Biomechanical Influence of Implant Neck Designs on Stress Distribution over Adjacent Bone: A Three-Dimensional Non-Linear Finite Element Analysis

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Abstract. The design of dental implant body has a major influence on the stress dissipation over adjacent bone as numbers of implant failure cases reported in past clinical studies. Besides, the inappropriate implant features may cause excessive high or low stresses which could possibly contribute to pathologic bone resorption or atrophy. The aim of this study is to evaluate the effect of different configurations of implant neck on stress dispersion within the adjacent bone via three-dimensional (3-D) finite element analysis (FEA). A set of computed tomography (CT) images of craniofacial was used to reconstruct a 3-D model of mandible using an image-processing software. The selected region of interest was the left side covering the second premolar, first molar and second molar regions. The bone model consisted of both compact (cortical) and porous (cancellous) structures. Three dental implant sets (crown, implant body, and abutment) with different designs of implant neck – straight, tapered with 15º, and tapered with 30º were modelled using a computer-aided design (CAD) software and all models were then analysed via 3-D FEA software. Top surface of first molar crown was subjected to occlusal forces of 114.6 N, 17.2 N, and 23.4 N in the axial, lingual, and mesio-distal directions, respectively. All planes of the mandible model were rigidly constrained in all directions. The result has demonstrated that the straight implant body neck is superior in attributing to high stress generation over adjacent bone as compared to others. This may associate with lower frictional resistance produced than those of tapered designs to withstand the applied loads.

1. Introduction

The use of dental implants for the oral rehabilitation of fully and partially edentulous patients has greatly broadened the scope of clinical dentistry [1]. The success rate of dental implants in replacing the missing teeth has well been proven over the years through many studies. However, minor complication of implant post-surgery is still inevitable with common marginal bone loss occurrence

found around oral implant locations. The marginal bone loss may significantly be associated with various factors such as gender, surgical trauma, plaque accumulation, smoking behaviour, biological bone width, bone quality, implant design and biomechanical factors [2].

Many previous clinical studies have been performed to review the biomechanical aspect of dental implant design, quality and strength of osseointegration, bone-implant interface, and their relationship to the long-term success of treatment. There is, however, no optimal design specifications of implant observed which could be considered for the best treatment outcome. The common design of dental implants can be improved to maximise their strength, interfacial stability, and load transfer by using appropriate material, surface treatment, and thread shape [1, 3].

According to a study conducted by Lee et al., the failures of implant were believed to be caused by poor biomechanics specifically poor implant stabilisation to anchor to the bones [3]. As far as stress within bones is concerned, the biomechanical design of dental implant, therefore, may not considerably be disregarded. The magnitude and dissipation of stress influence the rate of bone loss around implant body.

To date, many dental implant manufacturers have great interest in developing new implant design to improve the outcomes of treatment [4]. Stress concentration around implants and within bones are affected by various factors such as shape, geometry, and taper of the implant fixture. Most of past studies that investigate the effect of implant design have merely focused on the implant diameter, length, and thread. There is a few studies, on the other hand, aim to analyse the influence of the neck design of implant body on the stress distribution over adjacent bones. Previous findings indicated that the cortical bone areas surrounding implant neck sustained high stress concentration [5, 6]. This is also supported by a clinical and radiographic study by Tan et al. which investigated on the bone remodelling process of different implant neck configurations [7]. It reported that the implants with reduced height turned neck of 1.8 mm may, indeed, reduce the crestal bone resorption, and may maintain higher crestal bone levels than implants with a 2.8 mm turned, when sunk to the same depth.

There are numerous previous studies conducted to improve dental implant performance via computational analysis. Most of them have examined the distribution of forces in peri-implant bone using finite element analysis (FEA) to predict any possible failures. Finite element analysis plays a vital role in solving mathematical modelling problems in many fields of science and industry [8]. It has widely been used for quantitative evaluation of such stress distribution on implant and its surrounding bone since past three decades [9-14]. Among the advantages offered by FEA are including reliable stress and strain dispersal, simple model modification and accurate representation of complex geometries.

To the best of authors' knowledge, there is less study has been found, to date, to address the influence of different implant neck designs via meticulous finite element modelling. It is therefore a necessity for the present study to examine the effect of different implant neck designs – straight (ST), tapered with 15º (T15º), and tapered with 30º (T30º) towards the stability of implant body using three-dimensional (3-D) FEA. In this study, the stress dispersion within adjacent bones were investigated.

2. Materials and methods

2.1. Three-dimensional mandibular bone model construction
In this present study, a series of computed tomography (CT) image datasets of craniofacial was processed and analysed to reconstruct a 3-D model of mandibular bone using an image-processing software, Mimics 10.01 (Materialise, Leuven, Belgium). In order to differentiate between cortical and cancellous structures, the image datasets of CT scan were threshold using appropriate bone density scale.

For the bone region of interest, it covers the left side of mandibular bone which include the second premolar, first molar and second molar tooth regions as illustrated in figure 1. The finalised bone model has a thickness (cortical), length, height, and width of 1.5 – 4.5 mm, 37.5 mm, 28.5 mm, and 10.5 mm, respectively. As the porous structure or cancellous bone was taken into consideration in the

analysis, it was modelled as a solid continuum structure with spongy material properties assigned and it was surrounded by the dense cortical bone. The placement of implant into bones was simulated by removing the first molar, whilst the other two teeth were remained in place. As for the crown model, it was created by altering the coronal portion of first molar with the use of Boolean operation.
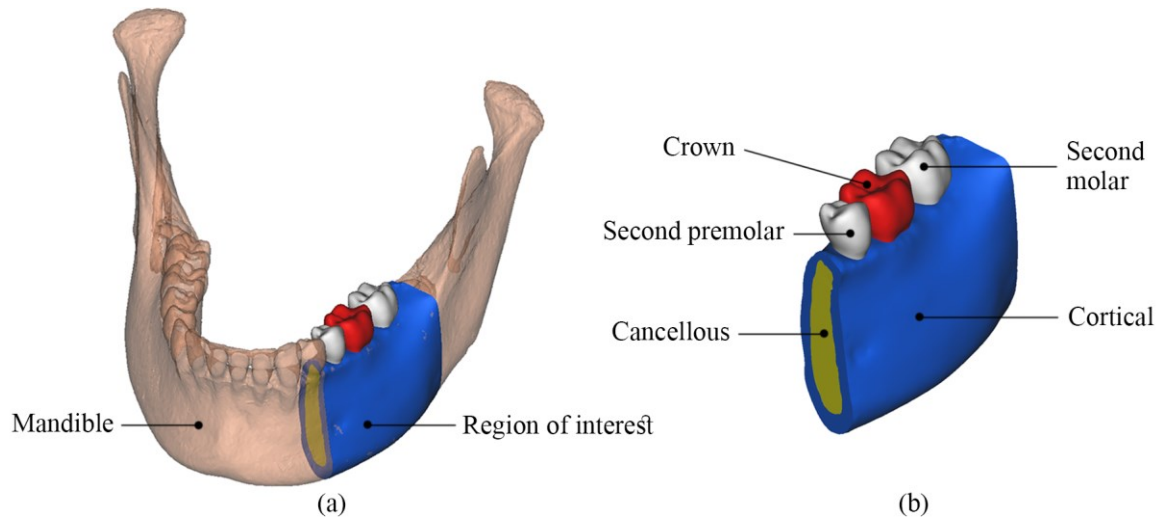
Figure 1. (a) Three-dimensional model of mandible with the selected region of interest. (b) The region of interest of analysis.

2.2. Three-dimensional implant model construction

A conventional computer-aided design (CAD) software (SolidWorks 2010, SolidWorks Corporation, Concord, Massachusetts, USA) was utilised to design the 3-D models of implant body and abutment. The length and diameter of implant body to be developed were 13 and 6 mm, respectively, which based on the existing dimensions obtained from a dental implant manufacturer, ANKYLOS®. The implant body was created as a one single body unit that would be attached to the abutment connection part.

In this study, there were three different types of common implant neck have been modelled – straight (ST), tapered with 15º (T15º), and tapered with 30º (T30º). The abutment-implant connection part had been designed as tapered integrated screw, whilst for the external implant thread profile, the buttress type was chosen. In other words, all the three cases investigated having an implant body with similar diameter, length, thread number, and thread profile as depicted in figure 2. As a result, the 3-D model of dental implant system in each case of ST, T15º, and T30º comprises three individual components which are crown, abutment and implant body.

2.3. Finite element modelling

The 3-D models of bone and implant system (implant body, abutment and crown) were converted to surface triangular mesh element with a size of 0.4 mm and saved in a stereolithographic file format (.stl). The element size considered was almost four times smaller than the one suggested by Lin et al [15]. For the validation of finite element models in this study, several comparisons had been made with the past related studies in terms of the methods of construction used, selection of parts to be analysed as well as complexity of model construction.

All 3-D models were then exported into a FEA software (Marc Mentat 2007, MSC Software, Santa Ana, California, USA) to convert surface triangular mesh into four nodes tetrahedral solid element with three degree of freedom. The total number of elements for each case of ST, T15º, and T30º was 184,988, 183,897, and 183,518, respectively.
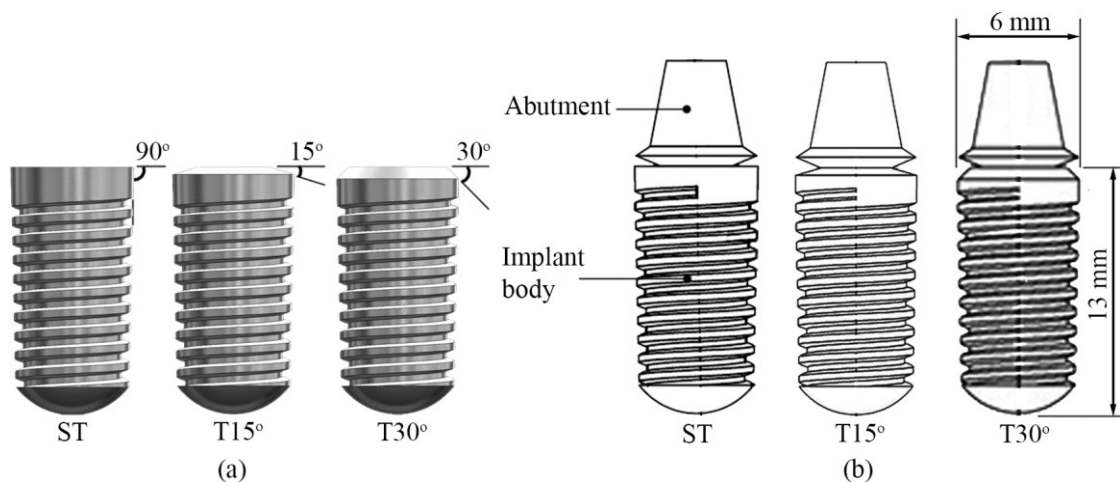
Figure 2. (a) Three-dimensional model of different designs of implant neck. (b) The placement of abutment in the implant body for all the three designs of implant neck.

2.4. Contact modelling

The implant body is rigidly anchored in the bone along its entire interface. This was therefore simulated via non-linear contact modelling in the pre-processing of analysis, accordingly.

A friction coefficient of 0.3 was assigned at the implant-bone, implant-abutment, implant-screw and abutment-screw interfaces to represent the immediate loading principle as well as to secure the transfer of force and prosthetic component deformation. Whilst, the contact surfaces between cortical-cancellous and cortical-mucosa soft tissue were assumed to be as perfectly bonded by merging the nodes between the two contacted models, therefore, no frictional contacts were assigned.

2.5. Material properties

All material properties of finite element model were assumed to be isotropic, homogeneous, static, and linearly elastic throughout the analysis. The crown was made of porcelain whilst the implant body and abutment were made of Ti-6Al-4V titanium alloy. The material properties of all models are shown in table 1.

Table 1. Young's modulus and Poisson's ratio for each finite element model.

Material	Young's Modulus, E (MPa)	Poisson's Ratio, v	References
Crown	68,900	0.28	[16]
Cortical bone	13,000	0.30	[17]
Cancellous bone	9,500	0.30	[18]
Implant body	110,000	0.35	[19]
Abutment	110,000	0.35	[19]
Teeth	18,600	0.31	[20]

2.6. Loading and boundary conditions

A resultant occlusal force of 118.2 N was applied obliquely at 75° respected to the occlusal plane on the top surface of the crown. This load, however, was represented by three different static occlusal load components. The load components with magnitude of –114.6 N, –23.4 N and –17.2 N were applied in the axial (z-axis), mesio-distal (x-axis), and bucco-lingual (y-axis) directions, respectively.

For the boundary condition, the bottom, mesial and distal surfaces of bone segment were fixed in the x, y and z directions to impede any movements or displacements. The loading configuration and boundary condition of the finite element model are illustrated in figure 3.
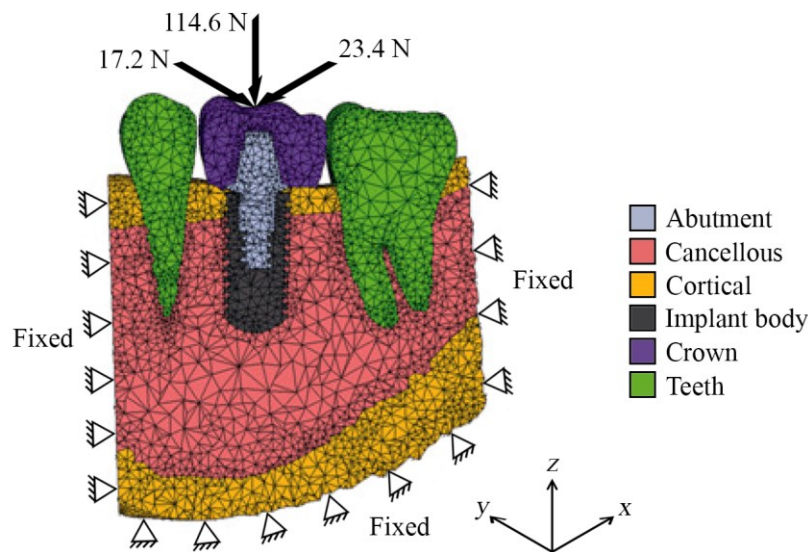
Figure 3. The boundary conditions showing rigid fixation at all planes of the bone segment and the static occlusal forces were applied on the top surface of crown.

2.7. Equivalent von Mises stress result index
The results of analysis were presented and discussed in terms of equivalent von Mises stress (EQV). The EQV index was analysed over adjacent bones for each design of implant necks.

Also, the results were presented in spectrum colouring scale with blue colour indicating low EQV magnitude while light grey colour indicating high EQV magnitude. The bone stress value and its distribution may provide significant information with regards to the influence of different designs of implant neck on mechanical understanding with low-value stress is favourable for a promising interpretation of the results.

3. Results
As far as stress parameter was concerned, our results showed that the greatest EQV value within the cortical bone was generated in ST with 2.8 MPa at the marginal region as exhibited in figure 4. A similar pattern of stress dissipation was found in T15º and T30º where the bone area towards apical portion seemed to sustain a lower stress level. The maximum EQV magnitude recorded in ST was observed to be approximately 2.8-fold higher than those in T15º (1 MPa) and T30º (1 MPa). In overall, the tapered implant neck designs (T15º and T30º) showed a more favourable stress dispersion within the marginal region of cortical bone. Figure 5(a) depicts the EQV distribution over the cortical bone for all designs of implant neck.

The stress results over the adjacent cancellous bone were parallel with the state of stress produced in the cortical bone where the implant neck through ST design recorded the highest value of EQV (2.1 MPa) as compared to others (T15º: 0.6 MPa and T30º: 0.5 MPa). There was less discrepancy of cancellous bone stress value between T15º and T30º which merely 16.7%. It seems that the high stresses were majorly concentrated at the edge region of second premolar-bone interface and gradually spread out towards the surrounding area as illustrated in figure 5(b). The level of stress developed in the cancellous was 1.3-fold lower than the one in the cortical bone for ST (2.8 MPa), whilst 1.7- and 2-fold lower than those in T15º (1 MPa) and T30º (1 MPa), respectively.

4. Discussions
The biomechanical factors of dental implant design such as size, shape, geometry, and neck type play a vital role in defining the success of teeth restoration treatment either for a short- or long-term evaluation. Based on past studies, the performance of dental implants is mainly dependent on the initial stability and osseointegration between implant body and bones. Implant neck or also known as

collar is defined as the coronal feature of a dental implant. There are several different designs of implant neck may be found in practices, to date, namely straight, tapered, and filleted. The angle of those from tapered group is measured from the coronal plane to the slanted surface of collar.
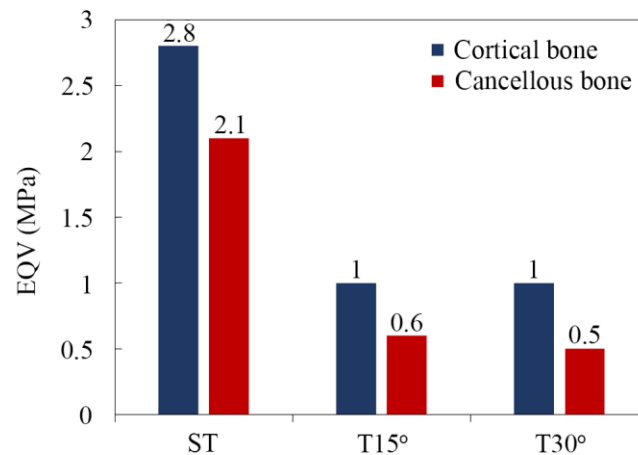
Figure 4. Comparison of EQV magnitude within the cortical and cancellous bone for all implant neck designs.
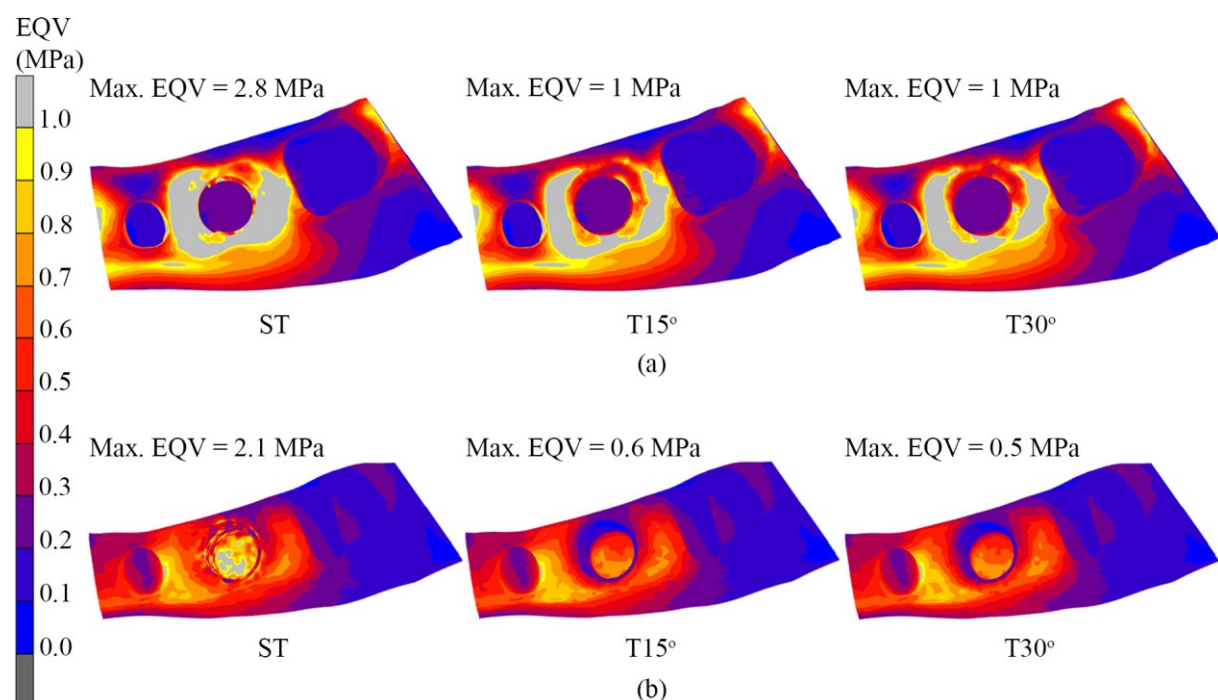
Figure 5. (a) Comparison of EQV magnitude within the cortical bone for all implant neck designs. (b) Comparison of EQV magnitude within the cancellous bone for all implant neck designs.

Crestal bone loss which occurred at the bone-implant interface as reported in previous studies could possibly be due to poor bone response towards mechanical factors of loading [21]. The findings from a study conducted by Karoussis et al., however, described that the hypothesised peri-implant marginal bone loss was also influenced by implant design [22].

The results of this study exhibited that the teeth restoration by the implant neck with ST design has increased the maximum cortical bone stress value approximately 2.8-fold greater than those by T15° and T30°. The stress magnitude difference between ST and T15°, and ST and T30° are similar with a

percentage of 64.3%. The implant neck with tapered designs regardless of angle considered, depicted a more encouraging stress dispersion than the straight one. A possible explanation for this observation is that there may be a progressive transfer of occlusal load from the implant body to the cortical bone. As the straight and tapered implant necks have different configuration of contacting surface between implant body and bone tissue, they therefore leave a significant different effect on stress distribution. The straight design had smaller bone-to-implant contact area compared with the tapered due to the sharp edge of implant collar. The tapered design, on the other hand, is likely to have high contact area since the implant surface area increases due to the bevelled edge of implant neck. The slanted surface seems to tolerate better occlusal load than the straight neck due to high frictional resistance produced.

The result of cortical bone stress was in accordance with the cancellous wherein the tapered designs (T15° and T30°) promoted the most promising outcome. It showed that ST design was mostly responsible for the high stress of cancellous bone with about 3.5- and 4.2-fold higher than T15° and T30°, respectively. This was in agreement with the stress distribution developed where ST implant neck produced more highly-stressed regions that concentrated at the apical portion of bone-implant interface which support the applied occlusal load.

According to Hudieb et al., high strain concentration at the implant neck should be avoided as it may lead to crestal bone resorption [6]. In average, the crestal bone loss rate is more than 1 mm in the first year of treatment and about 0.1 mm for each of the following years. The potential zone for fracture when a dental implant system subjected to high bending forces is the neck of implant body. Past studies indicated that stress in the collar was higher than the other sections of dental implant [23]. Thus, it clearly shows that the implant neck plays an important role in stabilising the implant body during its final tightening especially in poor bone quality and marginal compact bone layer [24]. The findings of this study were also parallel with a study performed by Merdji et al. which specified that the mechanical stresses propagate in the areas of bone which are closer to the implant body and decrease towards the outer regions [5].

In all models tested, the greatest value of bone stress was recorded within the cortical bone specifically in ST design (2.8 MPa). Moreover, the maximum stress magnitudes recorded in the bones for all collar designs have no tendency to cause bone failures since the cortical bone is known to be able to sustain stress up to 69 MPa [25].

The limitations of the present study were as follow: (1) all material properties of finite element model had been assumed to be homogenous, isotropic, and linearly elastic; (2) the simulated occlusal load was only applied at one specific node; and (3) the scope of stress outcome was only presented in terms of equivalent von Mises in which may further be expanded in other types such as maximum principal stress.

5. Conclusions

The results of simulated static loadings and non-linear analysis support the following conclusions. The dental implant body with tapered implant neck was evident to be superior as depicted the most encouraging bone stress outcomes in comparison to straight design. The stress was fairly dispersed over the adjacent cortical and cancellous bones specifically at the bone-to-implant contact areas.

Acknowledgments

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