SHAPE OPTIMIZATION AND TOLERANCE ANALYSIS OF DENTAL IMPLANTS BY MEANS OF VIRTUAL MODELS

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ABSTRACT

Osseointegrated implants are commonly used to support the partial or full structure for dental replacement. Many practical techniques use a dental impression to extract information about the positioning of implants in order to improve the precision of fitting. Due to different expertise, geometrical misalignments and interference defects, some permanent deformations and misfits may occur during components mounting and dismounting activities. These errors cannot be completely avoided, but an accurate choice of the geometrical parameters, materials and procedures may reduce the risk of system failure, local damages or harmful behaviour for the patient. For this purpose computer aided design modelling and finite element analysis can be valid instruments to build virtual simulation, have objective assessment of mechanical behaviour, perform tolerance allocation and optimize shapes. In this paper some case studies integrating CAD and FEM for implant biomechanical evaluation and shape optimization are discussed and innovative solutions have been presented.

Keywords: dental implants, tolerance analysis, shape optimization

1. Introduction

The clinical treatment of partial or complete dental replacement has been significantly improved after the diffusion of osseointegrated implants to support dental prostheses. There are a lot of different technique about the construction and the assembling of these biomechanical systems [1-2]. They are all based on the insertion of one or more titanium screwed implants into the mandibular or maxillary bone [3] and on the placement of a bridging structure (framework) to support the overdenture [4-5-6]. Although implant are directly inserted in the mouth, the bridging structures are modelled outside and then connected at the implants [7]. In order to transfer information form the internal implant positioning and bridging structure connecting extremities, many dental techniques prescribe the use on a resin impression [8]. Mounting and dismounting impression tray in the mouth of the patient is one of the critical task, because a correct placement of the bridging structure [9] can be obtained only with an accurate building of an impression tray. Due to difficulties in accessing the oral cavity and due to the variety of bone properties structures and due to irregular geometrical features, mechanical errors can occur during all the operations, such as misalignments, misfit or deformations [9-10] or irregular osseointegration. These errors can be avoided refining the mounting procedure, understanding the assembling mechanics and prescribing the tolerance of single components. Literature includes work describing different approaches, but many researcher or dentists support their own method based on intuition, practice and experience. It is difficult to choose the best methodology and judgement is often limited to subjective considerations. It depends on many factors: ability of the dentist, anatomical properties of the mouth [11-12] and the typology of the implant [12]. Among these varieties an objective study seems to be a valid instrument to improve the assessment of these techniques. For this reason numerical methodologies seem to be very useful to simulate different working conditions or mounting-dismounting actions and optimize both geometrical, biomechanical and procedural aspects [13]. Literature reports many works about the use of finite elements mathematic techniques in dental implant investigations, but the studies often focus on local problem or on a single implant connection at time [14-15-16].

An accurate understanding of influence of mounting errors on system performance can also guide the tolerance allocation for optimizing manufacturing.

In general the effect of tolerance may be investigated using a sensitivity approach based on statistics. Supposing to have a target variable (specification) ψ as a function of different design variables (t_i) subjected to tolerances which are not correlated among them, we can deduce the sensitivity of the variation of ψ to the variations of t_i:

$$\psi = \psi\left(t_i\right) \tag{1}$$

$$d\psi = \sum_i \left.\frac{\partial \psi}{\partial t_i}\right|_{t=t_m} \left(t_i - t_{i,m}\right) \tag{2}$$

where $t_{i,m}$ is the i-th design variable mean value and t_m is the vector of t_i mean values. In this case we can define sensitivity coefficients χ_i as:

$$\chi_i = \frac{\partial \psi}{\partial t_i} \tag{3}$$

The knowledge of these coefficients is very useful for allocate tolerances, because the express the cause-effect of any change of design variable reference value.

The previous approach is very useful for problem in which a closed form expression can be deduced. In this case the derivatives in (3) can be algebraically computed. When a closed form can not be found due to the complexity of the system, the assessment of the derivatives has to be made numerically. This is the case of three dimensional model of dental implants. Since the shapes are very complex, the connection are based on contact condition or screwed fasteners, the sensitivity analysis can be performed only using numerical models and computer aided methodologies.

For all these reasons, the virtual models of dental implant systems have to be built with high detail and they have to include many subcomponents. First of all a detailed three-dimensional model of each part is required because clearances, geometrical interferences and mating surface shapes are very important to be taken into account. Moreover the virtual model assembling constraints have to mimic what happened in the actual mounting/dismounting procedure. An accurate elastic properties determination of each material included in the system is also required.

In this paper two different cases will be presented. The first is about a conceptual redesign of implant coping connection shaper to reduce the stress induced by mechanical misfits; the second is about the effect of deformation due to elastic compliance of structure during mounting and dismounting of impression tray.

2. Case study 1: Redesign shapes to simplify tolerance allocation and reduce stress induced by misfit error.

The first investigated solution is about a standard system which is composed by several implants which are screwed into the bone and support a unique bridging frameworks my means of other screws. Because each screw-implant-framework connection can be considered as a fixed constraint due to facetted surface of the screw heads, the presence of more than one fastener cause the system to be overconstrained. On the other hand, the presence of several fasteners ensure a correct load distribution from the overdenture to the bone. Due to these overabundant constraints, an occasional misfit or misalignment can not be compensated by rigid motion and causes internal mechanical stresses. These stresses are transferred to the bone with discomfort problem for the patient and, with a long time application, they may cause implant failure.

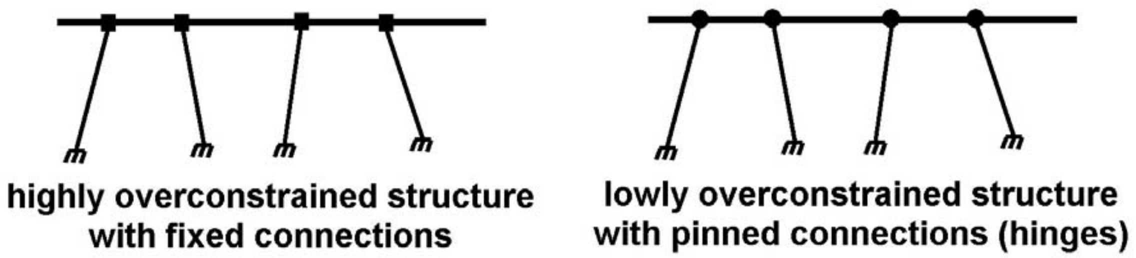

Figure 1: Comparison between bridging structure with different constraints

The basic idea for redesign is to change the shape of connections reducing the number of overabundant constraints ensuring stability and good load distribution at the same time. A well addressed engineering comparison can be that of a bridge (the frameworks) that can be constrained to the pillars (the implants) with fixed connections (the standard solution) or pinned ones (Figure 1).

This solution ensures not only a less overconstrained structure, allowing relative rotation between framework and screws, but it allows a better damping of tolerance errors. Following mounting sequence, the first step is to drill holes in the bone where the implants have to be inserted. According to this, the axes of the drilled holes (i.e. the axes of the implants) are a datum for the assembly. The second step is the placement of bridging structure on the implant(s), thus another datum is the plane of contact defined by implants upper surface. Because the attitudes of these planes (i.e. their normal vectors) are randomly oriented (the axis inclination of an implant is chosen by the dentist considering the consistency of the bone around the implant), there are several mating planes and often the dentist is compelled to reshape the external portion in order to reduce misalignments in the patient mouth. Using global dimensioning and tolerancing (GD&T) standards we should define one of these planes as datum plane, and express the angular tolerance of others with respect to it (Figure 2).

The choose of tolerance in this case is highly dependent on the assembling sequence. Moreover the tolerance for the location of the holes centres has to be correctly allocated. This would lead to have a lot of information to be checked. This is not a smart way to face the problem. Substituting the mating surface constraints with the spherical ones the tolerance allocation effort is reduced. It is sufficient to check holes location and misalignments between implants and framework structure axis, neglecting the attitude of local contact plane. The tolerance allocation procedure in this case is quite independent from the assembling sequence.

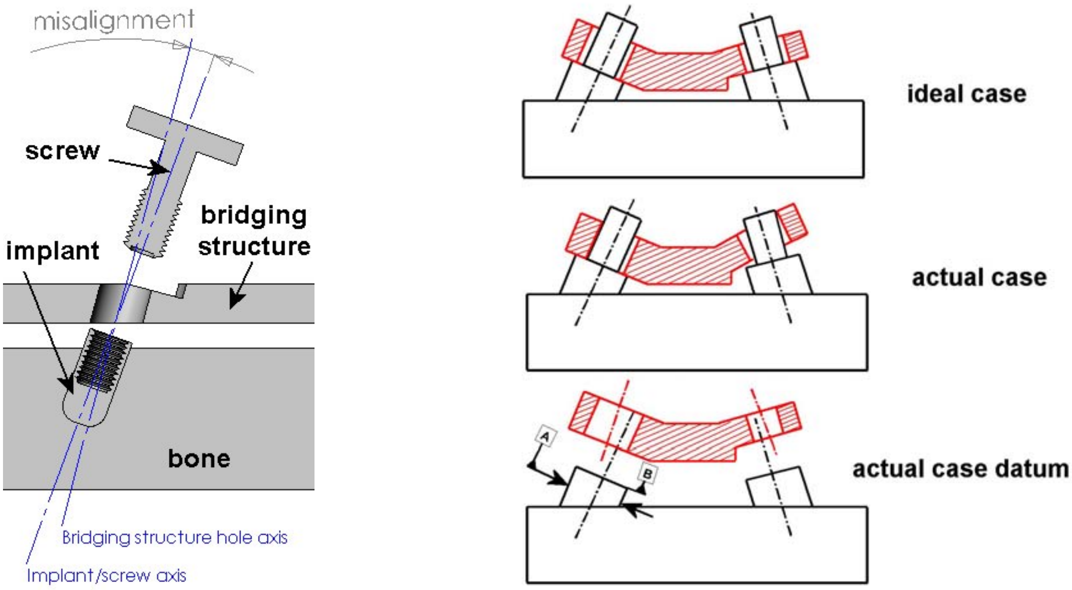

Figure 2: Standard connection leads to overconstrained system with difficulties in tolerance allocation and specification (abutments have not been considered)

The other advantage of using spherical joint is the possibility to better distribute the loads (coming from both location errors and from biting) along the framework and on the bone (stress shielding effects). Moreover the screws have a lower stress level. The comparison between fixed constraint system and spherical connection system has been evaluated using a three dimensional complete model of bone (both cortical and trabecular) and implants and skrews (Figure 5). In the next part of the section the fixed constraint system will be referred as "classic" and that with spherical connection as KiSSI (acronym of Kinematic Stress Shielding Implant). Both models are made of a bridging structure mounted on four implants with four screws. The fixed connections have been simulated using tie contact model between mating surfaces and spherical constraints have been simulated placing fictitious nodes at the centre of the spherical surfaces and using a pinned node-to-node constraint. For spherical connections, friction in joint has been included using a Coulomb approach. Two different load cases have been implemented.

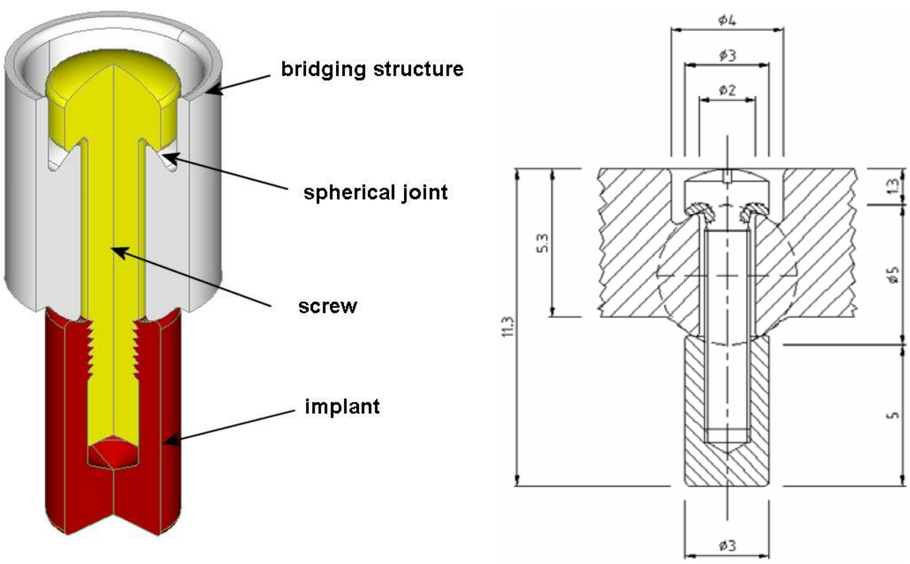

Figure 3. Spherical joint connection: CAD model and dimensions

The first is about the presence of location error due to hole centre misfits and the second is a set of the following biting loads (Figure 4):

- Load set 1: bridging structure is loaded with an vertical force of Fz = -60N and a radial force of Fr = 60N on the central incisive. Lateral incisive is loaded with a Fz = -20N and Fr = 10N.
- Load set 2: canine is loaded with Fz = -50N and Fr = 7N. First premolar is loaded with Fz = -150N and Fr = 7N, while second premolar is loaded with Fz = 250N and Fr = 10N.
- Load set 3: on one mouth side is applied a total force of Fz = 200N, on the other side is applied Fz = 150N. Then, all three molar and two premolar are loaded with Fz = 40N on the first side, and with Fz = 30N on the second side.
- Load set 4: the entire load of Fz = -400N is applied on the second premolar.

Material properties used in the model are summarized in Table 1. Some interesting results coming from the simulations are reported in Table 2. It can be noted that in case of a misfit of the KiSSI model the stress in the system is reduced of about 30÷45%. Contour plots of some simulations are depicted in Figure 5. It can be noted that the effect of mounting errors generates high level stress around the misfit. In the KiSSI solution both stress transferred to the bone and that on the bridging structure is well distributed without sensible peaks. This behaviour improves the comfort for the patient and reduces the risk of system failure .

Table 1: Material properties used in finite element models

Component	Material	Properties
Implants and screws	Titanium	Young's modulus E =1.05e11 Pa
		Poisson's ratio ν = 0.37
Cortical bone	Bone	Young's modulus E = 1.7e10 Pa
		Poisson's ratio ν = 0.30
Spongy bone	Bone	Young's modulus E = 2.25e8 Pa
		Poisson's ratio ν = 0.30

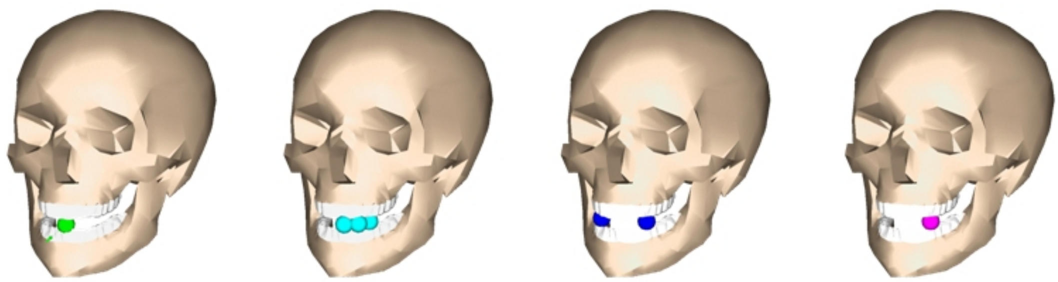

Figure 4. Loads from biting activity

Table 2: Comparison between classic and KiSSI solution (misfit)

Misfit	**Classic**		**KiSSI**	
	Max Von Mises stress [MPa]	***Location***	***Max Von Mises stress [MPa]***	***Location***
0.1 mm misfit of 33rd pos. implant location	37.39	Bridging structure	20.35	33rd screw
0.1 mm misfit of 36th pos. implant location	47.50	36th pos. implant	34.40	Bridging structure

Since the proposed finite element models are based on linear equation (i.e. small deformation), the results in Table 2 can be used to compute sensitivity coefficient. (as those the first section of the paper). Considering max stress as design specification and misfit as parametric variable t_i, the sensitivity coefficient may be approximated with a simple ratio between maximum stress and the misfit amplitude which has caused it:

$$\chi_i = \left. \frac{\partial \psi}{\partial t_i} \right|_{t=t_m} = \frac{\sigma_{\max,i}}{t_i} \quad i = 1..n\_implants \tag{4}$$

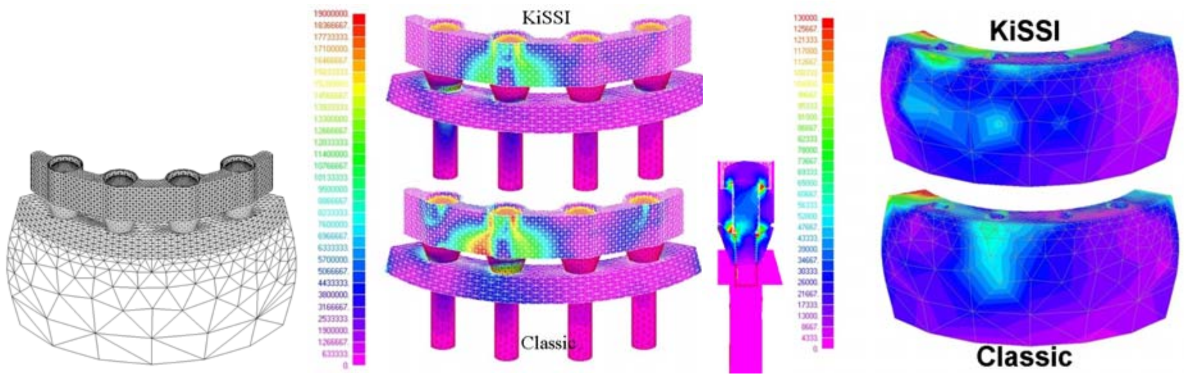

Figure 5. Finite elements analysis of different solution in case of misfit

3. Case study 2: Tolerance and shape analysis of impression tray

The second case study is about the investigation of the influence of holes clearance and shape variation on impression tray dismounting errors in order to improve tolerance allocation. The impression tray (Figure 6) is necessary to acquire information about the position of the implants in the mouth of the patient and to built the framework structure. Generally it is made of pattern resin and it has as many copings as the implants are. After the insertion of implants, the dentist builds a reference resin structure (individual tray) with several holes in correspondence to implants. Then, he inserts the copings into the implants through the holes and fixes them to the individual tray filling the clearance with other liquid resin which hardens in the mouth. Since small copings' positioning adjustments are permitted by the resin before it hardens up (it takes less than 1 min), a good accuracy can be achieved. As discussed in the previous section, the angular misalignments among the axes of the implants can not be completely avoided because their inclinations are chosen by the dentist according to biological and biomechanical opportunities. Clinical practice shows that the angle between two different axes can be up to 40°. Due to these misalignments the mounting and dismounting operations the copings (titanium supporting elements fixed in the impression tray by resin) interfere with the implants geometry and it is necessary to have a small compliance in order to insert or extract them from implant housing.

In this case, because the axial inclination of implants is independent from the manufacturing problem, shapes has to be design to ensure successful operations in the worst case. It means that our design specification will be the maximum stress, and design variables will be geometrical dimension excepting axial misalignments which are chosen in the worst case.

The geometry of the components has to be model and reconstruct with accuracy. The entire assembly is made of the following components:

- an external portion of cortical bone;
- an internal portion of trabecular bone;
- 6 implants (different in shape and dimensions);
- 6 copings (different in shape and dimensions);
- 1 substructure (individual tray);
- 6 resin inserts to connect the coping with the individual tray

Figura 6. 3D virtual model of impression tray and bone with implants

Titanium and bone properties have been chosen according to Table 1, Individual tray and insert resin properties are reported in Table 4.

Table 4: Resin properties

Part	Material	Properties
Individual Tray	Resin	Young's Modulus $E = 8.74e9$ Pa
		Poisson's ratio $\nu = 0.35$
Connecting inserts	Pattern resin LS	Young's Modulus $E = 1.58e9$ Pa
		Poisson's ratio $\nu = 0.35$

As design variables, we have chosen the clearances in the individual tray which affect the thickness of connecting resin inserts (Figure 7, on the right). What we are going to investigate is the influence of these clearances on maximum stress in the structure during dismounting procedure. During this extraction, due to axial misalignments, the copings lower surfaces interfere with those of the implants and dismounting is possible only with a small compliance (Figure 7, on the left). This compliance causes mechanical stresses in the structure which may cause permanent deformations or impression tray failure [17].

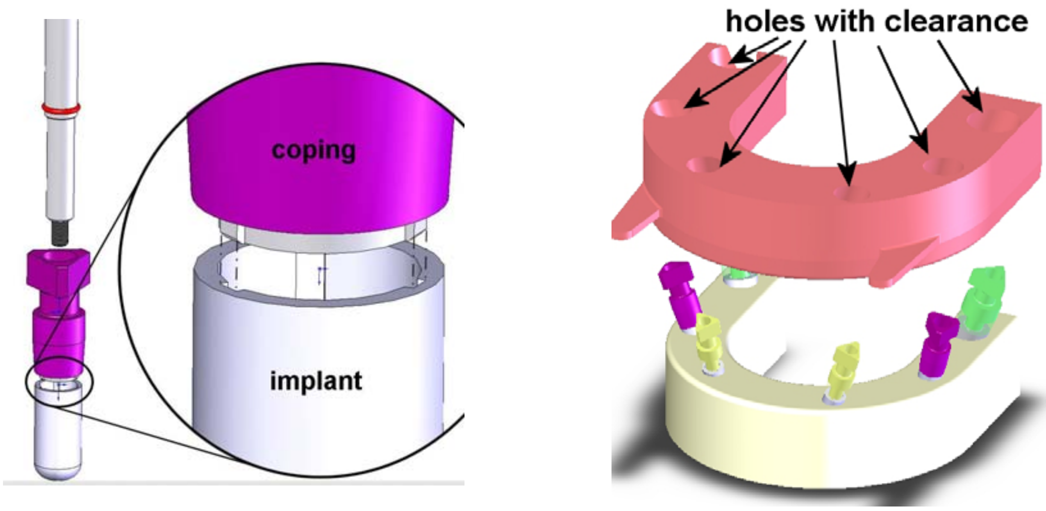

Figure 7: Implant-coping connection and clearance of the holes

Because of the contact condition, which has to be modelled as a free surface contact (i.e. an intermittent contact with possible separation) the problem is non linear and the computation of the sensitivity coefficients is quite more difficult than the previous case. It needs several runs of different models with different values of design variables [18]. Although the equations of the system are non linear, the stress distribution is qualitatively the same for each run; an example of results is depicted in Figure 8. It can be noted that there are some zone of stress concentration in the bone, at the insert/individual tray interfaces and at coping/insert connections. This last zone is the most critical because an high stress may cause the detachment of coping. The influence of impression tray clearances on this max stress level is presented in Figure 9.

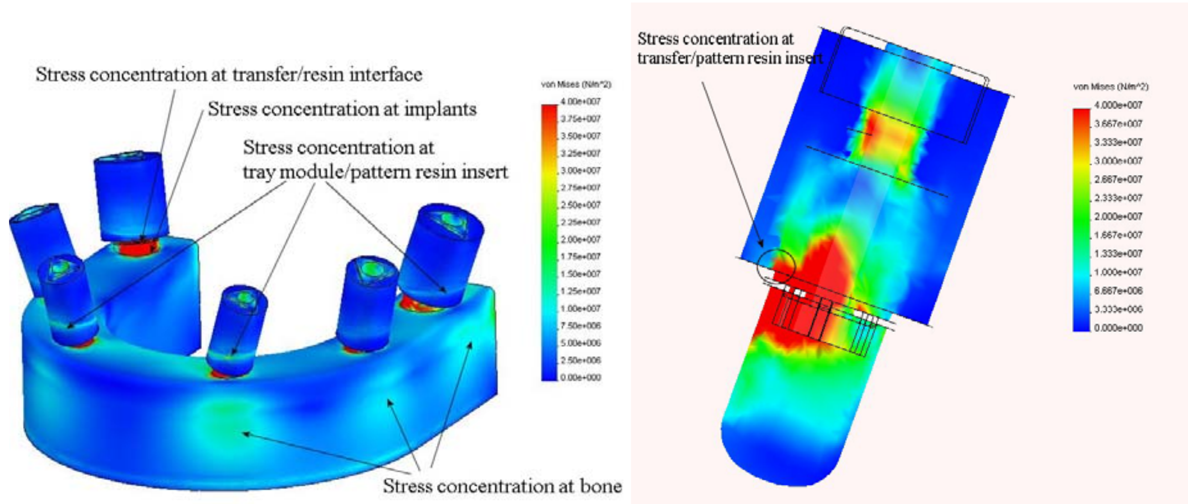

Figure 8: Von Mises stress in components.

In Figure 9, the influence of coping shape is also presented. It can be noted that the influence of hole clearance (an consequently of pattern resin insert thickness) on stress has a non linear behaviour. For small clearance the stress level is very high and it happens because the thickness is to small to allow elastic compliance. In this zone an increasing of the clearance gives a sensible benefits. For clearance value greater than 3 mm an increasing of its value gives not benefits, and it happens because the local stress concentration does not reach the boundaries of the pattern resin insert. This behaviour is also common for a different shape of the copings with small difference. Tolerance of both dimension and geometry of copings have not been investigated because their accuracy is higher than those of manual manufactured components such as insert and tray.
Choosing a reference value for clearance, the sensitivity coefficients can be computed as the derivative of plots in Figure 9 with respect to clearance. These coefficients can suggest to the operator to choose an appropriate clearance avoiding the waste of material and the risk of too long hardening time.

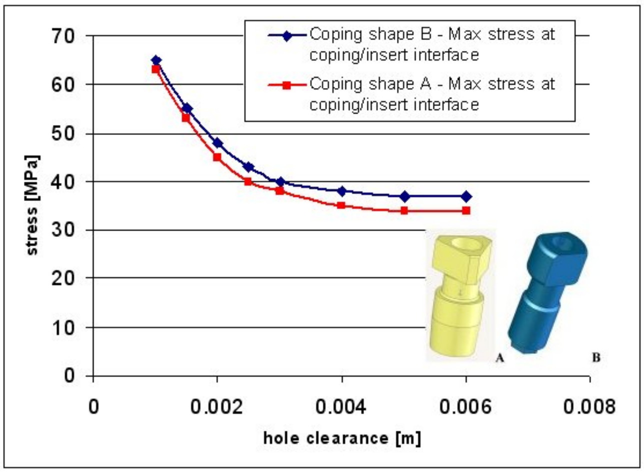

Figure 9: Maximum stress for different shapes as a function of clearance.

4. Conclusions

In this paper two different kinds of investigation on dental prosthesis based on screwed implants have been presented. They both have been based on the performing of simulations using virtual model (CAD and Finite Element Model). These methodologies allowed to study the effect of misalignments,

misfits and shape modifications on the performance of the systems. In particular, starting from their results, the sensitivity to design variable variation can be explored, and these information can be used to allocate the optimal tolerances.
In the first case study it has been proposed a modification of the shape of screws head in order to reduce the stress generated by misalignments. Numerical simulations confirms that the reduction of stress level can reach the 30÷40% with respect to the standard solution. On the other hand the modification of the shape requires an accurate manufacturing of the components.
In the second case study it has been investigated the variation of the impression tray holes clearance and its effect on stress produced during impression tray dismounting. Results reveal that above a threshold clearance of 3 mm an increasing of its value gives no benefits for reducing stress.

References

[1] Helldén, L.B., Dérand, T., 1998, Description and Evaluation of a Simplified Method to Achieve Passive Fit Between Cast Titanium Frameworks and implants, *Int J Oral Maxillofac* Implants, vol. 13, pp. 190-196.

[2] Goll, G.E., 1991, Procedures of accurately fitting full-arch implant frameworks. Part I. Clinical Procedure, *Journal of Prosthetic Dentistry*, vol. 66, pp. 377-84.

[3] White, G.E., 1993, Osseointegrated Dental technology. *London: Quintessence*, pp.61-94.

[4] Adell., R., Lekholm, U., Rockler, B., Brånemark, P.I., 1981, A 15-year study of osseointegrated implants in the treatment of edentulous jaw. *Int J Oral Surg*, vol. 10, pp.387-416.

[5] Davis, D.M., Rimrolt, R., Zarb, G.A., 1988, Studies on frameworks for osseointegrated prostheses: Part 2. The effect of adding acrylic resin or porcelain to form the occlusal superstructure, *Int J Oral Maxillofac Implants*, vol. 3, pp. 275-280.

[6] Riedy, S.J., Lang, B.R., Lang, B.E., 1997, Fit of implant frameworks fabricated by different techniques, *Journal of Prosthetic Dentistry*, vol. 78, pp. 596-604.

[7] Helldén, L.B., Dérand, T., Johansson, S., Lindberg, A., 1999, The CrescoTi precision method: description of a simplified method to fabricate titanium superstructures with passive fit to osseointegrated implants, *Journal of Prosthetic Dentistry*, vol. 82, pp. 487-491.

[8] Carr A.B., 1991, A comparison of Impression techniques for a five implant mandibular model, *Int J Oral Maxillofac Implants* vol. 6, pp. 448-55.

[9] Pietrabissa, R., Contro, R., Quaglini, V., Soncini, M., Gionso, L., Simion, M., 2000, Experimental and computational approach for the evaluation of the biomechanical effects of dental bridge misfit, *Journal of Biomechanics*, vol. 33, pp. 1489-1495.

[10] İpilikçioğlu, H, Akça, K., 2002, Comparative evaluation of the effect of diameter, length and number of implants supporting three-unit fixed partial prostheses on stress distribution in bone, *Journal of Dentistry*, vol. 30, pp. 41-46.

[11] Sevimay, M., Turhan, F., Kilicxarslan, M.A., Eskitascioglu, G., 2005, Three-dimensional finite element analysis of the effect of different bone quality on stress distribution in an implant-supported crown, *Journal of Prosthetic Dentistry*, vol. 93, pp.227-234.

[12] Bozkaya, D., Muftu, S., Muftu, A., 2005, Evaluation of load transfer characteristics of five different implants in compact bone at different load levels by finite elements analysis, *Journal of Prosthetic Dentistry*, vol. 92, pp. 523-530

[13] Ekici, B., 2002, Numerical Analisis of a dental implant system in three-dimension, *Advances in Enginnering Software*, vol. 33, pp. 109-113.

[14] Sertgoz A., 1997, Finite element analysis study of the effect of superstructure material on stress distribution in an implant-supported fixed prosthesis. *Int J Prosthodont*, vol. 10, 1997 pp. 19-27.

[15] Koca, O.L., Eskitascioglu, G., and Usumez, A, 2005, Three-dimensional finite-element analysis of functional stresses in different bone locations produced by implants placed in the maxillary posterior region of the sinus floor, *Journal of Prosthetic Dentistry*, vol. 93, pp. 38-44.

[16] Geramy, A., Morgano, S.M., 2004, Finite element analysis of three designs of an implant-supported molar crown, Journal of Prosthetic Dentistry, vol. 92, pp.434-440.

[17] Bozkaya, D., Műftű, S., 2003, Mechanics of the tapered interference fit in dental implants, *Journal of Biomechanics*, vol. 36, pp. 1649-1658

[18] Himmlová, L., Dostálová, T., Kácovský, A., Konvičková, S., 2004, Influence of implant length and diameter on stress distribution: A finite element analysis, Journal of Prosthetic Dentistry, vol. 91 issue 1, pp. 20-25.