Estimation Requiring Torque of Prosthetic Screw by Finite Element Analysis and Experiment

Xiao Zhang, Jingyan He, Wei Feng, Xianshui Chen
1 Guangzhou Janus Biotechnology Co., Ltd., Guangzhou, China, 511458
2 Foshan Angels Biotechnology Co., Ltd., Foshan, China, 528000
3 Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences
E-mail: zx623@126.com

Abstract. The purpose of the study was to find the influence of screw tightening torque to the prosthetic screw and screw-retained abutment-implant complex in long-term using. In this study, a method of FEM simulation is presented to estimate a suitable tightening torque of prosthetic. Torsion test has been carried out to find the ultimate torque secondly. The results of experimental are compared with simulation ones and shows a good agreement. A FEM modelling of occlusal loading with considering tightening torque is performed to investigate the influence of tightening torque under external loading subsequently. And the safety factor of $10^7$ cycles is calculated based on the present modelling to judge the reliability in long-term using. The result shows that tightening torque not only affect the stress of prosthetic screw significantly but also the stress of screw-retained abutment. According to the study, a tightening torque less than 18N·cm is recommended to use ensure the functionality of implant system.

1. Introduction
Nowadays, dental implant operation becomes a popular therapy for edentulous patients, due to it could both restore chewing function of edentulous patients and satisfied patients’ aesthetic needs. So, there is a huge market potential of dental implants. However, prosthetic complication in clinical practice such as looseness of screws, fatigued failure, fracture of parts of implant system still needs to pay attention. Looseness of screws is one of the most common problem which may turns up in the following days. According to a previous study [1, 2], up to 12.7% patients were bothered by screw loosening problem, which puts patients’ health in a high risk of danger. Do Nascimento etc. [2] has reported that loosening of abutment screw would lead to leakage brings bacterial penetration, and the abutment screw is tightened and loosened more frequently, a higher chance of bacterial penetration dose it occurs.

Looseness of screw result from many reasons. For example, both the changing of lubricating condition and vibration may cause a reduction of bolt pretension results in screw loosening. Without external subsidiary conditions, such as using double nuts or thread adhesive, increasing the bolt tightening torque is the simplest way to improve bolt pretension, resist looseness or screw. The lack of bolt tightening torque brings screw loosening problem which reduce the reliability of implant system during chewing. A too large screw tightening torque makes the thread to be compressed and causes the plastic deformation, even breaks the screws. So that an appropriate size of screw tightening torque is necessary for the stability of dental implant system.
For the stability of dental implant system, several researches are launched such as clinical observation research[1-3], mechanical experiment[4-7] and finite element method (FEM) modelling[8-14] previously. A great part of the previous studies about thread loosening of dental implant system focus on the interface of implant body and bone, connection and central bolt of abutment and implant boy, but the prosthetic screw of dental prostheses and screw-retained abutment. According to Jung R E’s study[1], cemented fixed dental prostheses presented a higher probability of survival then the screwed fixed dental prostheses. Hence the fastening of prosthetic screw needs more attention. In the article, a FEM modelling will be applied to investigate a suitable tightening torque of prosthetic screw and the result will be testified with torsion test. Another static structural FEM modelling will be used to verify the reliability and figure out a safety factor of dental implant system with respect to the previous estimated torque. Thereby this study provided a suitable tightening torque of prosthetic screw and offered a simple accurate method of assessment.

2. Theory

2.1. Bolt tightening theory

When a screw mates with its inside thread, the tightening of the screws in the following days is mainly maintained by the bolt pretension, which is distributed by bolt tightening torque and frictional force [16]. Frictional force consists of two parts, one part comes from the friction of bolt head bearing surface, another part is provided by the friction of inside thread and outside thread. He relation of screw tightening torque and bolt pretension is expressed as torque coefficient $K$ at engineering (equation (1)).

$$K = \frac{1}{2d} \left[ d_p \left( \frac{\mu_t}{\cos \alpha} + \tan \beta \right) + \mu_n d_n \right]$$  

(1)

Where, $T$ is bolt tightening torque, $F$ is bolt pretention, $d_p$ is pitch diameter of screw threads, $\mu_t$ is friction factor of threads, $\alpha$ is half angle of screw threads, $\beta$ is lead angle, $\mu_n$ is friction factor of bearing surface at bolt head, and $d_n$ is meaning pitch diameter of bearing surface.

Formulation to the tightening torque becomes equation (2).

$$T = FKd$$

(2)

Lead angle and thread angle are identical of standard threads hence the needed torque mainly depends on pretension force, bolt dimension, and coefficient of friction. Obtained the geometry specifications of prosthetic screw from CAD model, the characteristic needed in equation (1) are thread size ($d_p$) 1.4mm, pitch diameter 1.2mm, thread angle($\alpha$) 60°, lead angle ($\beta$) 4.5°, meaning diameter of bearing surface ($d_n$) 1.6mm. coefficient of friction at thread surface ($\mu_t$) and bearing surface ($\mu_n$) are both 0.35 by Jorn D.’s study[15]. Results that coefficient of torque is about 0.48.

2.2. Goodman criterion of failure

Goodman criterion of failure is a simple method for calculating the safety factor of Mechanical elements suffer from the cycle load[16]. It expresses as equation (3):

$$\frac{\sigma_m}{S_{ut}} + \frac{\sigma_a}{S_f} = \frac{1}{n}$$

(3)

Where, $\sigma_m$ is midrange component stress of cycles, $\sigma_a$ is amplitude component stress of cycles, $S_{ut}$ is ultimate strength of material, $S_f$ is fatigue strength of material in numbers of cycle, $n$ is safety factor. Midrange component stress and amplitude component stress comes from a half of the sum and difference of the largest load and smallest load in cycles, shown in equation (4) and (5) respectively.
\[ \sigma_s = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \]  \hspace{1cm} (4)  
\[ \sigma_m = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \]  \hspace{1cm} (5)  

A larger safety factor it has, a more reliable mechanical element it is. Criterion requires that safety factor should larger than 1 at least in order to ensure the safe of mechanical element during cycling.

3. FEM modelling of screw tightening torque simulations

3.1. CAD model of FEM modelling

A 3D CAD model of assembly consists of wrench, prosthetic screw, screw-retained abutment and gasket which instead of bearing position of upper structure is built by Solidworks and shown in Figure 1. The thickness of gasket is 0.5mm. The size of prosthetic screw is M1.4, and the diameter of its head is 2mm. Wrench is used for tightening the prosthetic screw with a hexagonal connection. The structure below abutment such as implant body and bone block are ignored because what we concerned about is just the connection statue of prosthetic screw here.

![Figure 1. Model of assembly (a) and prosthetic screw (b)](image)

3.2. Analysis setting

Material of the prosthetic screw and screw-retained abutment is TI-6Al-4V ELI titanium alloy. the gasket is made of pure titanium metal. The wrench is considered as a rigid body because it is a tool. The material properties are listed in the following Table 1:

| Material                  | Ti (grad4) | TI-6Al-4V ELI (mill Annealed) | Resin |
|---------------------------|------------|-------------------------------|-------|
| Young’s Modulus (GPa)     | 104 [17]   | 110 [17]                      | 3 [8, 9] |
| Poisson ratio             | 0.3 [9]    | 0.35 [9]                      | 0.3 [8, 9] |
| Yield Strength (MPa)      | 485 [17]   | 875 [17]                      | \     |
| Ultimate Strength (MPa)   | 550 [17]   | 965 [17]                      | \     |
| Fatigue Strength of 1e7 cycles (MPa) | \     | 598 [17]                      | \     |

In the modelling, the cone and threads at the end of the screw-retained abutment is fixed to imitate a prefect fixed situation. an axial moment increasing from 10N·cm to 25N·cm is applied to the wrench as the tightening torque. And fixed the displacement of y-axial component to prevent from rigid body motion.

Element Solid187 is defined for analyzing. The contact type of the interface of wrench and prosthetic screw, prosthetic screw and gasket, outside thread of prosthetic screw and inside thread of
screw-retained abutment, gasket and screw-retained abutment are the linear contact bonded consider as a properly assembled situation. When finished setting, FEM analysis would be carried out by ANSYS19.0 workbench.

3.3. Result of FEM modelling

The contour of Von Mises stress when the wrench suffered a 23N·cm tightening torque is shown in Figure 1. The stress contour reveals that the maximum stress of screw occurs at corner of hexagonal connection of wrench and prosthetic screw. It is about 863MPa almost near yield strength (875MPa) of TI-6Al-4V ELI titanium alloy. In the other hand, there was also a large stress about 852MPa at first thread of the prosthetic screw. It revealed that fracture of prosthetic screw is most likely to happen at these two positions. With respective to the hold assembly. The maximum stress of 911MPa occurred at contact area of gasket and screw-retained abutment. The wrench is considered as a rigid body so that the stress contour of wrench is not calculated.

![Figure 2. Contour of Von Mises stress](image)

What we concerned about is that the value of maximum Von Mises stress at prosthetic screw is shown in Figure 2. The figure presents a trend that the maximum Von Mises stress of prosthetic screw increase from about 365MPa to 978MPa with the increasing tightening torque. According to Figure 3, when the tightening torque exceed 22N·cm, the maximum Von Mises stress would larger than the yield strength of TI-6Al-4V ELI which means there is a plastic permanent deformation occurs.

![Figure 3. Resulting maximum Von Mises stress at prosthetic screw](image)

4. Torsion test of prosthetic screw

Torsion testing machine shown in Figure 4 mainly consists of torsional driving device, torsional displacement transducer, torque transducer and a pair of rigid specimen holders. The minimum reading range of the torque transducer is 0.01N·cm, which is much smaller than the strength of TI-
6Al-4V ELI. And the maximum inaccuracy is about 1%. Maximum torque of torsional driving device is 2000N·cm which is large enough to carry out a torsional failure test.

Figure 4. Torsion test machine

Prosthetic screw wearing gasket inserts into screw-retained abutment as a testing sample. And wrench is mated with prosthetic screw by hexagonal connection. Wrench and specimens are shown in Figure 5. One side of holder clamps wrench and the other side clamps the end of screw-retained abutment during testing. There are 5 samples would be carried out the torsion test. Torque applying to the sample are at the rate of 150°/min continuously. And the test is conducted in air at room temperature. Samples would be torqued until damage. Maximum torque during experiment would be recorded.

Figure 5. Specimens (a) wrench (b) prosthetic screw wearing a gasket inserts into screw-retained abutment

The maximum torque of testing samples are listed in Table 2. There are 5 prosthetic screws broken at the first thread and 3 of them slips at the hexagonal connection. Maximum torque of samples are range from 16N·cm to 34N·cm. Average torque is about 30.2N·cm. And the photo by microscope with 30 times of broken sample and slipping sample are as shown in Figure 6.

Table 2. Maximum torque of the prosthetic screws

| No.     | Maximum Torque (N·cm) | Situation                        |
|---------|-----------------------|----------------------------------|
| Sample 1| 29                    | Broken at the first thread.      |
| Sample 2| 26                    | Broken at the first thread.      |
| Sample 3| 32                    | Slipping at the hexagonal connection. |
| Sample 4| 34                    | Slipping at the hexagonal connection. |
| Sample 5| 30                    | Slipping at the hexagonal connection. |
| Average | 30.2                  |                                   |

Figure 6. damage sample of torsion test

(a) broken sample (b) slipping sample
5. FEM modelling of occlusal loading

5.1. CAD model of FEM modelling during occlusal loading

The CAD model is built according to the standard ISO 14801[18]. Prosthetic screw and abutment are the same as above mention. Abutment is inserted into a 4.3mm diameter implant. Implant is a sample model omitting surface detail including outer threads. Prosthetic screw fixes a 10mm diameter hemispherical crown with screw-retained abutment. The whole complex is embedded into resin in a 30° angle and clamp by a holder.

![Model of assembly](image)

Figure 7. Model of assembly

5.2. Analysis setting

All parts of assembly are considered as linear elastic isotropic homogenous materials. Hemispherical crown is made of pure titanium in grade 4. Resin is a 3GPa material as the standard ISO 14801 required. Material of all other parts are titanium alloy TI-6Al-4V ELI. Specification of materials are listed in Table 1. above mentioned.

Model is meshed with Solid187 tetrahedral 10-node element. Total element and node number are about 79693 and 199719 respectively. The contact of interface between hemispherical crown and prosthetic screw, hemispherical crown and screw-retained abutment, prosthetic screw and screw-retained abutment are defined as bonded. Other interfaces are combined into a same plane by merging nodes for reducing computation.

Bottom surface of holder is fixed so as to prevent from rigid body motion. According to the tightening torque within a range from 10N·cm to 25N·cm, bolt-pretension (see Figure 8.) was calculated and applied to the prosthetic screw in first step, then lock in second step, which in order to incarnate the influence of tightening torque. An axial concentric vertical force of 250N is borne by the hemispherical crown to simulate a realistic occlusal force.

![Bolt-pretension force according to tightening torque](image)

Figure 8. Bolt-pretension force according to tightening torque
5.3. Simulation result

For realizing the reliability of prosthetic screw, Von mises stress and vertical normal stress (in z-axis of local coordinate of screw, see Figure 9) is concerned about. Von Mises stress distribution indicates the possible fracture region, z-component normal stress implies the resistance to bolt-pretension. Maximum stress shows an increase tendency with the increasing bolt-pretension, correspond to the tightening torque of prosthetic screw. Maximum Von stress increase from 425MPa (T=10N·cm) to 1065MPa (T=25N·cm), maximum z-component stress increase from 474MPa (T=10N·cm) to 1222MPa (T=25N·cm). Figure 9 presents that maximum Von Mises stress is smaller than yield strength of Ti-6Al-4V ELI (875MPa) when tightening torque is less than 20N·cm (845MPa). And for maximum z-component normal stress, situations happened while tightening torque less than 18N·cm (875MPa).

![Figure 9](image-url) Maximum Von Mises stress, z-component stress and safety factors of prosthetic screw

Base on the maximum stress in static loading, safety factor of dynamic fatigue test with $10^7$ cycles is estimated with equation (4) and shown in Figure 9. In contrast, chart of safety factor exhibits a trend that the lower tightening torque applies the higher safety factor does the screw occurs. And safety factors are higher than 1 when prosthetic screw suffer a 18N-cm tightening torque. Maximum safety factor 2.10 of Von Mises stress occurs at 10N·cm tightening torque and the minimum one 0.84 occurs at 25N·cm tightening torque. And the highest safety factor of z-component normal stress is 1.88 (T=10N·cm) and lowest is 0.73 (T=25N·cm).

With the tightening torque increasing, maximum Von Mises stress of screw-retained abutment decrease from 601MPa to 462MPa, and maximum Von Mises stress of implant maintains at 288MPa. Safety factor of both are higher than 1, the screw-retained one increase from 1.48 to 1.93, and the one of implant consist on 3.21 (see Figure 10).

![Figure 10](image-url) Maximum Von Mises stress, z-component stress and safety factors of prosthetic screw

![Figure 11](image-url) Stress contour of prosthetic screw (a)z-component normal stress (b)Von Mises stress
Stress contours of prosthetic screw with a bolt-pretension at a 18N·cm tightening torque are shown in Figure 11. Both maximum Von Mises stress and z-component normal stress of prosthetic screw take place at the first thread.

Figure 12 shows that the larger Von Mises stress of abutment and implant is located at the edge of screw hole (612MPa) and transition zone to implant. Similarly, maximum Von Mises stress of implant occurs at edge of screw hold and the interface between resin.

6. Discussion

In the traditional engineering project, though a larger tightening torque brings a larger bolt-pretension and fixes well the bolt connection. A too large tightening torque makes thread undergoes permanent irreversible plastic deformation during long term using, which decrease the reliability of abutment-implant system, evenly breaks the screw. Same situation is also appropriate for the case of abutment-implant system. So, it is necessary to assess a suitable tightening torque for the screw in the system.

This study aims at influence of prosthetic screw tightening torque to the screw-retained abutment-implant complex system. In the FEM modelling of this study, several assumptions are made to optimize the modelling. Material properties are considered as isotropic homogeneous linear elastic. Once a stress larger than yield strength, which means permanent deformation occurs and the component suffers a damage. Components of model are mate with each other perfectly in CAD model. CAD model has been simplified such as taking out chamfering and threads in order to prevent from singular value or involving fewer calculations. Contact in FEM modelling has been simply as co-node interface or bonded contact. All of these assumptions may influence the simulation result.

The prosthetic screw tightening torque simulation present a result that a 23N·cm tightening torque cause permanent damage, but the torsion test shows that at least a 26N·cm tightening torque is enough to break the prosthetic screw. The reason of the difference is that yield strength is defined as the critical point of damage in simulation, but the criterion of broken in torsion test is maximum torque. Once the plastic deformation occurs would damage the implant system and brings reduction in functionality. It is better to avoid the situation of plastic deformation. In addition, main focus of the study is the behavior of prosthetic screw, tool is considered as a rigid body in order to optimize the simulation. Actually, wrench is made of 405 stainless steel which would breaks under a large external loading as well. So that an extremely torque should be avoided during tightening process.

According to the torsion test, the broken torque of the prosthetic screw is a range from 26N·cm to 34N·cm but a certain value. Dimension tolerance of component, surface smoothness, fitting allowance would and so on can cause an effect to the strength of prosthetic screw.

In simulation of occlusal loading, bolt-pretension cause by tightening torque is considered in analyzing. Bolt-pretension mainly depends on frictional coefficient, screw geometry and tightening torque. Frictional coefficient is determined as 0.35 at an unlubricated condition[15]. If interface is contaminated by saliva or blood, frictional coefficient will become smaller so than bring a larger bolt-pretension and cause a higher stress of implant system[13].
Result shows that tightening torque affect not only the stress distribution of prosthetic screw. A higher tightening torque leads to a higher stress occurs on prosthetic screw because a higher boltpretension squeeze the prosthetic screw heavily. While the tightening torque higher than 18N·cm, stress on prosthetic screw exceed the yield strength.

On the contrary, a high tightening torque could fix components well. So that higher the tightening torque it is, lower the stress on abutment occurs. Same tendency was reported by a previous study[13]. Stress of implant is mainly influenced by external load and contact with abutment and resin. External loading is defined as 250N in 30° to imitate reaction force of dental cusp to dental cusp while occlusion. At the situation of constant external load, idealized co-node interface between resin and implant, prosthetic screw does not contact with the implant, the tightening torque hardly has impact on stress on implant, which keeps at about 288MPa.

According to the result of static analyzing, safety factor of $10^7$ cycles’ dynamic loading is estimate base on Goodman criterion. $10^7$ cycles is about the chewing times that a patient has 3 meals a day in 10 years[19, 20]. Result exhibits that safety factor higher than 1 when tightening torque is larger than 18N·cm, which means prosthetic screw will come through $10^7$ cycles loading safely. For the screw-retained abutment and implant, safety factors are always higher than 1 while screw is suffering a torque in range of 10N·cm to 25N·cm.

7. Conclusion

Based on the result of the study, conclusions were drawn below:

1. The acceptable tightening torque estimated by FEM simulation is close to the torsion test result. It proves that simulation method is available for studying the project in same type.
2. Bolt-pretension affected the stress of not only the prosthetic screw itself but also screw-retained abutment. Hence is better to consider bolt-pretension in FEM simulation of dental implant system.
3. According to the result of FEM simulation of tightening, torsion test and FEM simulation of occlusal loading, best tightening torque of prosthetic screw is 18N·cm.

Acknowledgments

This study is supported by

1) The Science and Technology Program of Nansha District, Guangzhou (Technology Development Program, No. 2017KF007);
2) The Science and Technology Program of Guangzhou (No. 201906010032);

References

[1] Jung R E, Pjetursson B E, Glauser R, Zembic A, Zwahlen M and Lang N P 2008 A systematic review of the 5-year survival and complication rates of implant-supported single crowns Clin. Oral Implant. Res. 19 119-30
[2] Nascimento C, Pedrazzi V, Miani P K, Moreira L D and de Albuquerque R F, Jr. 2009 Influence of repeated screw tightening on bacterial leakage along the implant-abutment interface Clin. Oral Implant. Res. 20 1394-7
[3] Menendez-Collar M, Serrera-Figallo M A, Hita-Iglesias P, Castillo-Oyague R, Casar-Espinosa J C, Gutierrez-Corrales A, Gutierrez-Perez J L and Torres-Lagares D 2018 Straight and tilted implants for supporting screw-retained full-arch dental prostheses in atrophic maxillae: A 2-year prospective study Med. Oral. Patol. Oral. 23 e733-e41
[4] Tiossi R, Lin L, Conrad H J, Rodrigues R C, Heo Y C, de Mattos Mda G, Fok A S and Ribeiro R F 2012 Digital image correlation analysis on the influence of crown material in implant-supported prostheses on bone strain distribution J. Prosthodont. Res. 56 25-31
[5] Katsuma Y and Watanabe F 2015 Abutment screw loosening of endosseous dental implant body/abutment joint by cyclic torsional loading test at the initial stage Dent. Mater. J. 34 896-902
[6] Watanabe F, Hiroyasu K and Ueda K 2015 The fracture strength by a torsion test at the implant-abutment interface Int. J. Implant Dent. 1 25
[7] Anchieta R B, Machado L S, Hirata R, Bonfante E A and Coelho P G 2016 Platform-Switching for Cemented Versus Screwed Fixed Dental Prostheses: Reliability and Failure Modes: An In Vitro Study Clin. Implant. Dent. R. 18 830-9
[8] Zhang X, Liu L, Wang Y and Chen X 2016 Effects of Dental Implant-abutment Interfaces on the Reliability of Implant Systems. In: MATEC Web Conf.: EDP Sciences) p 08006
[9] Zhang X, Liu L, Chen X, Feng W and Chen Y 2016 Design and the Reliability Research of the Restorable Dental Implant System Aiming At the Central Screw Fracture. In: 5th International Conference on Mechanical Engineering, Materials and Energy (5th ICMEME2016): Atlantis Press)
[10] Kayabaşı O, Yüzbasoğlu E and Erzincanlı F 2006 Static, dynamic and fatigue behaviors of dental implant using finite element method Adv. Eng. Softw. 37 649-58
[11] Presotto A G C, Bhering C L B, Caldas R A, Consani R L X, Barão V A R and Mesquita M F 2018 Photoelastic and finite element stress analysis reliability for implant-supported system stress investigation Braz. J. Oral Sci 17 1-13
[12] Bulaqi H A, Barzegar A, Paknejad M and Safari H 2019 Assessment of preload, remaining torque, and removal torque in abutment screws under different frictional conditions: A finite element analysis J. Prosthet. Dent. 121 548 e1- e7
[13] Jorn D, Kohorst P, Besdo S, Rucker M, Stiesch M and Borchers L 2014 Influence of lubricant on screw preload and stresses in a finite element model for a dental implant J. Prosthet. Dent. 112 340-8
[14] Cicciu M, Bramanti E, Matacena G, Guglielmino E and Risitano G 2014 FEM evaluation of cemented-retained versus screw-retained dental implant single-tooth crown prosthesis Int. J. Clin. Exp. Med. 7 817-25
[15] Fellah M, Labaiz M, Assala O, Dekhil L, Taleb A, Rezag H and Iost A 2014 Tribological behavior of Ti-6Al-4V and Ti-6Al-7Nb Alloys for Total Hip Prosthesis Adv. Tribol. 2014 1-13
[16] Budynas R G and Nisbett J K 2008 Shigley's mechanical engineering design vol 8 (New York: McGraw-Hill)
[17] Niinomi M 1998 Mechanical properties of biomedical titanium alloys Mater. Sci. Eng. A. Struct. Mater 243 231-6
[18] Geneva 2007 International Standard ISO 14801 dentistry implants dynamic fatigue test for endosseous dental implants.
[19] Binon P P and McHugh M J 1996 The effect of eliminating implant/abutment rotational misfit on screw joint stability Int. J. Prosthodont. 9
[20] Alkan I, Sertgöz A and Ekici B 2004 Influence of occlusal forces on stress distribution in preloaded dental implant screws J. Prosthet. Dent. 91 319-25