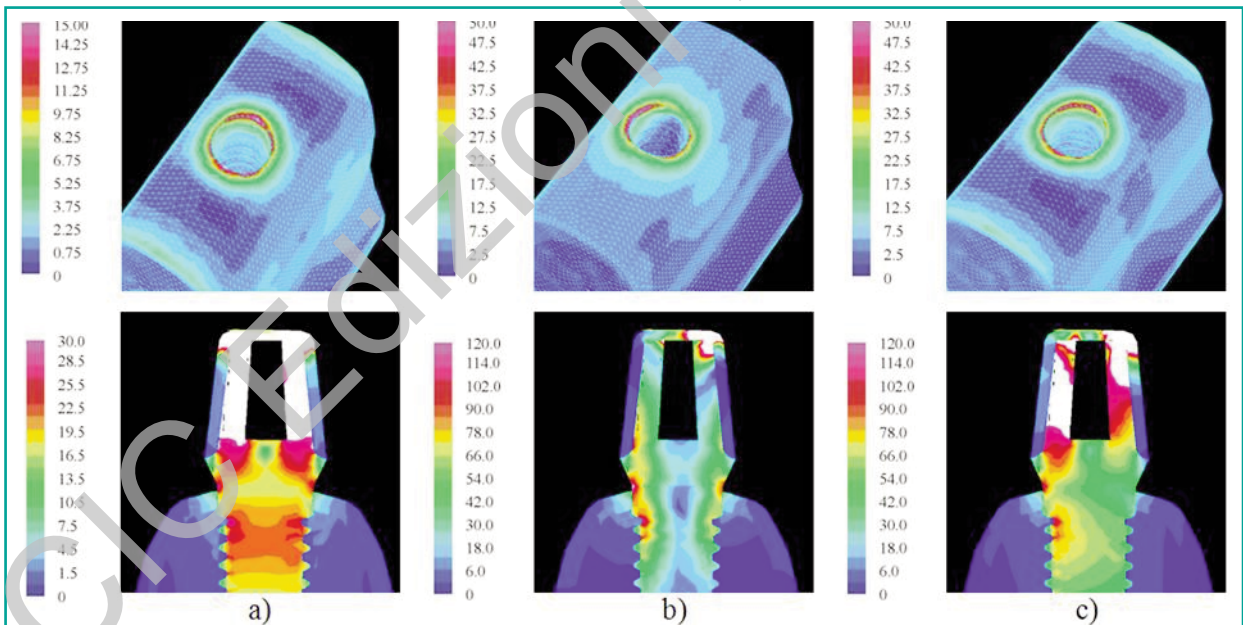


Figure 6 von Mises equivalent stress values (MPa) and distribution at the bone - implant interface - T Abutment and micro-hybrid composite core; (a) Load Combination 1, (b) Load Combination 2, (c) Load Combination 3.

figure 8. Average distribution in the cortical bone varying anomaly angle to the implant axis are reported. The results clearly show that the stresses rose

in the bone tissue are highly dependent on the load conditions applied to the implant. In particular bone - implant interface, was the region most stressed and

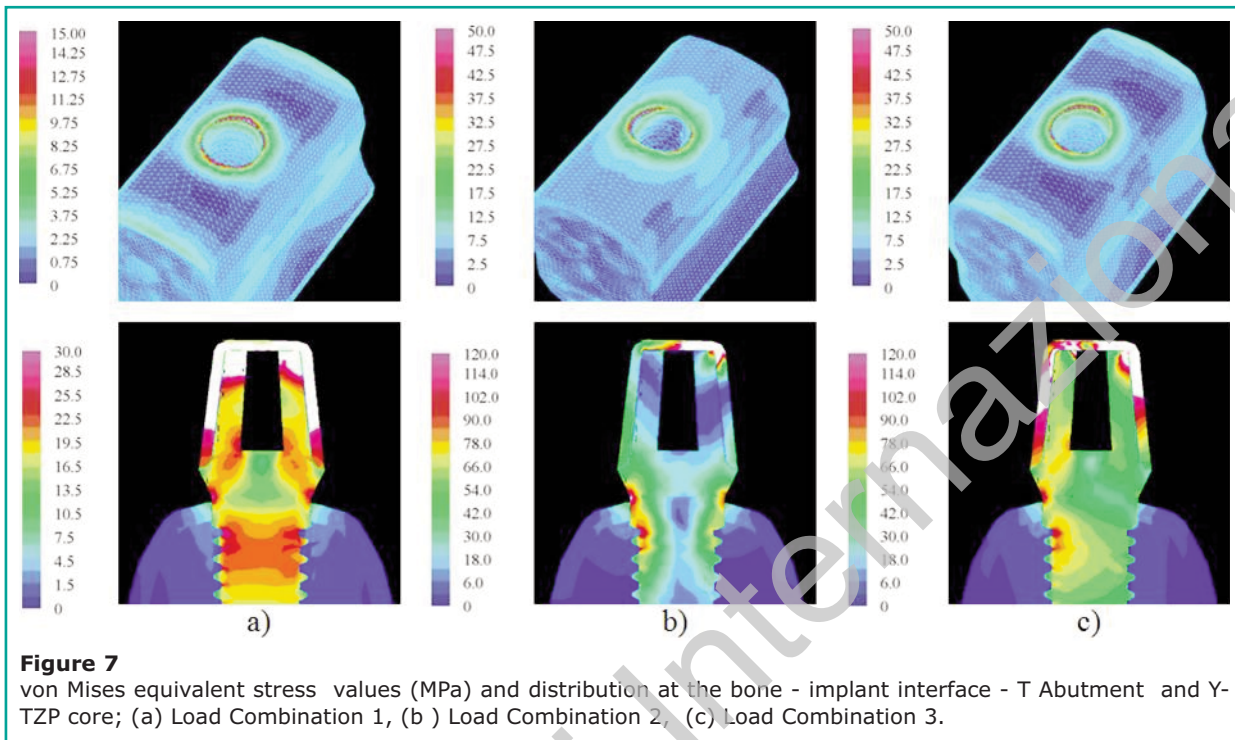


Figure 7 von Mises equivalent stress values (MPa) and distribution at the bone - implant interface - T Abutment and Y-TZP core; (a) Load Combination 1, (b) Load Combination 2, (c) Load Combination 3.

highest tensions were localized in the cortical layer. The physiological loading conditions most heavy, although having a force module smaller than the other, was the one associated with a horizontal component, parallel to the occlusal surface (combination 2). The load combination 3 (relating to accidental or pathological condition) induced stress concentrations in the cortical bone comparable with those obtained for the combination 2, but with a greater extension to the cancellous bone. The use of materials with different elastic properties for the core and the abutment influenced stress distribution at the bone – implant interface less than the type of loading applied. In contrast, stress analysis of the prostheses – implant system showed how material choice was determinant for the stress distribution within the different components. It should be noticed that, due to large difference in stiffness between system materials, the major stress gradient in the cement layer rose in the configuration 2 (Y-TZP abutment and micro-hybrid composite core) and 3 (T abutment and micro-hybrid composite core). For the configuration 1 (Y-TZP abutment and core) and 4 (T abutment and Y-TZP core) stress distri-

bution in the cement layer was more homogeneous. Material configurations 2 and 3 produced highest risks of failure for the cement layer placed between core and abutments. Therefore, the non-linear analysis was performed using the material configuration with load combination 2. The results of the analysis, maximum principal stresses σ_{11} (tensile), minimum principal stresses σ_{33} (compressive) and Von Mises stresses acting at the bone-implant interface, varying anomaly angle and increasing load applied, are shown in Figures 9, 10 and 11. Increasing load applied stresses show the same linear increase (Fig. 12). When a 800 N load is applied, every bricks of cement layer shows the failure, so stress value is lower.

Discussion

In this study, the results of tests performed on three-dimensional finite element model of a dental implant placed in the lower jaw were presented. At first, the real model and the interactions between its different parts were studied, then the analysis

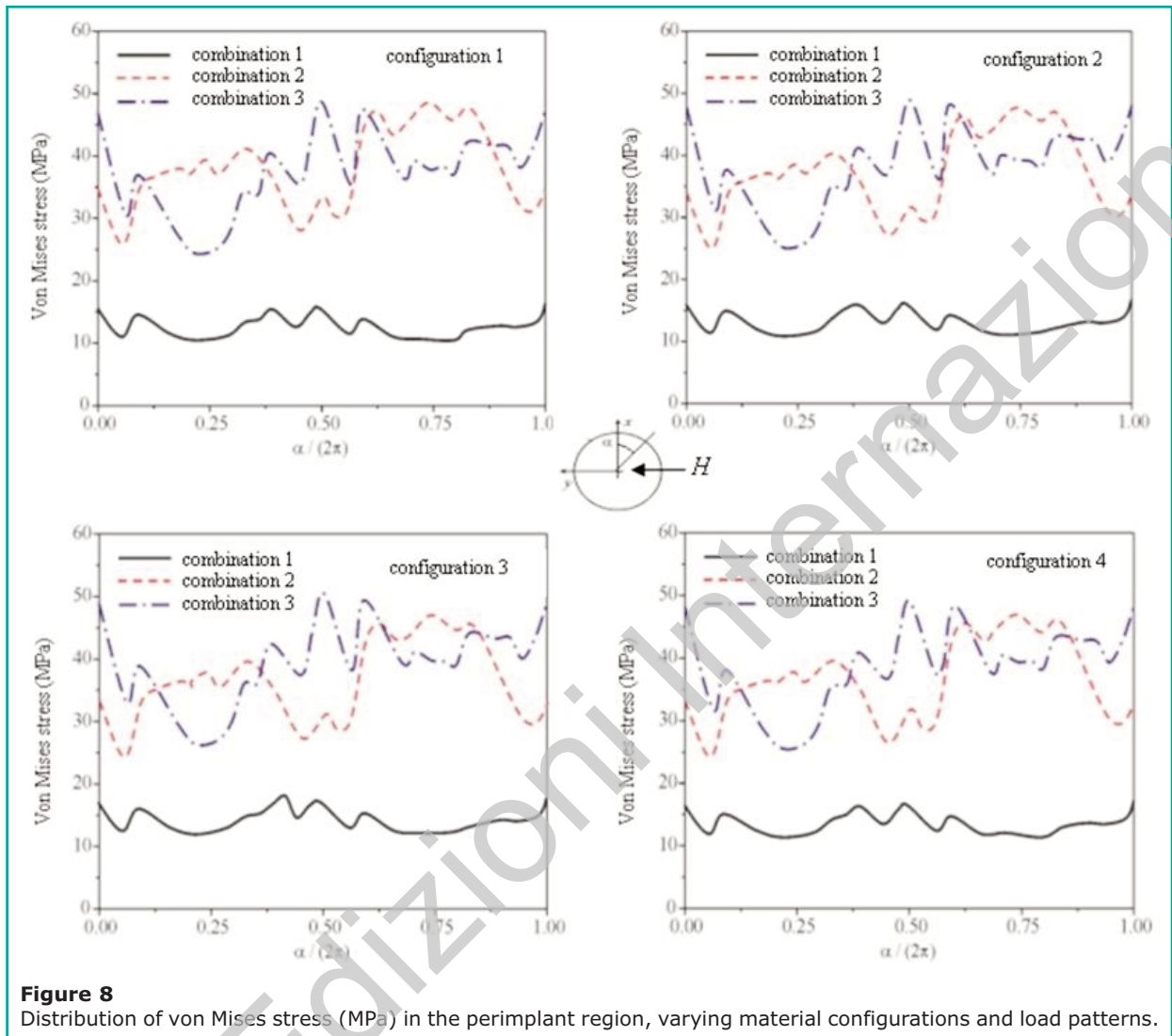


Figure 8 Distribution of von Mises stress (MPa) in the perimplant region, varying material configurations and load patterns.

of the discretization of the numerical model with real geometries and loading type of its typical working mode were carried out.

The predictions of the numerical model, were in agreement with experimental and theoretical results obtained from the literature. The proposed results, obtained from linear static analysis considering different load conditions as well as different prosthetic materials, have provided useful information for implant design and clear evidence about the influence of some factors on the risk of implant failure. In particular bone - implant interface, was the region most stressed and highest tensions were localized in the cortical layer. However, for all loading mode and pro-

sthetic material combinations investigated, the maximum values of equivalent von Mises stress in the perimplant cortical bone were always much lower than commonly assumed physiological limits (100-190 MPa [14, 23]), with no risks of bone resorption due to overloading. In contrast, oblique loads and / or accidental high intrusive could induce the activation of bone resorption processes in the cancellous region, especially near the interface with the cortical bone, due to stress values exceeding the threshold physiological (5 MPa [14, 23]). Performance evaluation of implant – prostheses systems based on use of materials with different elastic properties have also revealed a minor influence on the stress distribution

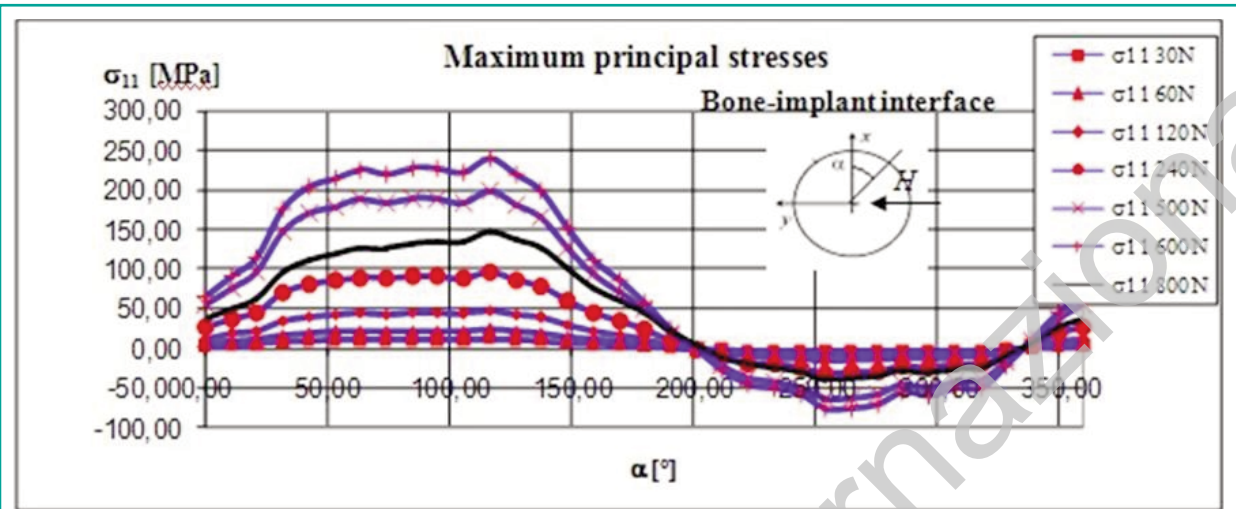


Figure 9
Maximum principal stresses at bone-implant interface.

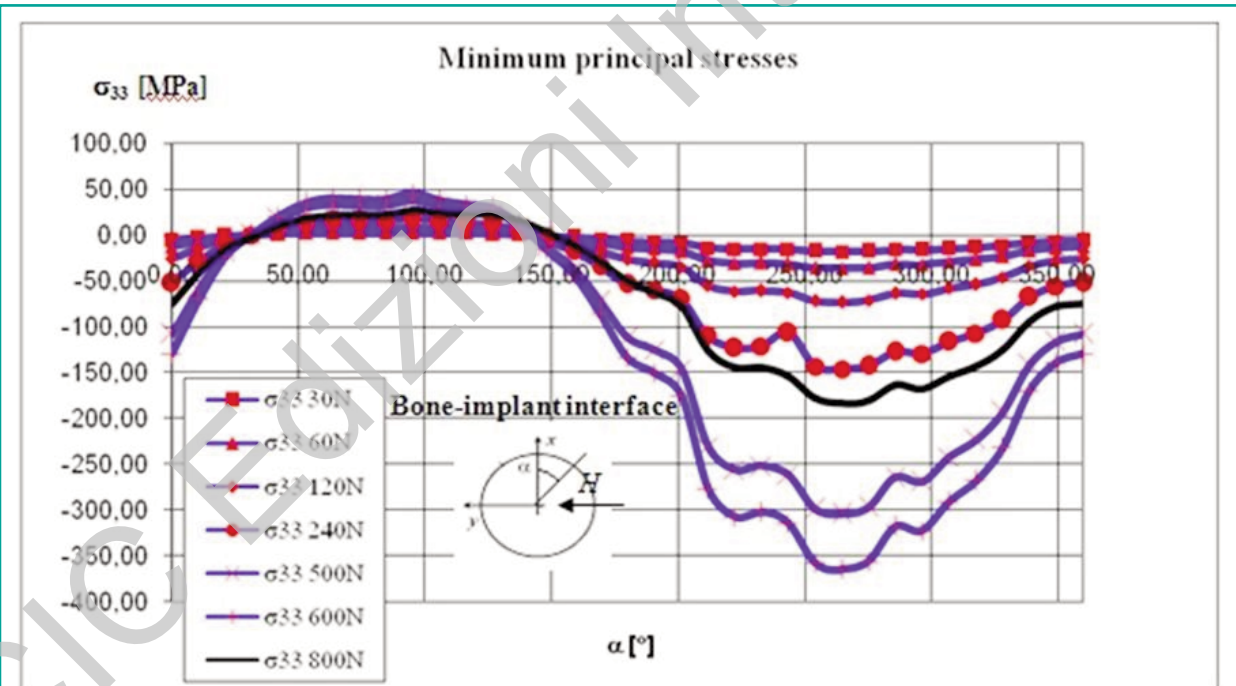


Figure 10
Minimum principal stresses at bone-implant interface.

in the bone and a major dependence of the loading conditions.

In the second part of the study, the non-linear dynamic analysis have shown that the stress magnitude acting at bone - implant interface increased with

increasing load as shown in the combination 2, despite the gradual breakdown of the layer of cement. In fact, the increase of principal tensile stresses was particularly evident in the circular area located on the same half-plane where acting H shear force, ma-

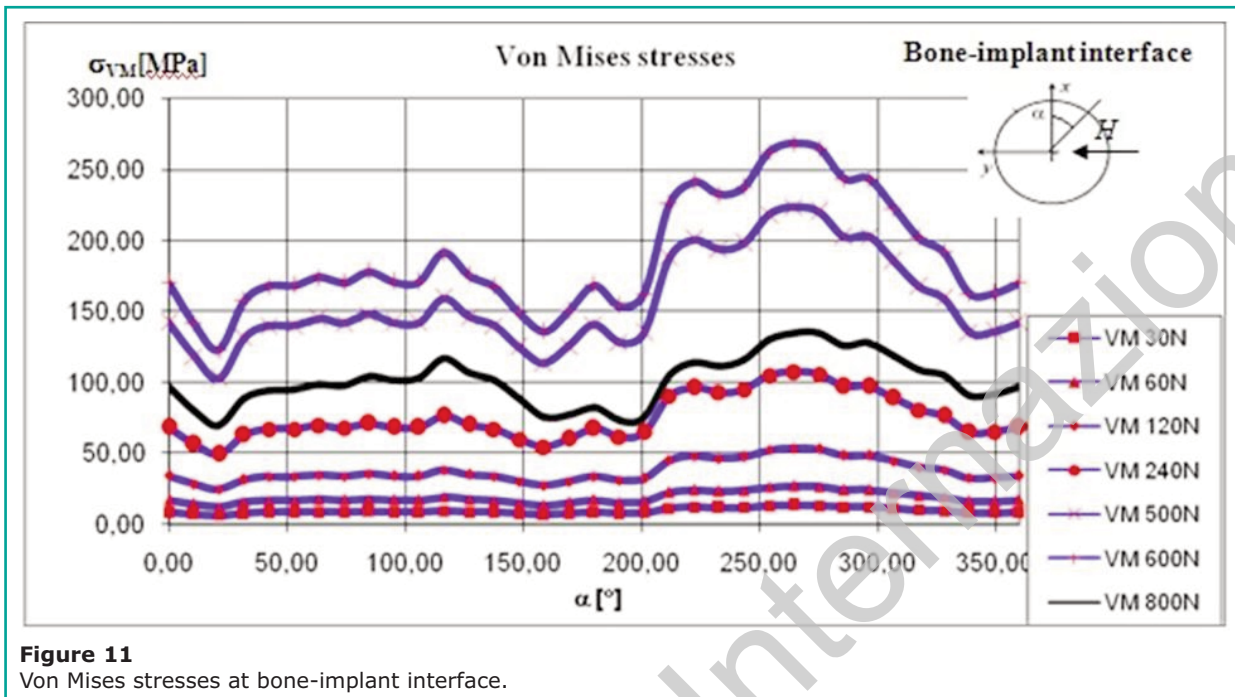


Figure 11
Von Mises stresses at bone-implant interface.

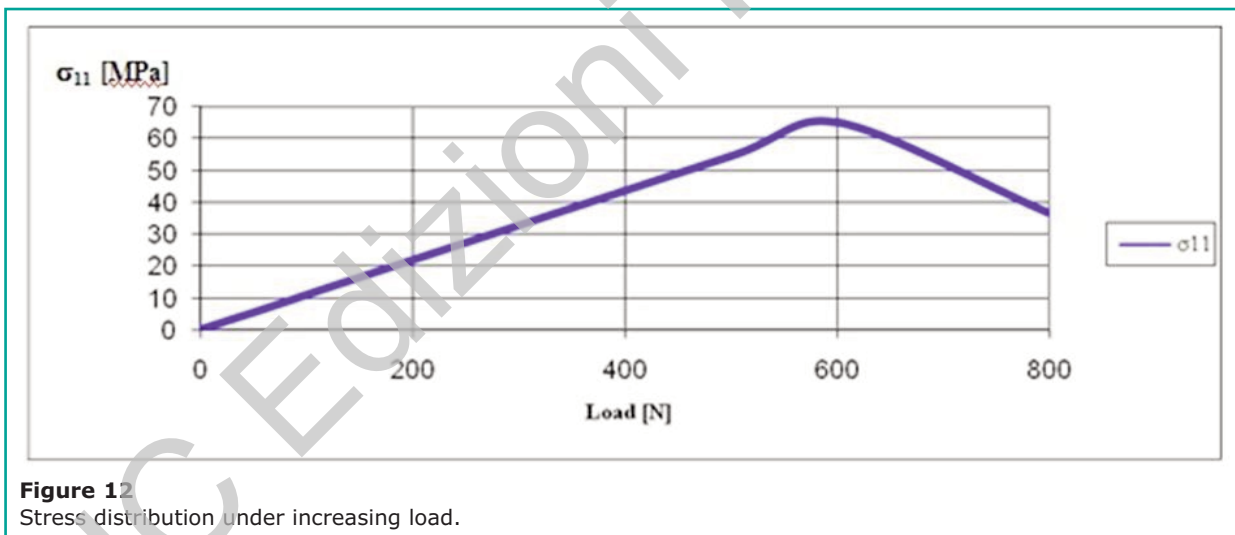


Figure 12
Stress distribution under increasing load.

king almost imperceptible increase tension in the circular area located in the other half plane. In contrast, the principal compression stresses showed a significant increase when the principal stresses tensile were minimum. The trend of the equivalent Von Mises stress values also are maximum in the circular area compressed.

These stress increases, although characterized by a gradual breakdown of the cement layer, continued

to show a linear behavior with increasing load, until the entire layer is almost completely compromised for loading values equal to 600N after which the tensions decreased. In fact, because of the load increased, the stress state of the cement layer grows up until the breaking for traction or compression of the three-dimensional elements of which it is composed.

Therefore, by the following loading stages, an ele-

ment that had reached failure due to traction was completely disabled and did not provide any more support as resistant area or stiff. In contrast, the element, that reached failure due to compression, provided a support area rather strong showing a high stiffness that, numerically, led to the choice of a high elasticity module (E).



Conclusion

The results show that, assuming an intrusive load condition, the use of Y-TZP for both the abutment and the core allows for lower equivalent stress (about 5-10%) than the other material combinations investigated, in the bone region around the implant neck. In contrast, in the presence of oblique loads, the use of titanium for the abutment and a micro-hybrid composite for the core allows to transfer occlusal loads more evenly and with peak values of von Mises tension slightly lower (7-11%) than in other cases. However, this material choice, as well as with combination 2 (Y-TZP abutment and micro-hybrid composite core), produces highest tension gradients in the cement layer, leading to increased risks for the implant due to cohesive failure of this layer. In this respect the non-linear analysis showed how the cohesive failure of the cement layer does not influence the development of tension, which is essentially linear up to values of the load equal to 2000% of initial load.



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Correspondence to:

Dott. Gianpaolo Sannino
Via Torri in Sabina, 14
00199 Rome, Italy
Tel.: +390686329347
Mob.: +393271747296
E-mail: gianpaolosannino@hotmail.it