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RESEARCH AND EDUCATION

Effects of abutment screw preload in two implant connection systems: A 3D finite element study

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ABSTRACT

Statement of problem. Finite element analysis (FEA) has been used to evaluate the biomechanical behaviors of dental implants. However, in some FEA studies, the influence of the preload condition has been omitted to simplify the analysis. This might affect the results of biomechanical analysis significantly. The preload condition requires analysis.

Purpose. The purpose of this FEA study was to evaluate and verify the effects of the presence of the preload condition on abutment screws under the occlusal load for external and internal hexagonal connection systems.

Material and methods. The finite element models consisting of bone blocks, 2 different implant systems (Osstem US and GS system; Osstem Implant Co), and crowns were created. With these components, a total of 6 models with different conditions were constructed for FEA: external hexagonal connection system only with preload (EO), external hexagonal connection system with no preload but occlusal load (EN), external hexagonal system with both preload and occlusal load (EP), internal hexagonal system only with preload (IO), internal hexagonal system with no preload but occlusal load (IN), and internal hexagonal system with both preload and occlusal load (IP). An 11.3-degree oblique load (100 N) to the axis of the implant was applied on the occlusal surface of the crown for the models with occlusal load. A preload of 825 N was applied in the abutment screw of the models EO, EP, IO, and IP. The maximum von Mises stress, maximum principal stress, and maximum displacement of the components of the models were evaluated.

Results. Both external and internal connection systems resulted in higher maximum von Mises stress and maximum principal stress values in the presence of preload in the abutment screw. The internal connection system showed higher displacement values than the external system with or without occlusal loading, and values tended to increase with the preload condition.

Conclusions. The presence of a preload condition significantly affected the biomechanical behaviors of the components of 2 different connection systems. The preload condition should be included in FEA to achieve more realistic results. (J Prosthet Dent 2019;122:474.e1-e8)

The long-term success of implant-supported restorations is related to the biomechanical environment[1] and depends on the stress distribution in the implant connection system.[2,3] However, evaluating stress distribution clinically in the implant-supported prostheses is problematic. Therefore, finite element analysis (FEA) has been widely used to evaluate the biomechanical problems that influence dental implant systems.[4–7]

The stress concentration on the components of different implant connection systems and supporting bone has been modeled with FEA,[8–11] which concludes that different connection designs significantly affect stress distribution patterns. The internal hexagonal connection design has been reported to lead to more favorable stresses than the external connection design.[9,10]

Understanding the biomechanics of implant connection systems requires an understanding of how the abutment is connected to the implant with an abutment screw,[12] which needs to be tightened with a certain amount of torque. When the abutment screw is tightened, a compressive force is generated along the interface between the abutment screw thread and the internal

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Clinical Implications

Although some assumptions were made to simplify the models in the finite element analysis, the results of the study indicated that considering the preload condition and applying the optimum preload in finite element analysis is necessary to achieve realistic biomechanical behaviors of implant systems during occlusal loading.

thread of the implant. This induces a tensile force, which is called the preload, in the shaft of the screw to clamp the implant and abutment together.[13–15]

The preload helps keep the 2 components clamped together as long as the effective force in the abutment screw is not dissipated by micromovements during functional loading.[7] Thus, the preload needs to be higher than the occlusal force to achieve a stable screw joint and to avoid screw loosening. When the tightening torque increases, the preload is also increased to a point called the optimum preload. The optimum preload protects the screw joint unless the external force exceeds the preload.[16–18] Optimum preload should induce a force in the screw joint that is 75% of the yield strength of the screw. The development of optimum preload should be considered during the dynamic loading of the implants during mastication.[12]

FEA studies have considered the influence of preload in the abutment screw.[19–23] Van Staden et al[20] reported that the preload applied to the abutment screw affected the stresses. They found that the stress in an implant system increased when the preload force increased. Although Khraisat et al[19] compared different connection systems, they reported that the abutment screw preload led to stress in the bone because of deformation in the collar area of an external connection system. Including the preload condition significantly influenced the results of FEA studies.

However, FEA studies of the preload condition with different implant connection systems are lacking, and the influence of the preload condition has frequently been disregarded in simplified FEA models without the abutment screw thread.[10,11,24] Modeling the preload condition of the abutment screw by using the exact geometry of the implant system is important for FEA studies to precisely simulate tightening of the abutment screw and will help achieve a more realistic biomechanical model.[25]

Therefore, the purpose of this FEA study was to evaluate the influence of the preload condition in abutment screws during occlusal loading for a better understanding of the biomechanical performance of different implant connection systems. It was hypothesized that the presence of the preload condition would not affect the stresses in 2 implant connection systems.

MATERIAL AND METHODS

Six 3-dimensional finite element models were built for this study according to the conditions of implant connection systems, the presence of preload condition, and the occlusal load. Two models had only preload without occlusal load: external hexagonal connection system only with preload (EO) and internal hexagonal system only with preload (IO). The other 4 models included occlusal load in the models: external hexagonal connection system without preload (EN), external hexagonal system with preload (EP), internal hexagonal system without preload (IN), and internal hexagonal system with preload (IP). The models were constructed with mesh generation software (Visual-Mesh; ESI Group). The implants were placed in the bone blocks of the mandible, and the abutments and abutment screws were located with the crowns in individual finite element models. An oblique load of 100 N on the occlusal surface of the crown was applied to the 4 models (EN, EP, IN, and IP), and a preload of 825 N was added to the abutment screws in the models EP and IP. For the models EO and IO, only a preload of 825 N was applied to the screws without the occlusal load. The maximum von Mises stress, principal stress, and displacement values in each component of the 4 models were compared and analyzed.

The geometries of bone blocks for finite element models were created similar to the characteristics of the posterior section of the human mandible by using simulation software (Visual-Mesh; ESI Group). The bone was composed of approximately 2-mm-thick cortical bone surrounding the cancellous bone. Implants with 2 different implant-abutment connection systems (Osstem US and GS system; Osstem Implant Co) were placed in the first molar position at the bone crest level in the center of the bone model. The dimensions of both implants were 5 mm in diameter and 10 mm in length. The geometries of the implant systems were provided by the manufacturers (Osstem US and GS system; Osstem Implant Co), and the tetrahedral meshes of the 2 implant systems with prosthetic components were generated separately (Visual-Mesh; ESI Group).

Each finite element model consisted of an implant, abutment, abutment screw, and a crown embedded in cortical and cancellous bone (Fig. 1). Those implant components were designed and modeled independently and then assembled with the selected implant systems.

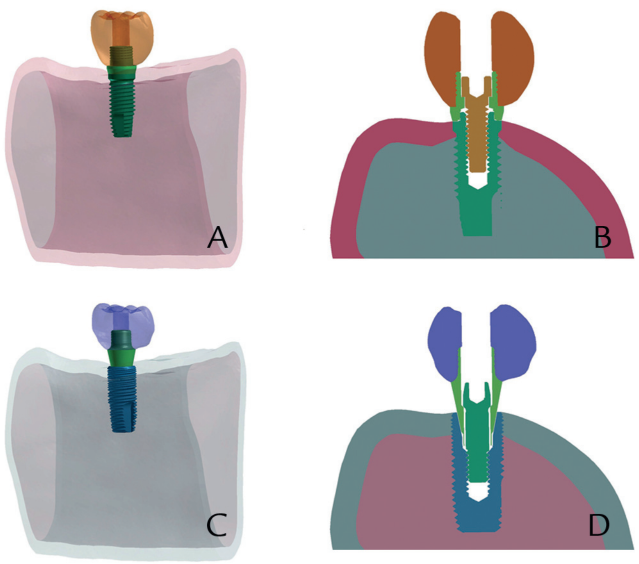

Figure 1. Finite element models. A, External view of external connection system. B, Coronal section view of external connection system. C, External view of internal connection system. D, Coronal section view of internal connection system.

Table 1. Description of finite element models

Model	Connection	Presence of Preload	Presence of Occlusal Load	Number of Elements	Number of Nodes
EO	External	Yes	No	449 291	86 480
EN	External	No	Yes	449 291	86 480
EP	External	Yes	Yes	449 291	86 480
IO	Internal	Yes	No	537 557	99 123
IN	Internal	No	Yes	537 557	99 123
IP	Internal	Yes	Yes	537 557	99 123

EN, external hexagonal connection system with no preload but occlusal load; EO, external hexagonal connection system only with preload; EP, external hexagonal system with both preload and occlusal load; IN, internal hexagonal system with no preload but occlusal load; IO, internal hexagonal system only with preload; IP, internal hexagonal system with both preload and occlusal load.

The configuration of the models is summarized in Table 1.

The material properties of each component were obtained from previous studies (Table 2).[26–28] It was assumed that all the materials used in the study were isotropic, homogeneous, and linear.[4]

Finite element analysis was performed with modeling software (Visual-Crash for PAM; ESI Group). All the nodes of the medial and distal surfaces of the bone in the models were constrained in all directions so as not to generate dislodgement of the models during simulation. A total occlusal load of 100 N[11,29] with oblique loading at an angle of 11.3 degrees to the axis of the implant was applied. The occlusal load was distributed to the nodes on the occlusal surface of the crown on the buccal side (Fig. 2).[30,31] The contact between the surfaces of the implant and the abutment and between the abutment and the screw was established with the frictional coefficient of 0.3.[16,32] The implant and the abutment screw were set as tied at the contact surface. A preload of 825 N as a body force was applied on the upper part of the shank of the abutment screw, where the elongation of the screw was expected with tightening (Fig. 3). The magnitude of the preload condition was selected from a previous study.[12]

After simulating the models with the finite element analysis software (Virtual-Performance; ESI group), the values and patterns of the maximum von Mises stress, maximum principal stress, and maximum displacement of each component in the external and internal connection systems with or without preload condition were compared and evaluated.

Table 2. Material properties[23–25]

Component	Elastic Modulus (GPa)	Poisson Ratio
Cortical bone	13.7	0.3
Cancellous bone	1.37	0.3
Titanium alloy (implant)	102	0.3
Gold alloy (abutment crown abutment screw)	100	0.3

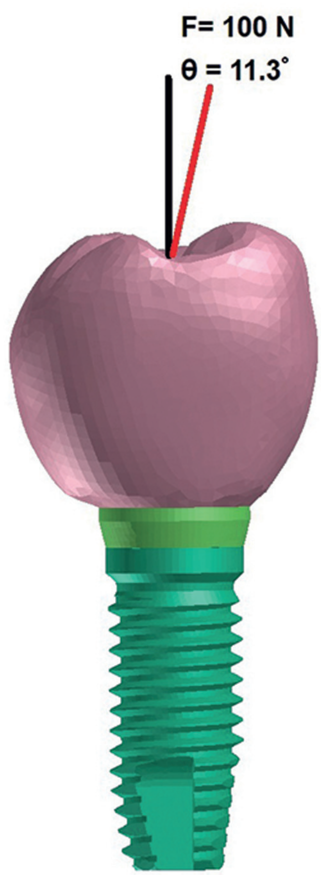

Figure 2. Finite element model with occlusal load (100 N) on buccal side of crown at angle of θ=11.3 degrees from implant axis.

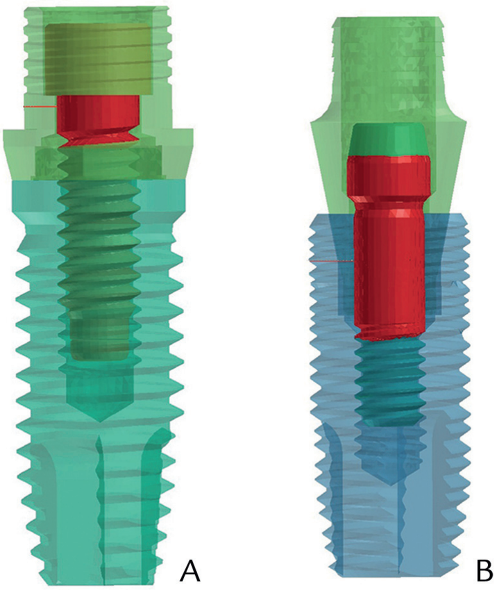

Figure 3. Simulation of preload (825 N) on upper part of shank of abutment screw. A, External connection system. B, Internal connection system.

RESULTS

The maximum von Mises stress values in the components of the model EP were generally higher than those of the models EO and EN. The stress values of the model EO were generally greater than those of the model EN in most of the implant components and the bone. The internal connection system had similar maximum von Mises stress values to the external connection system. The stress values in each component were higher in the model IP compared with those in the model IN. The model IO also had lower stress values than the model IP, however, they were greater than those of the model IN. The maximum von Mises stress values for each component of the external and internal connection models with different conditions are presented in Table 3. Overall stress distribution patterns of the models are described in Figure 4. The stresses were mainly concentrated on the top of the implants and the bottom of the abutments.

Among the components, the abutment screw showed the greatest increase under occlusal load in the von Mises stress values with preload conditions between 104.5 MPa in the model EN and 850 MPa in the model EP and between 37 MPa in the model IN and 674 MPa in the model IP. Regardless of the preload condition, the implant showed the highest stress values of all parts, followed by the abutment.

When comparing the external connection with the internal connection under occlusal load without preload, the maximum stress values of the external connection were higher in the screw, crown, and cortical bone (104.5, 76, and 53 MPa in the model EN and 37, 28, and 37 MPa in the model IN). However, those of the internal connection were higher in the implant and abutment (834 and 600 MPa in the model IN and 346.5 and 346 MPa in the model EN). With the preload condition, the model IO showed lower stress values than the model EO in the abutment and screw (670 and 563 MPa in the model IO and 716 and 696 MPa in the model EO). With both preload and occlusal load conditions, the external connection also had higher stress values in the abutment and screw, whereas the internal connection showed higher values in the implant, crown, and cortical bone. For both connection systems, irrespective of the preload or occlusal load, the smallest stress values were obtained in cancellous bone, followed by cortical bone (Fig. 5).

Table 3. Maximum von Mises stress values in each component of models

	Maximum von Mises Stress (MPa)					
Model	**EO**	**EN**	**EP**	**IO**	**IN**	**IP**
Component						
Cortical bone	84	53	101	262	37	284
Cancellous bone	12	4	25	24	5	25
Implant	550	346.5	573	849	834	852
Abutment	716	346	731	670	600	675
Screw	696	104.5	850	563	37	674
Crown	139	76	164	277	28	282

EN, external hexagonal connection system with no preload but occlusal load; EO, external hexagonal connection system only with preload; EP, external hexagonal system with both preload and occlusal load; IN, internal hexagonal system with no preload but occlusal load; IO, internal hexagonal system only with preload; IP, internal hexagonal system with both preload and occlusal load.

The maximum principal stress values of all the models are summarized in Table 4. The trends for maximum principal stress values and stress distribution patterns were similar to those for maximum von Mises stress. Regardless of the conditions of occlusal load, the models with preload showed higher stress values than the models without preload in both external and internal connection systems.

The maximum displacement values for each component of both external and internal connection models with different conditions are presented in Table 5. The overall displacement values of the external connection system were mostly lower than those of the internal connection system (Fig. 6). Without preload, the values were generally low in both connection systems, while those in all components were higher with preload in the internal connection system. Similar to the results for the maximum stress values, the value of displacement in the screw with preload showed the greatest increase compared with the screw without preload in both connection systems.

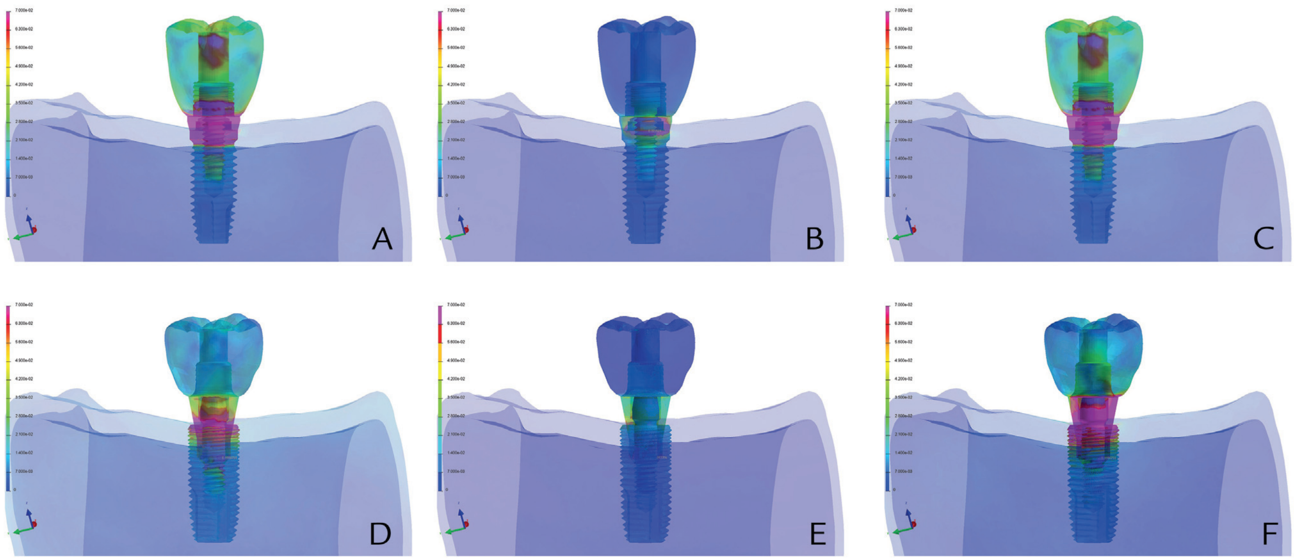

Figure 4. Stress distribution of external and internal connection models. A, Model EO. B, Model EN. C, Model EP. D, Model IO. E, Model IN. F, Model IP. EN, external hexagonal connection system with no preload but occlusal load; EO, external hexagonal connection system only with preload; EP, external hexagonal system with both preload and occlusal load; IN, internal hexagonal system with no preload but occlusal load; IO, internal hexagonal system only with preload; IP, internal hexagonal system with both preload and occlusal load.

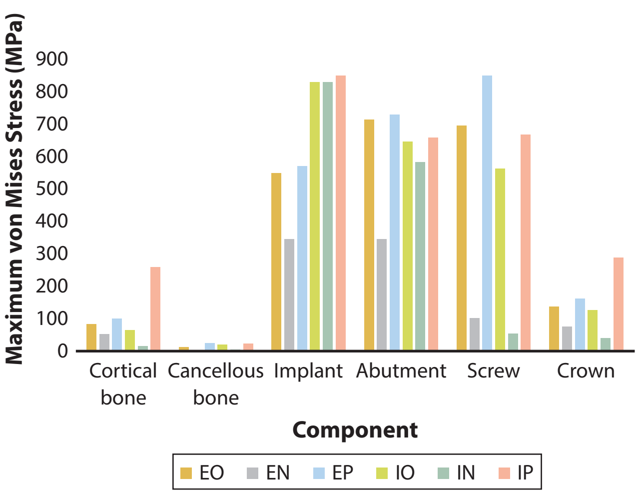

Figure 5. Comparison of maximum von Mises stress values (MPa) for each component of external and internal connection models. EN, external hexagonal connection system with no preload but occlusal load; EO, external hexagonal connection system only with preload; EP, external hexagonal system with both preload and occlusal load; IN, internal hexagonal system with no preload but occlusal load; IO, internal hexagonal system only with preload; IP, internal hexagonal system with both preload and occlusal load.

Table 4. Maximum principal stress values in each component of models

	Maximum Principal Stress (MPa)					
Model	**EO**	**EN**	**EP**	**IO**	**IN**	**IP**
Component						
Cortical bone	58	26	68	131	20	134
Cancellous bone	11	3	17	31	6	35
Implant	592	355	867	966	434	996
Abutment	504	111.5	617	776	535	1009
Screw	994	163	1106	1324	231	1587
Crown	104	17	173	58	19	250

EN, external hexagonal connection system with no preload but occlusal load; EO, external hexagonal connection system only with preload; EP, external hexagonal system with both preload and occlusal load; IN, internal hexagonal system with no preload but occlusal load; IO, internal hexagonal system only with preload; IP, internal hexagonal system with both preload and occlusal load.

Table 5. Maximum displacement values in each component of models

	Maximum Displacement (μm)					
Model	**EO**	**EN**	**EP**	**IO**	**IN**	**IP**
Component						
Cortical bone	9	8	12	38	6	39
Cancellous bone	9	6	9	35	6	37
Implant	12	8	12	38	10	40
Abutment	21	20	24	202	119	204
Screw	38	28	41	359	7	359
Crown	18	32	23	208	149	218

EN, external hexagonal connection system with no preload but occlusal load; EO, external hexagonal connection system only with preload; EP, external hexagonal system with both preload and occlusal load; IN, internal hexagonal system with no preload but occlusal load; IO, internal hexagonal system only with preload; IP, internal hexagonal system with both preload and occlusal load.

DISCUSSION

This study showed that the maximum von Mises stress and maximum principal stress values in models with preload were higher than those without preload in both systems, rejecting the null hypothesis. When Pessoa et al[1] investigated the maximum von Mises stress of the screw under loading of 100 N without including preload condition, the value was 128.6 MPa in internal connection. Silva et al[23] included preload condition in their study to evaluate the maximum von Mises stress of the screw under the same load, and an increased value of 490 MPa was reported in

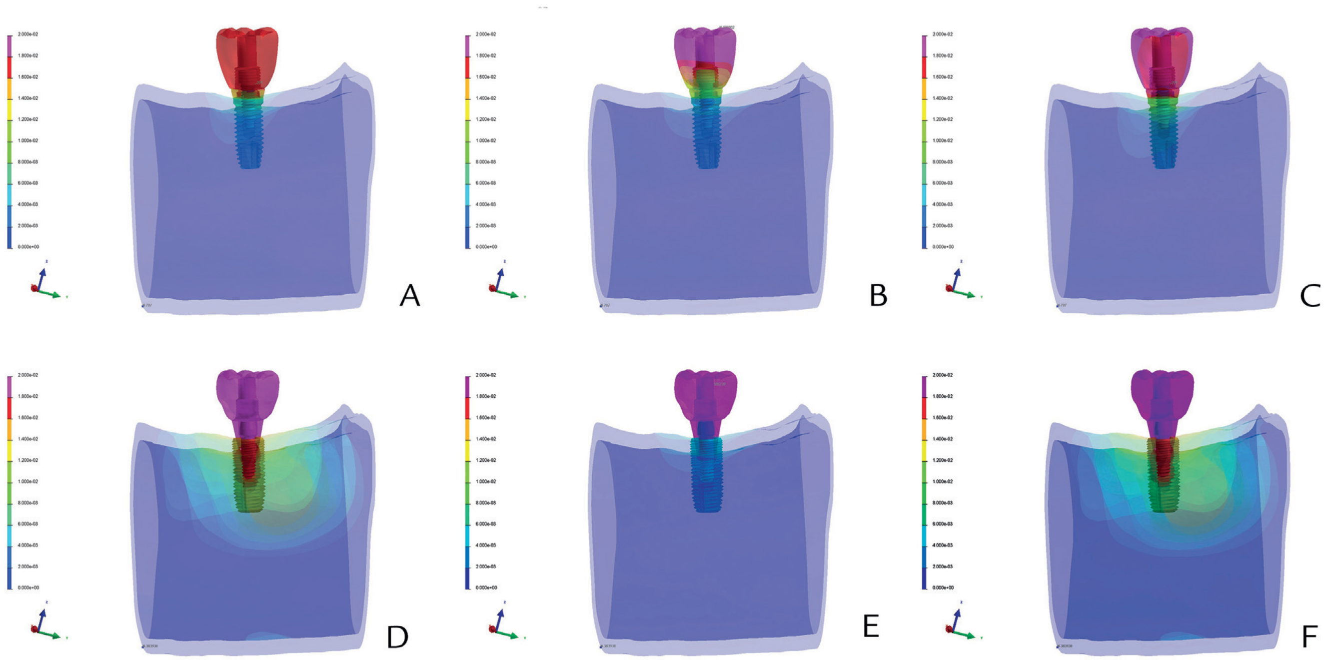

Figure 6. Maximum displacement of models. A, Model EO. B, Model EN. C, Model EP. D, Model IO. E, Model IN. F, Model IP. EN, external hexagonal connection system with no preload but occlusal load; EO, external hexagonal connection system only with preload; EP, external hexagonal system with both preload and occlusal load; IN, internal hexagonal system with no preload but occlusal load; IO, internal hexagonal system only with preload; IP, internal hexagonal system with both preload and occlusal load.

the model with an internal connection. The results from these 2 studies are consistent with those of this present study in which the stress value of the model IP (674 MPa) was higher than that of the model IN (37 MPa).

The results of this study showed that the presence of the preload condition affected the stress values significantly. It seems essential to consider including the preload condition in finite element analysis. The authors have considered preload condition as an essential factor and agreed that preload applied to the abutment screw influences the stress level in the implant system and bone.[19–21]

Screw loosening or screw fracture is one of the most common complications with implant-supported restorations. Obtaining the proper preload can be critical in preventing screw loosening and long-term implant failure.[15] Adequate torque to tighten the abutment screw should be applied to achieve the optimum preload. The optimum preload should not exceed the yield strength of the screws and was reported to be ideally 75% of the yield strength.[12,14] The yield strength of gold alloy abutment screws was reported to be 1100 N.[12] Thus, 825 N of preload, which is 75% of the yield strength of 1100 N, was set for this study to simulate the presence of optimum preload conditions in the implant system.[12]

Generally, more favorable stress distribution patterns have been reported in the internal connection system and provide better stability than those of the external connection system.[9,10] However, the stresses of certain components such as implant, crown, and cortical bone were higher in the model IP than in the model EP when the preload condition was included in this study. Takahashi et al[10] said that the internal connection system would have lower stress values due to the greater contact area between the abutments and the implants, reducing the effect of bending caused by the oblique load. However, they did not include the preload condition in their research, and the results of this study showed a different aspect of the presence of preload. Chun et al[11] also mentioned in their FEA study to evaluate the effects of different implant connection types on stress distribution that the influence of preload in the abutment screw has been neglected to simplify the analysis since it might have a small influence on stress concentration in the bone. Similarly, Quaresma et al[24] evaluated the influence of 2 implant connection systems on stress distribution. However, they did not refer to preload condition in their study. Higher incidence of screw loosening has been found in external connection systems than in internal connection systems.[7,24] The present study found that the screw in the models EN and EP had higher maximum von Mises stress values (104.5 and 850 MPa) than those in the models IN and IP (37 and 674 MPa). The greater the stress the screw bears, the greater the possibility of screw loosening is.[15] Michalakis et al[14] concluded that the internal connection design also could not prevent screw loosening under excessive loading. Consistent with the study by Michalakis et al, the present study found a high stress magnitude around the abutment screw as compared with other components of the model IP with the internal connection design.

In addition, the maximum displacement values of most of the components in the internal connection system in this study were higher than those of the external connection system. Guda et al[15] suggested that the internal connection system still can cause microdisplacement in the joint, resulting in the loosening of screws. The reason the internal system had a higher displacement value could be the design of the internal connection system since it can be forced down more easily compared with the external connection system.[18] Also, since the internal connection has a wider and greater contact area than that of the external system, it could show more errors during contact analysis.[3]

In this study, an oblique loading of 11.3 degrees angled to the long axis of the implant was used.[30,31] The occlusal force normally varies greatly among different individuals according to their muscles of mastication, teeth, and the texture of the food.[11] An occlusal force of 100 N was selected in this study, based on previous studies, to simulate the clinical force.[11,29]

The significance of the results from this study was that including the preload condition in the FEA models was essential for replicating the actual clinical situation. However, this FEA study should be validated with in vitro and clinical experimental data in an effort to evaluate the biomechanical behaviors in implant systems with the preload condition. Furthermore, several assumptions were made to simplify the study. The materials used in the study were all isotropic, homogeneous, and linearly elastic.[4] Future studies with more developed models having anisotropic, nonhomogenous, and nonlinear conditions need to be performed to evaluate the influence of simulating the preload condition in the abutment screw for the advanced application of FEA.

CONCLUSIONS

Within the limitations of this FEA study, the following conclusions were drawn:

1. The presence of the preload condition significantly increased the values of the maximum von Mises stress, principal stress, and displacement in components of 2 different connection systems.
2. Considering the preload effects under occlusal load on an implant-prosthesis complex in computer simulation would help obtain more realistic results for better biomechanical analysis of implant systems.

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