Design Improvement of Dental Implant-Based on Bone Remodelling

Solehuddin Shuib, Koay Boon Aik, Zainul Ahmad Rajion

***Abstract*—**There are many types of mechanical failure on the dental implant. In this project, the failure that needs to take into consideration is the bone resorption on the dental implant. Human bone has its ability to remodel after the implantation. As the dental implant is installed into the bone, the bone will detect and change the bone structure to achieve new biomechanical environment. This phenomenon is known as bone remodeling. The objective of the project is to improve the performance of dental implant by using different types of design. These designs are used to analyze and predict the failure of the dental implant by using finite element analysis (FEA) namely ANSYS. The bone is assumed to be fully attached to the implant or cement. Hence, results are then compared with other researchers. The results were presented in the form of Von Mises stress, normal stress, shear stress analysis, and displacement. The selected design will be analyzed further based on a theoretical calculation of bone remodeling on the dental implant. The results have shown that the design constructed passed the failure analysis. Therefore, the selected design is proven to have a stable performance at the recovery stage.

***Keywords*—**Dental implant, FEA, bone remodeling, osseointegration.

I. Introduction

DENTAL implant is a prosthetic replacement for missing teeth on the patients. Basically, a dental implant is a tiny screw that makes of a material known as titanium. Other types of implant material are a polymer, ceramic and ceramic coated as well as carbon compound implant. The length of the screw is about 5-8 mm is placed in the jawbone of the mandible bone. Natural teeth consist of the crown and the teeth root.

The crown is covered with the white enamel which is the visible section by naked eyes. The teeth root is used to support the crown as it is extended into the jawbone. The dental implant consists of three parts. The implant screw itself which is used to insert directly into the jawbone. The abutment is used to connect the implant screw with the artificial crown.

The third part is the artificial crown or denture. This artificial crown will be made to match the natural enamel color to each of the patient in order to have natural appearances and smile.

A dental implant is manufactured by using titanium which is bio-compatible and offer strength and durability as well as a unique property of fusing directly to the bone. This process is known as osseointegration as shown in Fig. 1 [1]. After the implantation of dental, the recovery period is between 12 to 24 weeks. The patients are recommended not to do any functional load towards the implant which can delay the healing process. Dental implantation success or failures are generally divided into patient-related factor and implant location as well as clinician experience [2].

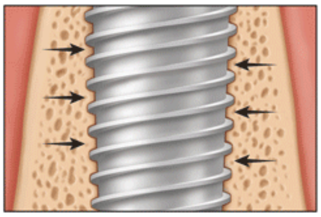

Fig. 1 Osseointegration process [3]

The effect of bone resorption or bone remodeling has become a major concern in the design of the dental implant and the successful recovery of the dental implant surgery on the patients.

The bone remodeling consists of several processes such as osteoclast, bone resorption, osteoblast, mineralization and quiescence [4]. In this project, the failure that needs to be taken into consideration is the bone resorption on the dental implant. Human bone has its ability to remodel after the implantation. When the dental implant is installed into the bone, the bone will detect and change the structure of the bone to achieve new biomechanical environment.

Consequently, the remodeling of the bone will affect the stability of the dental implant [5]. Thus, some simulation such as finite element method on the dental implant for the bone resorption needs to be carried out.

The objectives of the project are to design the dental implant by using CAD software, to analyze the dental implant by using FE software, and to predict the bone remodeling of the dental implant system.

II. Materials and Methods

The overall methodology is illustrated in Fig. 2. The first phase is to review and to verify the design of dental implant followed by the development of dental implant system. Then,

Assoc. Prof. Dr. Solehuddin Shuib is with the Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia (phone: +603-5543 64715; fax: 603-5543 5160; e-mail: mesoleh@gmail.com).

Koay Boon Aik, was with School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 NibongTebal, Penang, Malaysia (e-mail: jack2_boonaik@hotmail.com).

Assoc. Dr. Zainul Ahmad Rajion is with the School of Dental Sciences, Universiti Sains Malaysia, Health Campus16150 Kelantan, Malaysia (e-mail: zar5057@gmail.com).

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the third phase is the development of simulation models by using finite element software namely ANSYS. The fourth phase is the result and analysis.

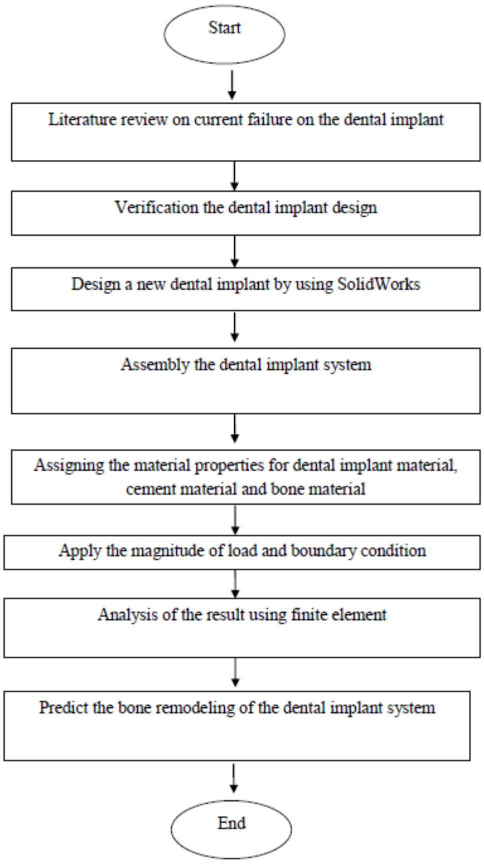
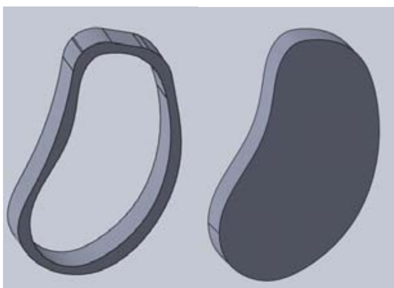


Fig. 2 Flow chart of the dental implant system

A. Bone Model

The bone model consists of two types, cortical bone and cancellous bone which are shown in Fig. 3 [6].



(a) (b)

Fig. 3 (a) Cortical Bone of the dental implant system, (b) cancellous bone of dental implant system

B. Types of Design for Dental Implant

There are five types of designs for dental implant [6]. Each design has two categories; cemented dental implant system and un-cemented dental implant system. The tapered dental implant will give higher stress distribution [6]. Fig. 4 shows the benchmarked design, which is to be modified for better performance of the dental implant.

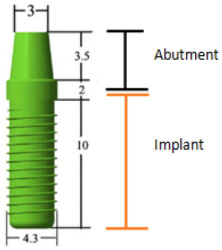


Fig. 4 Benchmarked design [6]

C. Material Property of Dental Implant, Cement, and Bone

The material used to design a dental implant is Titanium. Titanium alloy is a nontoxic and allergy-free for human body [7]. Meanwhile compared to specific strength the titanium and its alloy are superior to any other biomaterials [8]. Titanium is biocompatible and offers strength and durability as well as a unique property if fusing directly to bone. This process is known as osseointegration [9], [10].

Tables I-III show the material properties of titanium, cement, and bone model.

TABLE I
MATERIAL PROPERTY OF TITANIUM [6], [11]

Material property	Value
Density, ρ	4.5-4.6(g/cm^3)
Young Modulus, E	110x 10^3 (MPa)
Poisson's ratio, v	0.3-0.36
Tensile Strength	210-1380(MPa)

TABLE II
MATERIAL PROPERTIES OF CORTICAL AND CANCELLOUS BONE [12]

Materials	Young Modulus (MPa)	Poisson's ratio, v
Normal cortical bone	13,000	0.30
Normal cancellous bone	1,370	0.3

TABLE III
MATERIAL PROPERTIES OF CEMENT [13]

Material Properties	Value
Density, ρ	2.24-2.40(g/cm^3)
Young Modulus, E	(14-41) x 10^3(MPa)
Poisson's ratio, v	0.20-0.21
Tensile Strength	2-5(MPa)
Compressive Strength	20-40(MPa)
Shear Strength	6-17(MPa)

D. Applied Force and Boundary Condition

Force is applied to the dental implant system as well as the boundary condition is set on the system. Type of force on the dental implant is known as occlusal load or axial force. The range of the applied force is in the range of 0 to 450N [10]. The force applied to this project is 100N which is perpendicular on the abutment head of the dental implant [14]. This load is similar to the benchmarked design. Fig. 5 shows the load applied on the abutment head of the dental implant.

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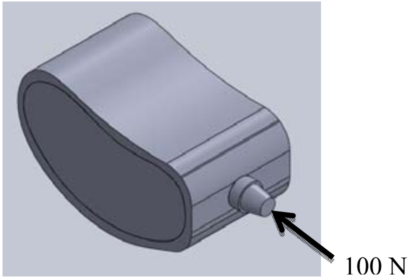


Fig. 5 Load applied on dental implant system

Furthermore, the boundary condition as shown in Fig. 6 is fixed at the two side of the dental implant system. The reason to fix two sides of the dental implant system is not to allow any movement of the system when the force is exerted on the dental implant.

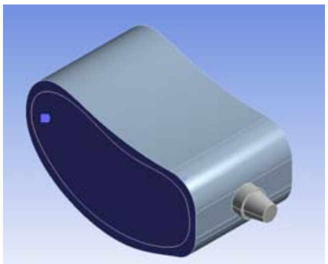


Fig. 6 Boundary condition on dental implant system

E. Prediction of Bone Remodelling

In the remodeling theory developed by Weinans [15], the change in bone density is expressed as a fraction of mechanical stimulus:

$$\dot{\rho}= B(S-k);\ 0<\rho<\rho_{cb} \quad (1)$$

where B is a constant, S represents the mechanical stimulus, k is the threshold value for the stimulus and ρ_{cb} is the maximum density of bone.

Further proposed (1) for various mechanical stimuli, a new term U is the strain energy density, and ρ is the local density. Hence, U/ρ represents the strain energy per unit bone mass. Thus, (1) becomes,

$$\dot{\rho}= B\,(U/\rho -k);\ 0<\rho<\rho_{cb} \quad (2)$$

The strain energy density *U* is taken as the apparent strain energy density, and there is no consideration for the stress history. Therefore, the empirical relationship between bone density and Young Modulus is also considered [16]:

$$E=c\,\rho^3 \quad (3)$$

where E is the Young Modulus with a unit of MPa, c is constant with a value of 3790MPa $(g/cm^3)^{-2}$.

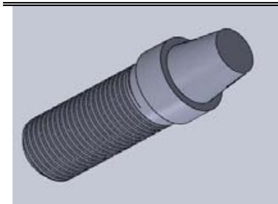
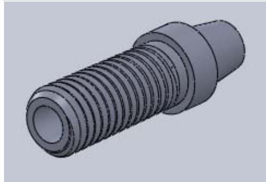
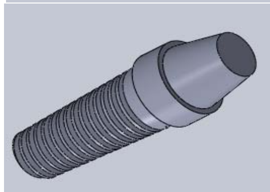
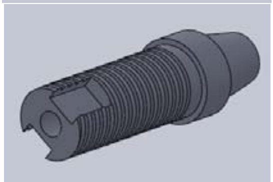
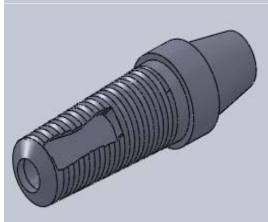
Thus, based on Weinans for ease of algebraic manipulation, the desired equation of change of density is formed.

$$\dot{\rho}= B\,(U/\rho -k) - D\,(U/\rho -k)^2;\ 0<\rho<\rho_{cb} \quad (4)$$

where B is the rate of remodeling constant, U is the strain energy; k is the strain energy density as well as D is the additional rate of remodeling constant [17].

The prediction of bone remodeling is based on the selected design of dental implant as shown in Tables IV and V.

TABLE IV
DESIGNS OF DENTAL IMPLANT

	A cylindrical shape with threads.
	A cylindrical shape with threads. The bottom of this design is cut into a cylinder shape hole.
	A cylindrical shape with threads. However, the body of the dental implant is tapered from the top of the body to the bottom of the body.
	A cylindrical shape with threads. However, the bottom edge of the dental implant is cut in order to improve the process of osseointegration as well as the surface area.
	A cylindrical shape with threads. This design is tapered from the top of the body to the bottom of the body.

III. RESULTS AND DISCUSSION

The results of five implant design simulation were analyzed and discussed in this section. The results for cemented implant were presented in terms of Von Mises stress, shear stress, normal stress, and displacement. By making a comparison among the designs, design 4 of the dental implant is the best of all analysis. It has the lowest Von Mises stress, displacement, shear stress and normal stress.

The maximum values of the stress and displacement are 13.734MPa, 2.998μm, 4.575MPa, and 1.971MPa respectively. Design 4 also has more surface area as compared to other designs and made it having a good contact with the bone. The existence of the cement reduces the stress and deformation on the bone. Design 4 is selected and compared with the benchmark design as shown in Table V.

TABLE V
BENCHMARK DESIGN BY ANOTHER RESEARCHER [18]

Benchmark, mm	Results
	Max. Von Mises Stress = 13.093 MPa Max. deformation = 3.0422μm Shear Stress, τ_{xy} = 4.851 MPa Normal Stress (MPa) = 1.852 MPa

Design 4 has improved the resultant displacement from 3.042μm to 2.998μm or 1.45% compared with the benchmarked design. Figs. 7 and 8 show the simulation results of design 4 of dental implant system by using commercial finite element software namely ANSYS.

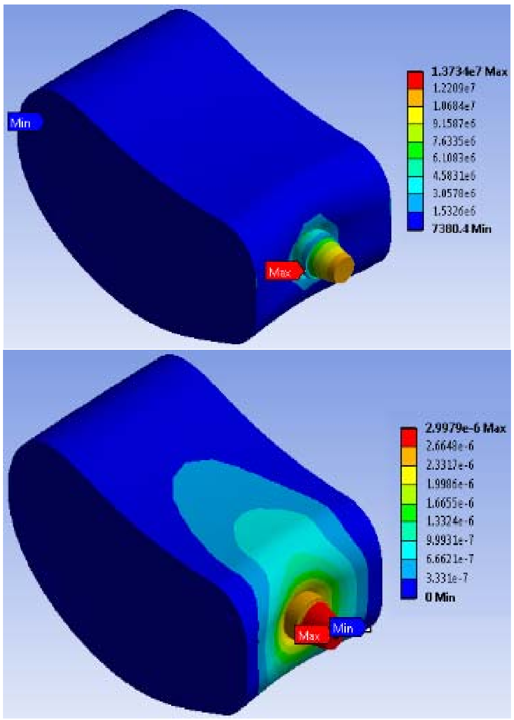


Fig. 7 Von Mises stress and resultant displacement analysis

In order to make the prediction, the density of the bone will be calculated. Thus, based on the (1) and (2) above, the strain energy and the density of the cancellous bone need to be obtained before the calculation of the rate of change for a density [17].

The strain energy as shown in Fig. 9, reaches a steady state. The strain energy, U obtained is 0.618 μJ. Then, the density of the cancellous bone was calculated. The density of the cancellous bone depends on the time.

Fig. 10 shows that the density of the bone is decreasing after 1800 days. The percentage difference of the density of the bone from 0 days to 1800 days is about 0.0128%. The change of density is very small. Based on the theoretical calculation, the decreases in the density of the cancellous bone is within 5 years or 1800 days.

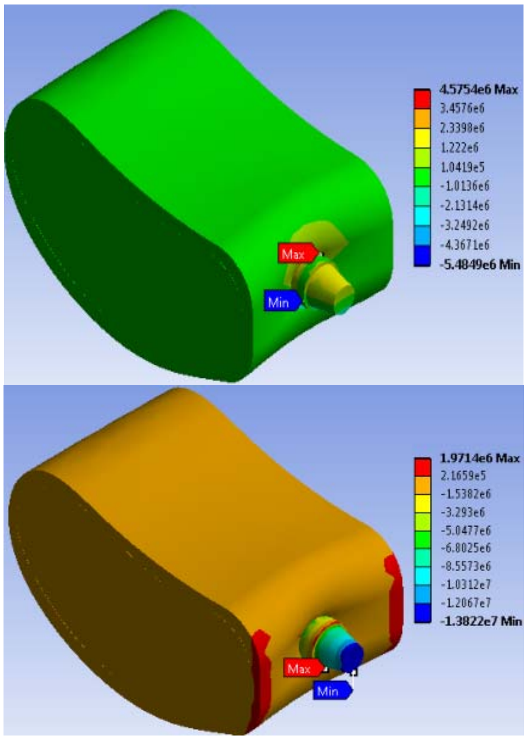


Fig. 8 Shear stress and normal stress analysis

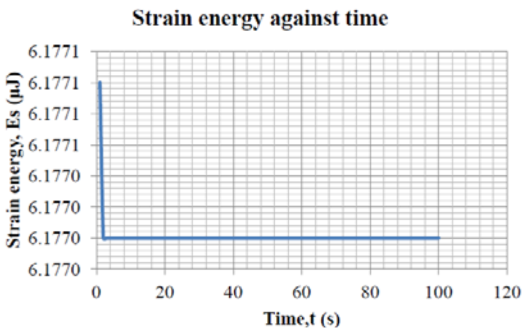


Fig. 9 Graph of strain energy against time

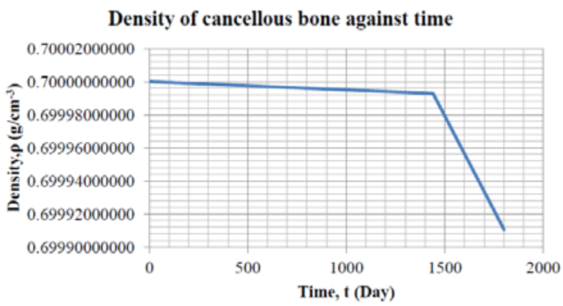


Fig. 10 Graph of density of bone against time

IV. CONCLUSION

1. As compared to the benchmarked design [6], design 4 was selected. Design 4 has a cylindrical shape, with a diameter

of 4.3mm; abutment length of 5.5 mm as well as the length of dental with 10 mm.

2. The resultant displacement is 1.45%. This design has the lowest displacement as compared to other design.
3. Regarding the prediction of bone remodeling, the theoretical result has been calculated. According to the empirical formula from references [14], [16], [17], the change of density has been calculated. The change of density is within 5 years.

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