Biomechanical Analysis of Different Implant-Overdenture Loading Protocols under Dynamic loads

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Abstract: Each implant loading protocol had its merits and demerits. After loading, immediate loading implants and surrounding bones may respond differently to the applied masticatory force. Two 3D finite element models were designed representing each loading condition (immediate and delayed loading). The implant components included implant fixture carrying a stud overdenture attachment. All materials were set as isotropic except for bones where anisotropic behavior was selected. A frictional surface-to-surface contact was assigned to the bone-implant interface of the immediate loading finite element model while a bonded contact was used for delayed loading model. Another frictional contact was also used between the plastic clip and stud abutment for both groups. The models were mesh and refined in the finite element meshing module. Both models were constrained at the inferior border of the bone with (0-Dgree) of freedom in all axes. Three combined dynamic loads (time-dependent) were applied on the outer surface of the metallic housing of the attachment. Von mises stress and strain were evaluated for implants and attachments and maximum and minimum principles stresses were assessed for both compact and cancellous bones. The results of the immediate loading model showed higher von misses stress values at the implant and the stud abutment components than the delayed loading group, respectively. Similarly, both maximum and minimum principle stress of the immediate loading bones were higher than that of the delayed loading bones.
[Hussein MO. **Biomechanical Analysis of Different Implant-Overdenture Loading Protocols under Dynamic loads.** *J Am Sci* 2013;9(12):77-85]. (ISSN: 1545-1003). http://www.jofamericanscience.org. 12

Keywords: Dynamic loading, immediate loading, delayed loading, implant-overdenture, frictional contact, 3D-finite element.

1. Introduction

Implant stability with absence of micromovement is essential requirement for successful implants osseointegration. Accordingly, four to six months of healing period was usually recommended. Although, this healing period was empirically based and not experimentally ascertained. Consequently, it is logical to realize whether this healing period is an absolute prerequisite for osseointegration, or under certain circumstances, this period could be shortened without jeopardizing osseo-integration and overall treatment outcome (Collaert & De Bruyn, 2008).

There is a competition between different implant loading protocols at the last few years. This competition seems to be a challenge between reducing treatment time and efficiency of osseointegration (Collaert & De Bruyn, 2008), (Bergkvist et al., 2009) and (Tealdo et al., 2011). Among various loading protocols used, the main types mentioned in the literature and applied in clinics are delayed loading and immediate loading (Bergkvist et al., 2009), (Tealdo et al., 2011), (Alfadda et al., 2009) and (Ibañez et al., 2005). Immediate loading was used successfully in the anterior zone of edentulous mandibles provided the most predictable results either fixed or overdenture prosthesis (Bergkvist et al., 2009). Tealdo et al. (2011) studied the long-term survival rate and radiographic outcome for edentulous maxilla after immediate and delayed loading. The results showed no significant difference between both loading types. Moreover, both loading types were assessed clinically and radiographically in fresh extraction sockets of the maxillary esthetic zone. They also found no significant clinical or radiographic differences after 2 years of follow-up between immediate and delayed loading (Crespi et al., 2008). Similarly, implant stability at maxillae of minipigs were studied to compare loading time. After four months of healing, the implant stability was improved under functional loading (Nkenke et al., 2005).

One-year results of a randomized controlled trial including different loading conditions of single mandibular molars showed comparable clinical outcomes (Meloni et al., 2012). Furthermore, Romanos et al. (2006) evaluated implant loading protocols at the posterior mandibular area in a prospective clinical study of 12 consecutive cases. They concluded that the difference between the studied groups were non-significant and recommended further studies with a larger sample size and a longer follow-up period. Moreover, Lahori et al.(2013) conducted a clinical study to evaluate the peri-implant bone changes after immediate and delayed loading periods. They evaluate crestal bone level and implant stability both radiographically and by periotester. They confirmed that changes between studied groups were significant for implant stability and bone density and insignificant for bone height.

After 6 months of functional loading in the maxilla, the loaded implants were evaluated histomorphometrically versus the unloaded implants. The results of both groups showed similar findings (Blanco et al., 2013). Although, experimental animal trials recognized increased bone density for immediately loaded, rigidly splinted implants compared to unloaded ones in the maxilla (Piattelli et al., 1993) and (Piattelli et al., 1997).

Change et al. (2012) used finite element method to evaluate the influence of various thread profiles of immediate implants on implant stability. The higher capability of the used profile to grip bones, the lesser the micromotion generated and so more implant stability. From all studied profiles, the square thread profile showed the most preferable design. Similarly, kong et al. (2009) examined the most suitable implant diameter and length for immediate loading plan. They applied a nonlinear finite element method to analyze the maximum von mises stress of bone and displacement of implant-abutment complex. The results showed that both increasing the diameter (above 4mm) and length (above 11mm) minimized the generated stress and displacement. Furthermore, Eser et al. (2009) confirmed the previous nonlinear finite element method using in-vivo strain gauge analysis. The results of both methods were comparable and confirmed the research hypothesis.

Akca et al. (2013) were not able to distinguish the difference of axial and lateral strains between immediate and delayed loading implant-overdentures. In contrast, Huang et al.(2008) concluded that immediately loaded implant with smooth machine surface ($\mu = 0.3$, μ represents frictional coefficient) increased the bone stress by 28–63% as compared with the osseointegrated implants (bonded interfaces). Roughening the implant surface ($\mu > 0.3$) did not reduce the bone stress; however, it decreased the interfacial sliding between implant and bone. Thus, several researches used the frictional type of contact with a frictional modulus ($\mu = 0.3$) to represent the interface between implant and bone of immediate loading condition (Hussein & Rabie, 2013), (Cehreli et al, 2004) and (Brunski et al., 2000).

Merdji et al. (2012) used the combined dynamic loading successfully to simulate masticatory process. The results indicated that the maximum stresses were located around the mesial neck of the implant facing the marginal bone. Benaissa et al. (2013) used the same technique to evaluate the mechanical behavior of a dental prosthesis under two loading types (dynamic and dynamic within overload).

To date, there is no decisive conclusion regarding suitable loading time. The clinical results were discordant; some authors recommended increasing the sample size, while others preferred within-subject studies ((Collaert & De Bruyn, 2008), (Bergkvist et al., 2009) and (Meloni et al., 2012). Other experimental studies were not able to finalize what is the optimal loading protocol regarding treatment time and osseointegration efficiency, (Nkenke et al., 2005) and (Blanco et al., 2013). Therefore, the aim of the present study is to compare the immediate and delayed loading protocol using standardized parameters under realistic loading environment.

2. Material and Methods

Two 3D models were designed using CAD software (SolidWorks Corporation, Concord, MA, USA). The implant fixture was designed by simulating the dimensions and configurations of the NobelActive implant fixture (NobelActive; Nobel Biocare AB, Göteborg, Sweden). Images of the target fixture were used as a base for several building and subtracting operations to represent the unique characteristics of this implant type. The fixture tapering, screw and groove were simulated. Additionally, the apical cutbacks and the coronal steps were formed. The attachment assembly was composed of four parts, abutment screw, gold stud locator, plastic clip and the metallic housing. All components were designed to fit preciously to its counterpart through using several Boolean operations available in the CAD program, (fig. 1). The cancellous bone was modeled to simulate part of the mandibular bone using simplified cross section outline. The compact bone was also designed by forming a shell of variable thicknesses (1-2 mm), (fig. 2).

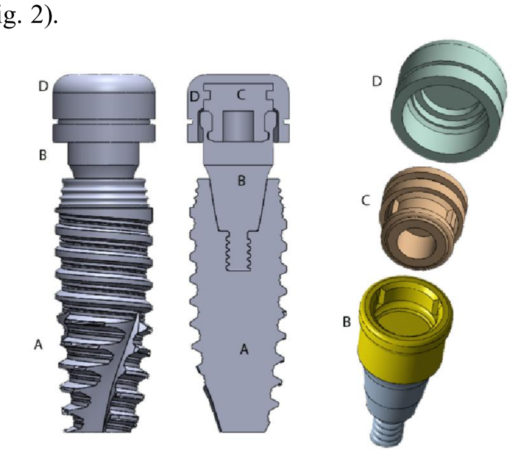

Figure 1: Nobel Active implant fixture and locator stud attachment assembly models. A; fixture, B; stud abutment, C; plastic clip and D; female housing.

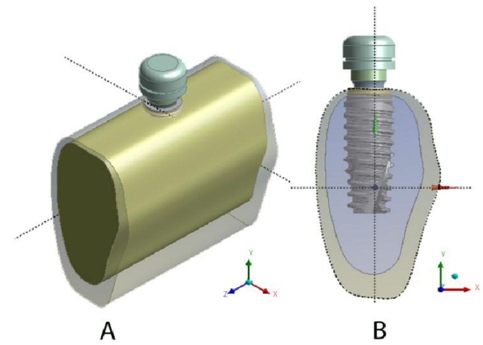

Figure 2: Compact and cancellous bones modeled by Solid Works surrounding implant fixture. A; isometric view and B; side view.

After model preparation, the Solidworks assembly was opened in the design modeler module of the finite element analysis software (ANSYS Workbench v 14 package; ANSYS, Inc., Canonsburg, PA, USA) directly through ANSYS plug-in for Solidworks. Material properties were assigned using two values (Young's modulus and Poisson's ratio) for all isotropic parts (fixture and its assembly). Bones were considered anisotropic materials where nine values were used for each type, (Table 1).

Table 1: Material properties assigned for different parts of the study.

`	**Young's modulus (MPa)**	**Poisson's ratio**	**References**
Gold alloy	90,000	0.3	Benzing et al. (1995)
Titanium	110,000	0.35	Benzing et al.(1995); van Rossen et al.(1990)
Clip	3000	0.28	Tanino et al. (2007)
Compact	Ey = 12,500 Ex = 17,900 Ez = 26,600 Gyx= 4500 Gyz= 5300 Gxz = 7100	γ yx = 0.18 γ yz = 0.31 γ xz = 0.28	Schwartz-Dabney and Dechow (2002)
Cancellous	Ey = 21 Ex = 1148 Ez = 1148 Gyx = 68 Gyz = 68 Gxz = 434	γ yx = 0.055 γ yz = 0.055 γ xz = 0.322	O'Mahony et al. (2001)

*E represents Young's modulus (MPa); G represents shear modulus (MPa); γ represents Poisson's ratio. The y-direction is infero-superior, the x-direction is medial–lateral, and the z-direction is anterior–posterior

The solid parts of the assembly were meshed in ANSYS using the tetrahedrons element type, which is more suitable to organic and complex shapes. Special concern at areas of contact was taken, particularly those at implant-bone interface and between the clip and the locator. These areas of contact were treated by finer mesh elements, (fig. 3). The total number of mesh elements and nodes could be seen at (Table 2).

Table 2: The total number of elements and nodes of the two models

	Elements	**Nodes**
Total number	27134	47133

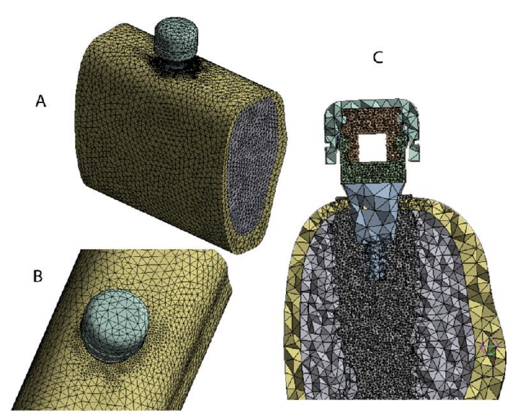

Figure 3: Meshing of the different components using tetrahedrons element. A; isometric view of the completely meshed components. B; top view showing the mesh refinements at contact. C; cross-section of the meshed components showing selected body mesh refinement.

The boundary conditions were performed to differentiate the models into two categories:

- Models I: This model represented the conventional loading protocol where the implant fixture is fully integrated in bones and so the bonded contact behavior was selected at the bone-implant interface.
- Model II: This model represented the immediate loading protocol where the frictional type of contact was used with a frictional modulus (μ=0.3), (Cehreli et al, 2004), (Brunski et al., 2000) and (Hussein & Rabie, 2013).

The contact type between plastic clip and gold locator was also set to frictional contact for both models (I, II), (Osman et al., 2013) and (Hussein, 2013). All other contacts between parts of all models were bonded contact.

After selecting contact types, the models were constrained by fixed constrain (0-degree of freedom in all axes). The inferior border of the bone model was the target of this constrain.

Loading of both models was performed by combined dynamic loading (Merdji et al., 2012). Thus, a 3D coordinate system was defined by three dynamic loads in the occluso–gingival direction, lingual–buccal direction and mesial–distal direction. The metallic housing of the female portion of the locator were subjected to 7 MPa in occluso–gingival direction (OG), 1.5 MPa in mesio-distal direction (MD) and 1 MPa in bucco-lingual direction, respectively. For dynamic analysis, time dependent masticatory load was applied. The time history of these dynamic load components for 10 s is shown in figure 4.

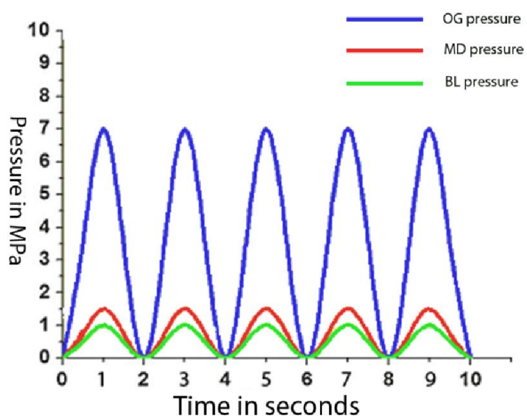

Figure 4: Chart representing sinusoidal pattern of the combined dynamic loads in three different axes. OG; occluso-gingival, MD; mesiodistal and BL; buccolingual.

Von mises stress of the implant and locator components were recorded and interpreted. On the other hand, compact and cancellous bone are considered friable materials that analyzed by maximum (tensile) and minimum (compressive) principle stress, (Barao et al, 2013).

3. Results

All data of the maximum von mises stress values (equivalent stress) of the implant fixture and overlying stud attachment components were collected, tabulated and charted, table (3) and fig. (5).

Table 3: Maximum Von Mises stress in (MPa) of different components after immediate and delayed implant loading protocols.

Components	(Von Mises) IMMEDIATE	(Von Mises) DELAYED
Implant	64.668	44.931
Stud	64.311	49.121
Clip	19.03	20.53
Housing	21.91	24.615

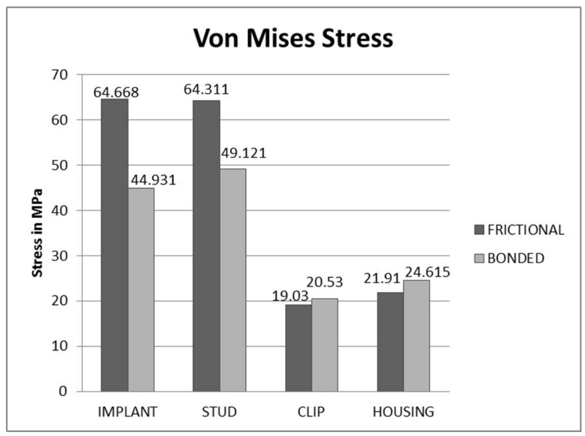

Figure 5: Chart showing difference in the maximum Von Mises stress in (MPa) between immediate implant loading protocol (frictional contact) and delayed implant loading protocol (bonded contact) for all components including implant, stud, clip and housing of the attachment.

According to the selected implant loading protocols, the highest maximum Von Mises stress value was recorded near the apical part of the implant surface of immediately loaded implants (σVM=64.668 MPa). The delayed loading implant showed less Von Mises stress than the immediate implant loading (σVM=44.931 MPa) as seen in the coronal part of the implant, (fig 5,6). Similarly, stud of the immediate loading implant showed higher Von Mises stress (σVM=64.331 MPa) than the stud of the delayed loading implant (σVM=49.121 MPa), (fig 5). Values of maximum Von Mises for studs of both loading protocols were detected at the internal recess cavity, (fig 6).

The maximum Von mises stress of the clip and housing of both groups showed minimal difference in stress values. The values of delayed loading housing and clip were (σVM=24.615 MPa and σVM=20.53 MPa), respectively. Similarly, stress values of immediate loading housing and clip were (σVM=21.91 MPa and σVM=19.03 MPa), respectively, (fig 5). Most of the stress concentration recorded in these components were seen in the collar areas where clip engage the housing undercut groove (fig 6).

The biomechanical condition of the compact and cancellous bone was analyzed by following the maximum principle stress (tensile) and minimum principle stress (compressive). All values of the maximum and minimum principle stress were collected and tabulated in Table 4.

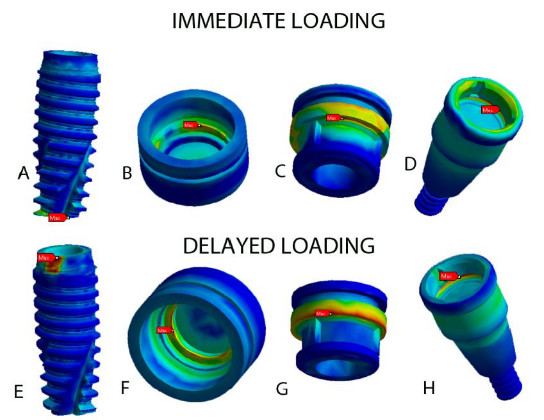

Figure 6: Von Mises stress (σVM) distribution in (MPa) within implant/attachment components for both immediate and delayed loading. Red annotation indicated the position of the maximum stress value in each component.

Table 4: Maximum principle stress and minimum principle stress in (MPa) of both compact and cancellous bone after immediate and delayed implant loading protocols.

		Immediate loading	Delayed loading
Maximum Principle stress	compact bone	114.06	92.4
	cancellous bone	36.2	25.6
Minimum Principle stress	compact bone	-13.13	-11.7
	cancellous bone	-10.72	-11.32

The maximum principle stress recorded at the crestal part of the compact bone of immediately loaded implant was higher than that of the delayed loading implant at values (σVM=114.06 MPa and σVM=92.4 MPa), respectively. Similarly, the maximum principle stress recorded at coronal part of the cancellous bone near first thread of immediately loaded implant was higher than that of the delayed loading implant at values (σVM=36.2 MPa and σVM=25.6 MPa), respectively, (fig. 7,8).

The minimum principle stress was detected at the crestal part of the compact bone of both immediately loaded implant and delayed loading implant at minimal changes in value (σVM=-13.13 MPa and σVM=-11.7 MPa), respectively. In contrast, the minimum principle stress of the cancellous bone of immediately loaded implant was slightly lower than that of the delayed loading implant at values (σVM=-10.72 MPa and σVM=-11.32 MPa), respectively. The minimum principle stress values for both loading conditions were recognized at the implant apex, (fig. 7, 9).

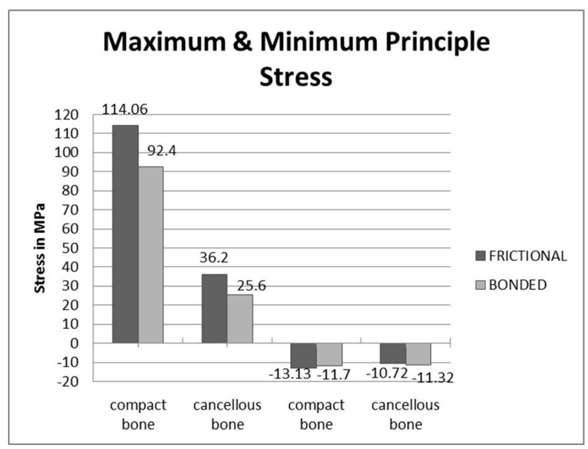

Figure 7: Chart showing difference in the maximum principle and minimum stress in (MPa) between immediate implant loading protocol (frictional contact) and delayed implant loading protocol (bonded contact) for compact and cancellous bone.

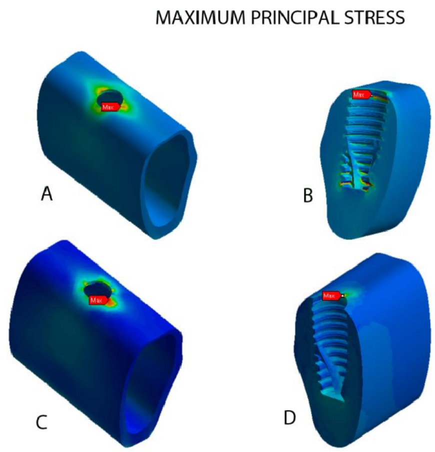

Figure 8: Maximum principle stress distribution in (MPa) at compact and cancellous bone for both immediate and delayed loading. Red annotation indicated the position of the maximum stress value in each component.

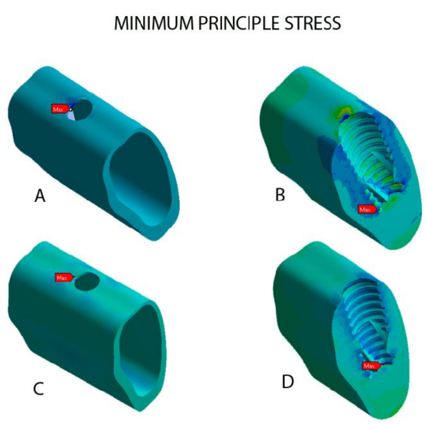

Figure 9: Minimum principle stress distribution in (MPa) at compact and cancellous bone for both immediate and delayed loading. Red annotation indicated the position of the maximum stress value in each component.

4. Discussions

Success of implant treatment depends on multiple parameters, which could be categorized as surgical, prosthetic or related to after-care treatment. Among all of these parameters, proper loading time is considered one of the most potent parameter that affects directly the success of implant treatment, (kong et al., 2009). Many clinicians used different loading protocols referenced by their experience and governed by their patient's demands. Using delayed loading, the patients were allowed to use a transient removable denture for 4 to 6 months, which is often difficult for the patient to accept functionally and psychologically, (Collaert & De Bruyn, 2008), (Bergkvist et al., 2009) and (Tealdo et al., 2011). Thus, there is a tendency to shorten the treatment time without undermining the healing process and affecting the osseointegration. Unless certain osseointegration assessment tool used, as resonance frequency analysis, loading time was done based on average data and not patient-specified, (Lahori et al., 2013) and (Romanos et al., 2006). Accordingly, a more detailed mechanical analysis of the most popular loading protocols should be conducted in a more realistic loading environment.

The present study offered various items have never been combined before to study implant loading. Moreover, the model of an actual implant profile was used, for an implant successfully used in immediate loading cases and had a good reputation of unique primary stability, (Manufacturer data, 2013). In addition, anisotropic properties were assigned to bones, (O'Mahony et al., 2001) and (Schwartz-Dabney & Dechow, 2002). Contact management was changed between implant surface and bones to represent the immature integration of the immediate loading case, (Hussein & Rabie, 2013), (Cehreli et al, 2004) and (Brunski et al., 2000). Finally, dynamic loading were applied to simulate masticatory function, (Merdji et al., 2012).

The results of the present study showed higher stress values for immediate loading implant than the delayed loading one. These values were recorded both at bone level between implant fixture and bones and on the abutment level at locator attachment. These findings are in agreement with clinical study conducted by lahori et al. (2013) regarding implant stability and bone density. They confirmed that delayed loading showed better implant stability and bone density than immediate loading. Similarly, the present study was coincident with Kim et al. (2008) results. In an experimental study, they found that the mean osseointegration was greater (65.5%) for the delayed loading implants than for the immediately loaded implants (60.9%). The proponents for this loading condition attributed their need for delayed loading to avoid disturbing the weak non-mineralized tissues during healing. These tissues are sensitive to force, trauma and micromovements at first week of healing, which may hinder bone differentiation and results to connective tissue formation. Moreover, the results were also coincident with Huang's et al. study (2008). They added that there is a correlation between the interfacial sliding and the generation of bone stress. Accordingly, more resistance to sliding at implant-bone interface was present, better stress-strain distribution will be expected. In the present study, the delayed loading condition was treated as full (100 %) osseointegration and so bonded contact was selected. This means that no sliding was permitted and better stress distribution was performed.

The use of actual profile of the Nobelactive implant was used in the present study to enable maximum mechanical interlocking between the bones and the immediate loading. This hypothesis was confimed by Huangs et al. (2010) and Pessoa et al. (2011). They clarified that improving the initial interfacial interlocking using a threaded implant has a higher priority than using cylindrical or step designs with a rough surface of an immediately loaded implant. They also added that the use of an implant with prominent profile highly reduce the generated stress and reduce the micromovement. Similarly, Change et al., (2012) confirmed that among five different implant profiles, the trapezoid cross section profile showed the least stress generation and minimal micromovement, which is the case of the nobelactive implant used in the present study. Unfortunately, the influence of the implant profile used in the present study seems to be inhibited by the negative effect of the contact type used (frictional contact).

On the other hand, many researches could not be able to distinguish the difference between both immediate and delayed loading. They claimed the success of the immediate implants to the new advances in implant manufacturing regarding implant shape and surface treatments. They also suggested immediate implant in certain circumstances where immediate loading were limited before. They attributed the success of the immediate loading to the proper implant selection, implant distributions and implant numbers. They also added that bone quantity and quality with proper transitional restorations might enhance treatment results, (Bergkvist et al., 2009), (Tealdo et al., 2011), (Alfadda et al., 2009), (Ibañez et al., 2005) and (Meloni et al., 2012). A striking finding of the ultrastructural immunocytochemical investigations was the synthesis and deposition of bone related proteins (osteonectin, fibronectin, fibronectin receptor) by osteoblasts from day one of bone/biomaterial interaction. Moreover, Calcium-phosphate needle-like crystallites were newly synthesized in a time-related manner directly at the titanium surface, (Meyer et al., 2004).

Unsurprisingly, the maximum values of stress in the bones were recorded at the crestal area and surrounding the implant neck. In addition, an area of stress concentration was seen at in the cancellous bone reaches greatest in the bottom of the dental implant that intuitively supports the occlusal load. The stress magnitude in the cortical bone is higher than the ones in the cancellous bone. All these findings were in agreements with several finite element analysis and were confirmed clinically by crestal bone resorption seen surrounding implant neck in several situations, (Akca et al., 2013), (Eser et al., 2009), Alfadda et al., 2009) and (Ibañez et al., 2005). These findings could also be attributed to the stress concentrations occurred at the initial area of contact at the interface between implant and bone.

Dynamic loading was used in the present study in order to simulate the masticatory function. Researchers believed that this type of force might accentuate implant loading and so it might accentuate the results of the present study. Therefore, Merdji et al. (2012) stated, “For the clinical success of dental prostheses, dynamic response of implant and bone to external occlusal force should be physiologically acceptable”. They also added that finite element study of implant prosthesis should be relied on the dynamic loading not the static one. In addition, Benaissa et al. (2013) explained that the use of dynamic loading might have a different outcome than the use of the static loading used in the majority of the Finite element studies.

Although the present study tried to simulate realistic environment in many aspects, it devoid the full implant overdenture CT based model that used masticatory muscles attachments as a constrain media. This simplification was used to facilitate the overall processing time that may will be highly increased if combined with the other simulation issues used in the present study. However, this could be applied in validated future studies using super computer.

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10/26/2013