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Interaction Phenomena between Dental Implants and Bone Tissue in Case of Misfit: A Pilot Study

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Abstract: The biomechanical response of cortical and trabecular bone tissues represents a fundamental aspect for the interpretation of the functional response of dental implants. In the case of misfit, the interaction phenomena occurring within the surgical and the subsequent healing phases must be interpreted primarily in the light of the response of bone tissue. This is influenced by the specific loadings induced, characterized by intensity and variable trends. The pilot study reported, which intentionally refers to a simple case of a two-implants frame, is addressed to define the method to approach the biomechanical investigation of the problem and to attest the necessity to integrate clinical competences with biomechanical analysis for interpreting different aspects of osseointegration. The action induced in cortical and trabecular bone regions depending on the implant frame conformation, the surgical procedure adopted, the varying condition at the bone–implant interface and the evolutionary trend of healing are the principal aspects to be considered to evaluate the osseointegration process. The biomechanical reliability of the specific implant frame is investigated in terms of bone–implant interaction by means of numerical models. This approach can offer valid information and support clinical practice under the fundamental condition that bone biomechanical behavior is properly characterized and represented in the model, in spite of the complex formulation to be adopted.

Keywords: dental implants; osseointegration; misfit; bone mechanics; biomechanical reliability

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1. Introduction

A dental implant ensures the replacement of oral functionality in totally or partially edentulous patients [1–5]. The use of endosseous implants has become quite common in dentistry and is characterized by a reasonable success rate. The fixity of the prosthesis and its reliability over time depends on biochemical and biomechanical factors. The functional behavior of the prosthesis from a biomechanical point of view is related to the interaction process of implants with peri-implant bone [2,6–10]. Within an implant frame, the manufacturing characteristics of components, such as coupling bars, must be evaluated to ensure the reliability of the overall system. Concerning multi-implant systems, misfit conditions can occur because the accuracy of the bar-manufacturing process is not always adequate for determining a perfect passive coupling between the bar and implants. Such misfit conditions can determine heavy stress in bone tissues and may compromise the reliability and durability of the prosthesis and the mandible bone health [11–15].

An important factor affecting the success of dental implants is the bone–implant interaction phenomena [16]. The stress and strain distribution at the bone–implant interface, related to the mechanical and biological properties of bone tissue in the jaw region, represents a term for the evaluation of process characteristics. At the interface, the biomechanical investigation pertains to an appropriate compressive strain that initiates osseointegration, while overstressing causes degradation with the consequent bone resorption, depending also on biological and biomolecular properties [17,18].

It is important to underline that the conformation of the peri-implant bone tissue and its mechanical properties undergo changes from the initial stage of implant insertion to the desired final stage of implant osseointegration. These changes are a function of different factors, such as the health conditions of bone tissues, and are influenced also by the specific surgical technique adopted. The subsequent change in the structural conformation of bone tissue over time, which is triggered and regulated by biomechanical and cellular factors, entails a variation of the strain and stress paths in the peri-implant region [17,19,20].

A growing interest has been shown for an analysis of these problems by means of computational methods, which make it possible to define accurate models of anatomical regions and prostheses and which also lead to the predictive information of the biomechanical response. The comparative analysis of the mechanical behavior of a fixed prosthesis as a function of different factors, such as bone strength, provides interesting data to evaluate the whole functional scenario that can be experienced [21–33]. In this sense, the proposed work aims to report a pilot study, which addresses the application of computational mechanics techniques in the field of dental implantology, providing information with regard to the required input data and output results.

The investigation of oral implants biomechanics by using computational approaches, such as the finite element method, needs the definition of geometrical conformation of the involved structures and the mechanical properties of bone tissue in the anatomical regions investigated and, in particular, in the peri-implant region that is characterized by a complex morphology. Bone tissue is a hierarchical, heterogeneous and anisotropic material [34–36]. The elastic properties of bone vary with anatomic location and orientation, and the great variability of the mechanical properties is evident [37–39]. Cortical and trabecular bone have distinct characteristics, varying in dependence on the location considered [11,31,32]. In addition, the peri-implant bone properties change, depending on biological and biomolecular characteristics and especially during the healing phase [20,40]. The correlation between material anisotropic properties and geometric conformation of a specific jaw region is demonstrated, showing the existence of an intrinsic optimization process, addressed to improve its mechanical performance. Similarly, the peri-implant tissue properties, which depend in general on biochemical and biomechanical factors, tend to an optimized conformation also as a consequence of the mechanical loading induced by the implant. Therefore, the accurate modeling of bone characteristics is an essential task for the development of reliable computational models of implant biomechanics [37,41,42].

The method proposed in this pilot study consists of distributing the bone properties in a specified region of the mandible model by using computational strategies and according to data from experimental investigation [37]. The capability of attributing bone mechanical properties with spatial variability leads to models characterized by high accuracy within different bone regions, such as the cortical and trabecular, or within the regions of transition between implant and cortical or trabecular bone, which undergo deep change over the healing trend [6,7,29,37,43].

The specific surgical approach to dental implantology can determine critical stress–strain conditions, up to the plastic deformation of bone material. Furthermore, the stress–strain field evolves in time because of viscoelastic phenomena [28,29,34]. Aiming at a reliable investigation of bone tissue functionality, the material behavior of both cortical and trabecular bones has been described by an orthotropic visco-elasto-plastic constitutive model [44]. The assumption of this complex formulation is imposed to have an accurate interpretation of implant biomechanics [30].

During the osseointegration process, the characteristics of the bone–implant interfaces progressively change, from a mutual-sliding condition to a full continuity between bone and implant material. Such an evolution of interface properties has also been implemented within the computational model by means of specific interaction strategies [21,30], aiming at an interpretation of the overall clinical procedure.

In summary, the paper aims at providing a pilot study that informs the different tasks of the computational investigation of dental implant functionality by means of a specific application to misfit conditions. Preliminarily, the focus is on the computational statement of the misfit problem. Subsequently, notes about the geometrical definition of both bone region and implants are provided. The next fundamental step pertains to the constitutive characterization of bone tissue, accounting also for the non-homogeneous distribution of bone mechanical parameters. Finally, a general overview of the post-processing of computational results is reported. The proposed investigations are performed by assuming an average model of a male Caucasian mandible [45,46]. In this sense, the model allows the development of "in silico trials", which entail a general reliability assessment for a wide segment of the population.

2. Materials and Methods

Figure 1 reports a scheme to define a misfit condition. In this specific case, the bar is assumed to be shorter than the gap between the two implants and the only misfit occurring is a translational gap along the line that joins the central position of the two implants [12,21].

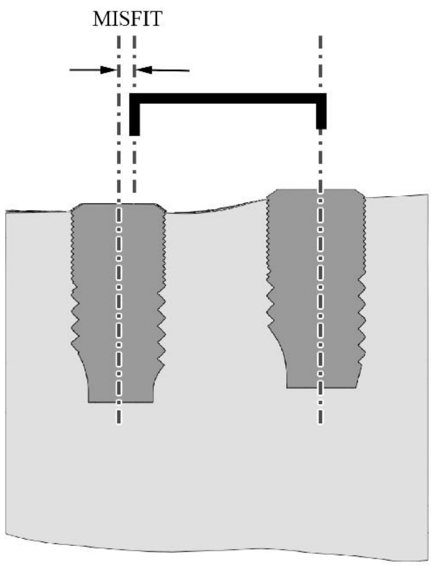

Figure 1. Transversal section of the mandible: scheme of the connecting bar, implants and detail of the misfit between bar and implant.

Computational strategies allow the analysis of many different misfit conditions, such as translational, rotational and coupled ones, according to different directions and to the coupling of different situations. In this sense, the computational approach makes it possible to investigate the mechanical effects of many different manufacturing inaccuracies.

2.1. Geometrical Definition

The geometrical conformation of the jaw segment is defined starting from anonymized CT data of different subjects. Image segmentation techniques lead to preliminary triangulated solid models (3D Slicer, Brigham and Women's Hospital, Boston, MA, USA). Subsequently, the interpolation by means of free form surfaces entails the virtual solid models (UGS NX, Siemens Software, Plano, TX, USA). Data from different subjects (Caucasian males) were processed while also accounting for anthropometric information, aiming to provide an average model for "in silico" trials [45,46].

3D CAD techniques are exploited to develop the implant model (AstraTech 4.0–8, Dentsply Sirona, Charlotte, North Carolina, USA). The specific implant is assumed because of its broad application. On the other hand, the proposed computational approach allows the analysis of all the implant shapes and conformations.

The virtual solid models are assembled and meshed using tetrahedral elements and assuming different element sizes for the different regions of the models (Abaqus/CAE 2022, Dassault Systèmes, Vélizy-Villacoublay, France).

2.2. Constitutive Model of Bone

Bone material properties must be characterized depending on the different phases of the interaction occurring between implant and bone. In the present investigation, the biomechanical effects of the press-fit process are not considered. The starting point for the analysis carried out is the condition where the implant finds its location on the basis of a standard surgical procedure, while the specific aspects of press-fit are not discussed while reference is given for research works in the literature [28,29]. The elastic phase of cortical and trabecular bone is characterized by the anisotropic configuration of the tissue, distributed along three orthogonal axes, as orthotropic conformation. This represents a form of optimization for the response of the tissue to different conditions. This entails relevant problems in the definition of the constants that characterize the behavior of the bone material and determines a considerable effort in its representation within the numerical model. In Figure 2, a representation is proposed for one of the nine fundamental parameters requested at each point for the definition of an orthotropic model. The cortical region shows a transition to the trabecular portion, recalling that all these data depend on the acquisition through an accurate experimental investigation. Particular attention must be paid to the peri-implant bone tissue, according to the fact that the properties vary depending on osteointegration process. In fact, these figures interpret the condition when osteointegration took place and it consequently follows the insertion of the implant.

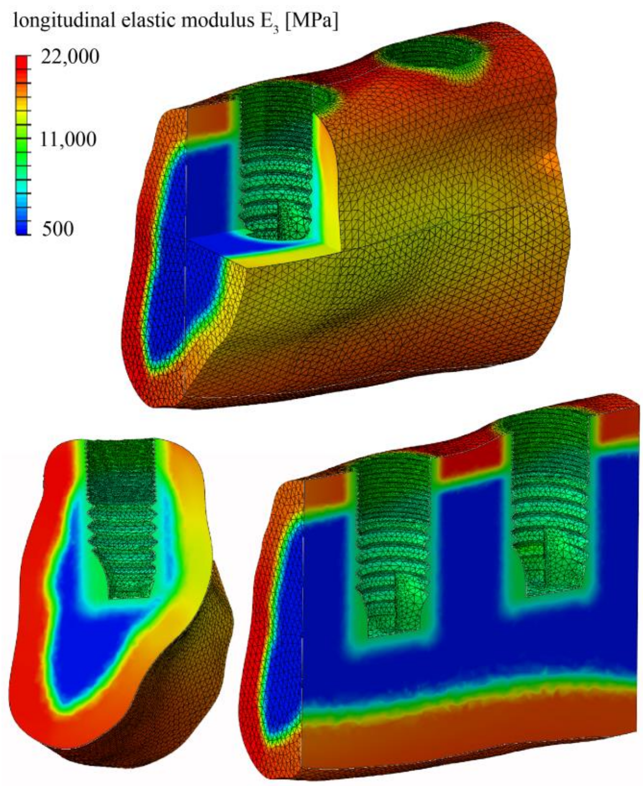

Figure 2. Numerical model: transversal and longitudinal sections reporting the values of elasticity modulus E_3, a parameter in the distal–mesial direction for anisotropy definition of bone material in the premolar region of the lower jaw. The figure refers to a condition that represents the osseointegration in progress.

Much more complicated is the description of the biomechanical behavior of trabecular and cortical bone tissue within the plastic phase and because of time-dependent phenomena. The general stress–strain relationship is reported below:

$$\sigma(\varepsilon, \varepsilon_p, t) = \mathbb{C} : (\varepsilon - \varepsilon_p) - \sum_i \mathbf{q}^i \tag{1}$$

where σ is the Cauchy stress tensor, ε is engineer strain tensor, ε_p is the plastic strain tensor, $\mathbb{C}$ is the orthotropic elasticity tensor and $\mathbf{q}^i$ are viscous variables that evaluate the relaxed stresses. The constitutive formulations which describe the behavior of bone tissues are fully reported in references, providing information regarding both model formulation and parameters identification [34,37,44]. In fact, the present work is mostly addressed to an overall evaluation of the relevance of these aspects and the necessity to consider them within a numerical model for an interpretation of the interaction phenomena occurring between the implant and the overall region of insertion.

2.3. Misfit Simulation

Finally, computational analyses are performed by means of the general-purpose finite element code Abaqus/Standard 2020 (Dassault Systèmes, France). The connecting bar–implant misfit is defined by means of a multipoint constraint approach. The upper surface of the implant is linked to the anchoring site of the bar. The imposition of a relative displacement between the implant and bar entails the misfit condition [21].

Particular attention is paid to the bone–implant interface, according to the fact that, depending on the osseointegration process, different cohesive forces can be expressed by the bone in the interaction with the implant. This aspect strongly affects the results, as reported in the following, and interprets the specific condition also in relation to the fact that the misfit can take place in case of immediate loading, where integration is not adequately active, and, on the contrary, in long-term conditions [21,30]. In detail, the properties of the bone–implant interface can be simulated by means of a tie condition, when complete osseointegration can be assumed, or contact strategy, when partial osseointegration characterizes the system and sliding phenomena can occur.

The computational analyses are performed by assuming an implicit static solver. On the other hand, when more complex situations are investigated (i.e., coupled press-fit and misfit simulations), explicit solvers must be adopted.

3. Results

In Figure 1, the basic configuration of the misfit is provided, while Figure 2 reports the anisotropic distribution of material properties. The identification of the orthotropic elastic constants results from the interpolation of data from experimentations on human cadaveric jaws, while the orthotropic directions are defined on the basis of both experimental results and local bone morphometry [37]. Figure 3 represents an overview of displacement magnitude and plastic strain induced by translational misfit on the implants. The manufacturing inaccuracy is assumed along the distal–mesial direction.

This view confirms the relevant stiffness of the implants that behave almost as a rigid body depending on the action induced by the coupling bar, without significant deformation in comparison with bone tissue. In particular, the specific situation pertains to the case of the potential detachment occurring on one side of the implant, where traction is overcoming the adhesive force expressed by osteointegration. On the opposite side of the implant, the compression is increased because of the reduced contribution of bone in traction to withstand the overall action induced. The section reported offers a clear view of the displacement field in a portion of the section, with an accuracy that is characteristic of numerical model potentialities and which overcomes every experimental test.

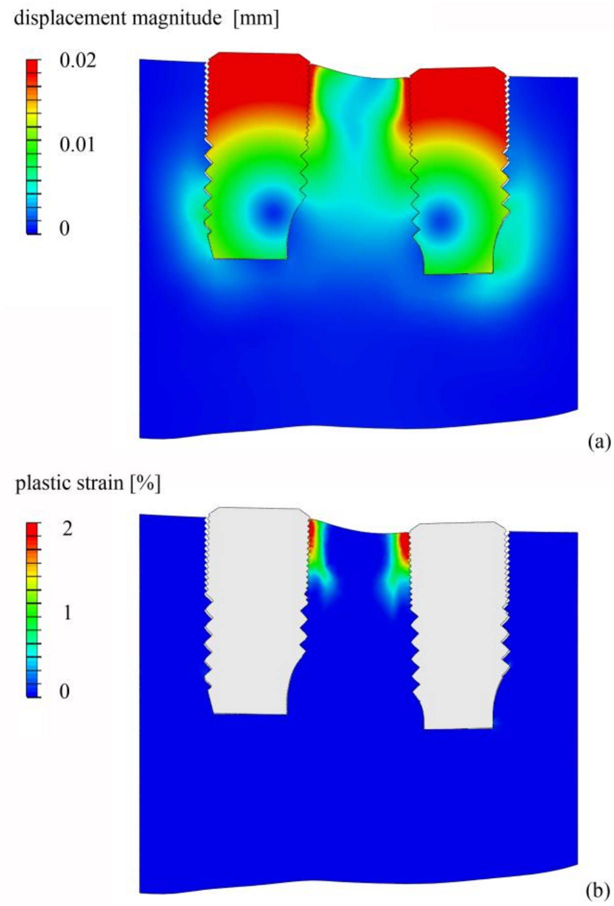

Figure 3. Numerical analysis. Magnitude displacement (a) and plastic field (b) on a longitudinal section of the mandible at the final time step of the application of the misfit. The specific condition considered entails the potential detachment of the implants, as outlined in magnitude displacement field contour.

Figure 4 reports a detail of displacement distribution within the mandible and implants because of misfit application. In Figures 5 and 6, the scheme of time-dependent response in terms of stress relaxation is proposed, considering the variation in time. In fact, the stress induced by the coupling of implants with the connecting bar shows a decreasing intensity in time depending on the so-called relaxation process (Figure 5). Bone time-dependent phenomena must be carefully considered, evaluating the effects in time of stress (Figure 5) and permanent deformation (Figure 6). The time gap assumed is of the order of 1000 min to cover the full range of the process, with a large margin, as the process usually arrives to a final configuration in a shorter time.

In Figure 7, the upper view of the mandible region in the numerical model is reported, with the indication of the strain path along the inter-implant distance. Along this path, strain distributions are reported for the three different conditions at the application of the misfit. In detail, three conditions of bone–implant interface are analyzed, such as full continuity, cohesive contact and sliding contact. The former conditions represent a fully and a partially osteo-integrated situation, respectively, while the sliding contact describes the structural response when the coupling bar is applied immediately after implant placement.

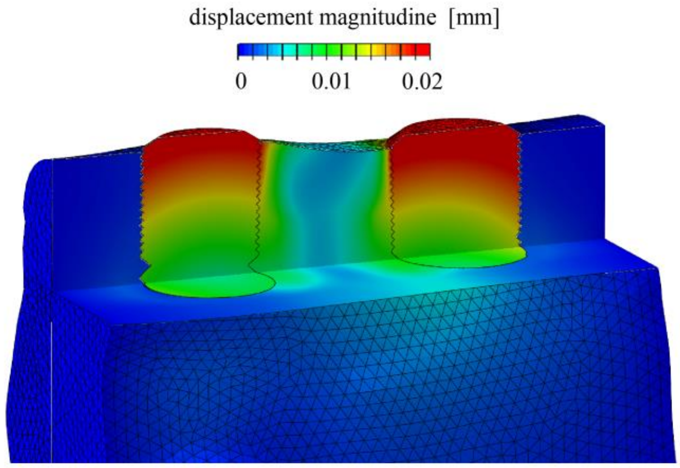

Figure 4. Numerical analysis. Displacement magnitude on the mandible at the application of the misfit.

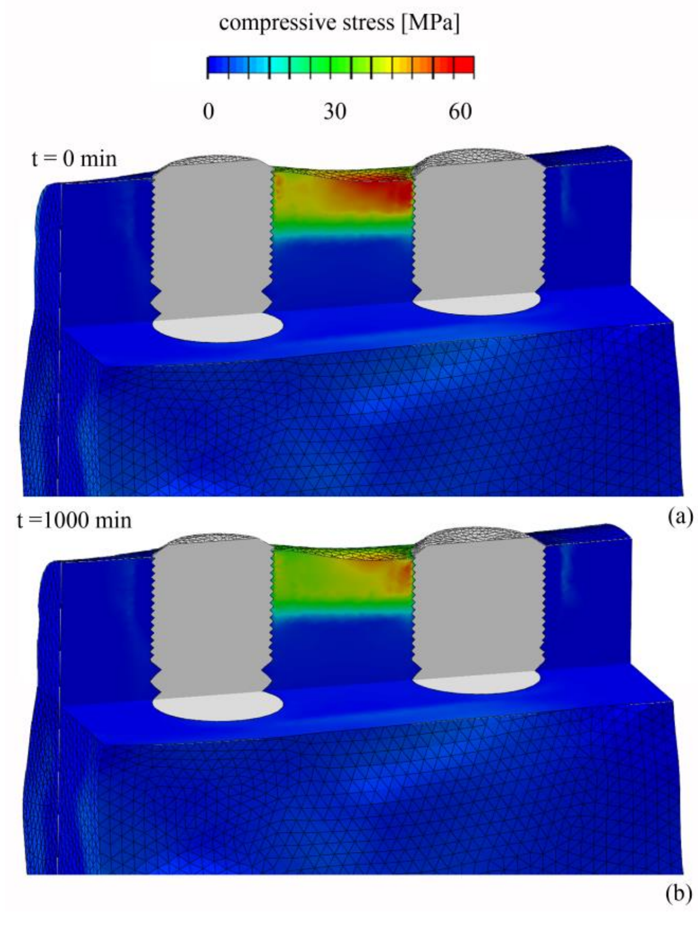

Figure 5. Numerical analysis. Compressive stress on the mandible at the application of the misfit (a) and at the end of the relaxation process (b).

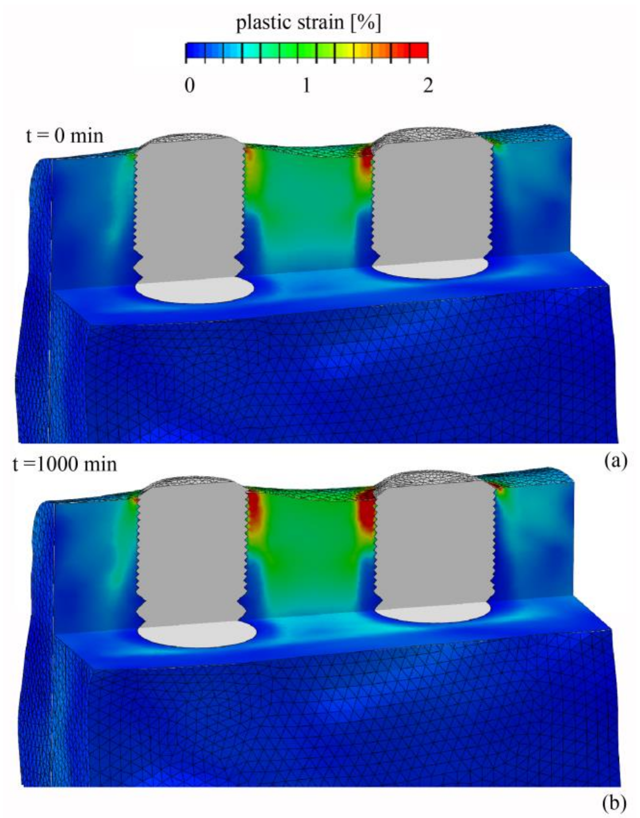

Figure 6. Numerical analysis. Compressive strain on the mandible at the application of the misfit (a) and at the end of the relaxation process (b).

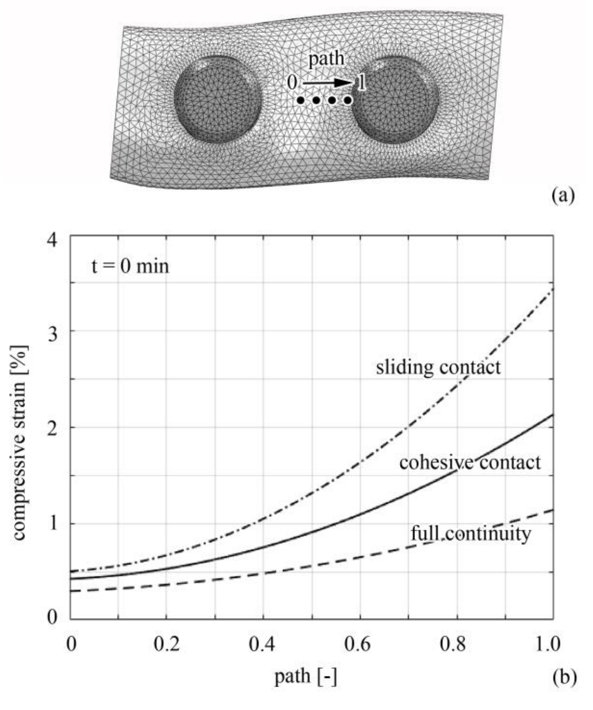

Figure 7. Upper view of the mandible region in the numerical model, with an indication of the strain path along the inter-implant distance (a). Compressive strain distributions along inter-implant distance are reported for the three cases analyzed at the application of the misfit (b).

As a reference case (Figure 8), images of a radiographic control of a real clinical case are reported with regard to a bar that couples two implants to recall the case investigated by numerical models. It also includes the view at delivery time, which shows the healthy status of peri-implant mucosa, with a valid emergence profile and access for self-performing oral hygiene.

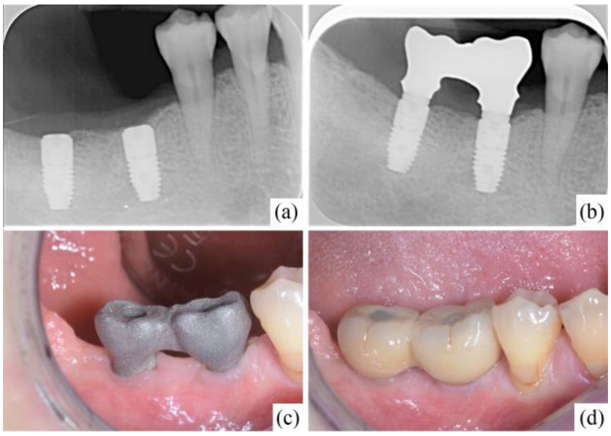

Figure 8. Two-implants framework, as a clinical case. Radiographic images without (**a**) and with (**b**) CAD–CAM coupling bar. Image of an imposed bar (**c**) and ceramic prosthesis (**d**) as final configuration.

4. Discussion

Results reported show a large and complete set of data that can represent in a very accurate and complete form the biomechanical problem proposed and can support the understanding of the overall process, allowing for the interpretation of the mechanical response in the different interaction conditions between bone and implants.

It is evident that the definition of the biomechanical properties of bone tissue represents a fundamental point for the analysis to be developed and determines the reliability of the results obtained. This task is heavy to be managed, as it entails the basic knowledge of mechanics in elastic, plastic and viscous phases. The difficulty is related to the capability to define the specific constitutive models, intended as models capable to represent the relationship between stress and strain history in the tissue, while also considering the variation in time having a constant deformation imposed because of the misfit. Evidently, a substantial degree of experience in material mechanics and in computational modeling is naturally required for the purpose because of the relevant complexity to consider all these data within the numerical model developed [21,30,37,41].

The reported activities and results pertain to the general approach of "in silico medicine", with particular regard to computational biomechanics [47]. Such a general approach is based on the computational models of the anatomical region under investigation. The models are developed by performing coupled experimental and computational activities. Experimental data are mandatory for model development, identification and validation. Subsequently, the computational model allows experimental results to broaden to an extremely wider scenario, considering many different conformations of the biological structure, such as many different patient conformations, as well as many different loading conditions, such as many different surgical procedures. Furthermore, the computational approach provides information that experimental activities barely supply, such as the stress and strain fields. Within the framework of the mechanics of biological tissues and mechanobiology, strains and stresses are responsible for many different phenomena, such as tissue damage, tissue adaptation and mechanotransduction. In detail, the proposed approach herein allows for evaluating plastic strain distribution within bone tissue and its evolution in time. Such data are mandatory to predict bone tissue adsorption/deposition and necrosis [48,49] and, consequently, intervention reliability.

The overall action requires a positive integration of competences between biomechanical, biomedical and surgical experience, and must be addressed to cooperate toward the formulation of models that adopts the very sophisticated approach to interpret the surgical practice in the most effective form.

With specific regard to the reported simulations herein, the results pertain to an average conformation of the jaw and to average mechanical properties of bone tissues. On the other hand, edentulous patients frequently show a modified conformation of the jaw and degenerated mechanical properties of the bone. Furthermore, the proposed investigations account for a linear misfit, while manufacturing techniques entail a more complex coupling of bar and implants. However, the computational approach here proposed can be used to simulate many different implant configurations, considering patient-specific morphometry for CT data and bone mechanical properties [41]. In this sense, computational models provide data that allow the presurgical evaluation of intervention reliability and efficacy.

It is necessary to underline the relevance of both biomedical and biomechanical investigations of dental implant procedures and devices [12,15]. The former provides the definition of novel techniques and approach together with experimentations on animal models and clinical trials [50,51]. On the other hand, biomechanical analyses specifically investigate mechanical suitability, accounting also for mechanobiological processes [25,52]. Biomechanical, biomolecular and cellular factors influence bone tissue properties and functionality after implant placement. Specific mathematical formulations can be implemented to interpret such phenomena within computational simulations of surgical implantology.

In general, a comprehensive and reliable investigation of dental implantology requires a correlation between biomechanical and clinical competence. It is evident that the complete formulation and a detailed numerical model can offer a valid interpretation from a biomechanical point of view and can investigate every single aspect of the phenomenon. The complexity of the approach must be faced avoiding much easier approaches based on unacceptable approximated assumptions that affect result reliability.

5. Conclusions

The present investigation confirms the potentialities offered by a numerical analysis of bone–implant interaction phenomena, mostly in complex conditions such as misfit, where manufacturing, surgical and tissue biomechanical aspects contribute to a mutual support for the definition of procedure reliability. The relevance of an accurate definition of the mechanical behavior of trabecular and cortical bone tissues in different phases results in strong evidence. The appropriate evaluation of tissues' mechanical properties and the different couplings between implant and tissues must be considered to reach to an appropriate characterization of the overall process. The identification of bone tissue mechanics must be defined in the framework of a theory that interprets all the involved phenomena. With specific regard to the investigated surgical procedures in this work, the analysis must account for permanent strain effects and time-dependent phenomena, suggesting the adoption of a visco-elasto-plastic formulation.

This investigation is also proposed for the possibility of interpreting different conditions that the surgeon must face during practice, considering, for example, the effects due to variable misfit intensity, bone mechanical properties and the integration process depending on age or on biochemical treatments. This consideration leads to a large set of potential simulations of different conditions that offer the opportunity to define a presurgical interpretation of different problems and a sensitivity toward a variety of effects induced by operational conditions.

The reported activities suggest the suitability of "in silico trials", which are performed on the basis of the average models of the anatomical district for the biomechanical investigation of surgical procedures in dental implantology. In detail, "in silico trials" allows the design, the optimization and the reliability assessment of both procedures and devices. An investigation of a misfit condition is reported to enforce the strength of the computational approach. Aiming to address the presurgical design of the intervention, "in silico medicine" can be further exploited by means of patient-specific models.

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