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Original Article

Biomechanical analysis of rigid and non-rigid connection with implant abutment designs for tooth-implant supported prosthesis: A finite element analysis

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Abstract *Background/purpose:* The design of the connectors and implant abutments could affect the stress distribution of the tooth-implant supported prosthesis (TISP) entire system after loading. Therefore, the purpose of this study was to investigate the stress distribution of the TISP in different connectors and different implant abutments after loading.
Materials and methods: The TISP design used in this study was divided into six models. R1, R2 and R3 represented the tooth and the one-piece, two-piece and three-piece abutment implant system connected by a rigid connector, respectively, while NR1, NR2 and NR3 were the corresponding tooth-abutment implant systems connected by a non-rigid connector. A vertical occlusal load of 50 N was applied at a right angle on the 6 occlusal points of the occlusal surface.
Results: As a result, regarding the maximum average stress distribution, R1 and NR1 appeared on the implant fixture, and the other four models were on the implant abutment. On the other hand, regardless of the abutment implant system, the maximum von Mises stress generated by the rigid connector was greater than the corresponding non-rigid connector in the cortical bone around implant. In addition, the three-piece abutment implant system had lower von Mises stress than the one-piece and two-piece implant systems in the cortical bone.
Conclusion: It is concluded that by adding a flexible non-rigid connector and three-piece

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abutment device design to TISP, the occlusal load of the implant was dispersed, and the stress could be gradually introduced into the relatively strong implant abutment.

Introduction

Since Brånemark put forward the concept of osseointegration in 1952, various types of dental implants have flourished, allowing patients to benefit through dental implant treatments that could not achieve oral reconstruction goals before.[1] Clinically, when treating patients with Kennedy Class I or Class II partially edentulous arch, the use of dental implants can avoid the trouble of wearing removable partial dentures and effectively improve their chewing function.[2] When choosing a fixed partial prosthesis with implants as a treatment option, some patients may not be able to apply a sufficient number of dental implants because of the anatomical factors of the adjacent inferior alveolar nerve[3] or maxillary sinus[4] caused by bone absorption. Therefore, dentists will consider connecting natural teeth with dental implants to restore their occlusal function.[5]

The essences of natural teeth and dental implants are different, and the mobility of the two is different after loading.[6—9] Sekine et al. pointed out that the vertical settlement of the dental implant was about 2—5 μm under the loading force of 10 pounds.[6] In contrast, upon loading natural teeth, Adell et al. showed that the vertical settlement could reach 28 μm because of the periodontal ligament (PDL).[7] Healthy natural teeth with a 500 g lateral force will reach a mobility of 56—108 μm.[8,9] When a natural tooth and an implant are combined to load the occlusal force, the stress transmission in the prosthesis system is not uniform due to the difference in mobility between the two. The main risks are the bone resorption around the implant and natural tooth intrusion.[10] In order to compensate for the difference in the amount of settlement between natural teeth and implants, many researchers have proposed designs such as non-rigid connectors,[11] shock absorbers[12] and implant abutment connection[13,14] that can be as a stress breaker.

Regarding the non-rigid connector, several finite element analysis studies have shown that the non-rigid connector as a flexible device can compensate for the difference in mobility between the tooth and the implant under axial load, and avoid excessive stress on the bone around the implant.[15,16] However, Koosha compared the three TISP design models with rigid and non-rigid connectors, the results reported that the finite element analysis stress distribution between the models did not significantly different.[17] In clinical observation, the clinical complications of non-rigid connectors have also been reported by many clinicians. For example, Tsaousoglou et al.[18] reported in the integrated analysis of TISP clinical trials that 8.19% was biological complication of natural tooth intrusion, which almost occurred with the use of non-rigid connectors, by contrast, there was no intrusion of natural tooth in the use of rigid connectors. However, according to Breeding' report,[19] the use of rigid or non-rigid connectors did not make an obvious difference in the movement of the natural tooth. Cordaro et al. retrospectively evaluated nineteen patients over a period of 24 months—94 months and reported that neither rigid or non-rigid connectors found intrusion of teeth in the prosthesis connecting reduced periodontal support tooth with implant.[20] Therefore, it is still unclear whether the use of non-rigid connectors or rigid connectors for tooth-implant supported prosthesis (TISP) is more effective for the stress distribution of prosthesis and avoiding the complications of bone loss around the implants and natural tooth intrusion.

For the implant abutment connection system, it is believed that the existence of flexibility between implant connections can allow the natural tooth of TISP for moving to a certain extent in the alveolar bone after occlusal loading. For example, Aalaei et al.[21] utilized a finite element model to compare the stress generated by two different types of screw-retained restorations (segmented and non-segmented abutments) in the bone around the implant. They found that under the loading, the non-segmented abutment had less stress concentration in the screw, while the segmented abutment had less stress and strain in the bone around the implant. Wu et al.[22] reported that the stress and strain of the bone around the one-piece implant were higher than those of the two-piece implant using the finite element analysis (FEA). Therefore, the implant-abutment connection design may contribute to therapeutic differences due to stress distribution.

Theoretically, the proposed non-rigid connection between the crown and the pontic supported by the implant will transmit favorable occlusal loads and disperse the stress concentration on the alveolar bone. However, research on the connector design used by TISP was still insufficient. One of the important reasons was that many clinical observations cannot obtain enough information to determine the biomechanics of the complex dental implant support system. Since FEA can conduct a series of assessments to simulate the difficulty of clinical analysis or conditions obtained by other methodologies.[23] FEA can be used to calculate the physical properties of entire element and provide a realistic method to approach the internal stress or relative displacement by modeling complex geometric structures and subdividing into many smaller problems.[24,25] Thus, in this study, FEA was used to investigate the stress distribution of the prosthesis that combines natural tooth and implant in different connectors and different implant abutments, thereby determining the potential components of the average stress and the maximum stress level to optimize the design of future prostheses.

Materials and methods

The construction of three-dimensional model

The FEA method was used to analyze the stress and strain distribution of the 3-unit TISP in the posterior region of the mandible under the occlusal load. Therefore, the 3D FEA model was established with the mandibular part that imitated the natural tooth of the second premolar and the implant abutment of the second molar region to receive the fixed prosthesis, which was described in Fig. 1. In Solidworks 2019 software environment (Solidworks Corp, USA), a 2 mm cortical bone covered spongy bone with a length of 55 mm, a width of 25 mm, and a thickness of 12 mm was constructed to simulate the 3D alveolar bone model of the mandible missing the first and second molars.[17] Then, Wheeler's measurement parameters[26] were referred to establish a second premolar root with a simplified 0.25 mm periodontal ligament (PDL) solid model. The height of the prepared crown was 5 mm and the margin of the prepared crown was 1 mm from the level of the bone block. In the design of the TISP structure and components, a simulation model of the Biotech KONTACT implant fixture with a diameter of 4.2 mm and a length of 10 mm was established at a distance of 16 mm from the center of the second premolar. The implant abutment system was based on the geometry and components of the original Biotech KONTACT standard abutment and simulated three pieces, two pieces and one piece models. The casting prosthesis with at least 1 mm thickness was established. The occlusal table of the simulated TISP was designed at monoplane and each crown had two circular fossae with a diameter of 2 mm and a depth of 0.25 mm, which provided occlusal force points. The material was set to nickel-chromium alloy. A cement space with a thickness of 0.05 mm was established between crown and abutment. The non-rigid connector with a vertical length of 4 mm and a width of 2.5 mm used in the current study was referred to as the non-adjustable friction grip dovetail slide attachment in the Beyeler intracoronal attachment (Cendres and Metax, Switzerland). The TISP design was divided into six models. R1, R2 and R3 represented the tooth and the one-piece, two-piece and three-piece abutment implant system connecting by a rigid connector, respectively, while NR1, NR2 and NR3 were corresponding tooth-abutment implant systems connected by a non-rigid connector.

Simulation

In order to analyze the stress distribution of TISP, the unit composition of the TISP structure was divided into two vertical pillars (vertical element of natural tooth and vertical element of implant system), a horizontal connecting body (prosthetic connection element) and a supporting medium (cortical bone and spongy bone) during the modeling process, as shown in Fig. 2. The vertical element of natural tooth had tooth solid, PDL and 0.4 mm cortical bone. The vertical element of the implant system was set to the implant fixture, the implant abutment and fixation screw. The prosthetic connection element part included four components: crown1+2, crown3, cement1 and cement3; supporting medium including cortical bone and spongy bone.

A linear static analysis was performed on the prepared 3D solid model, and it was assumed that the materials used in this study were homogeneous, isotropic and linear elastic conditions. Table 1 described their various physical properties, such as elastic modulus and Poisson's ratio.[27] The proximal and distal planes of the bone block was set as fixed boundary conditions. The implant osseointegration was assumed to be 100%, and all 3D components were constructed in bonding which does not allow relative micromotion and the displacement between different materials. In addition, the non-rigid connector matrix and parent surface were allowed to slide perpendicular to each other without penetrating. There was also no penetrating contact condition between implant fixture, implant abutment and fixation screw.

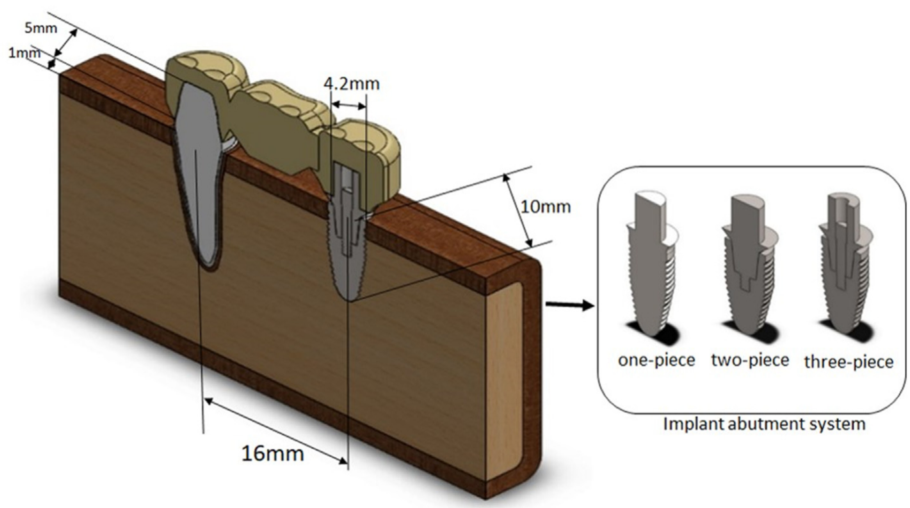

Figure 1 3D FEA model.

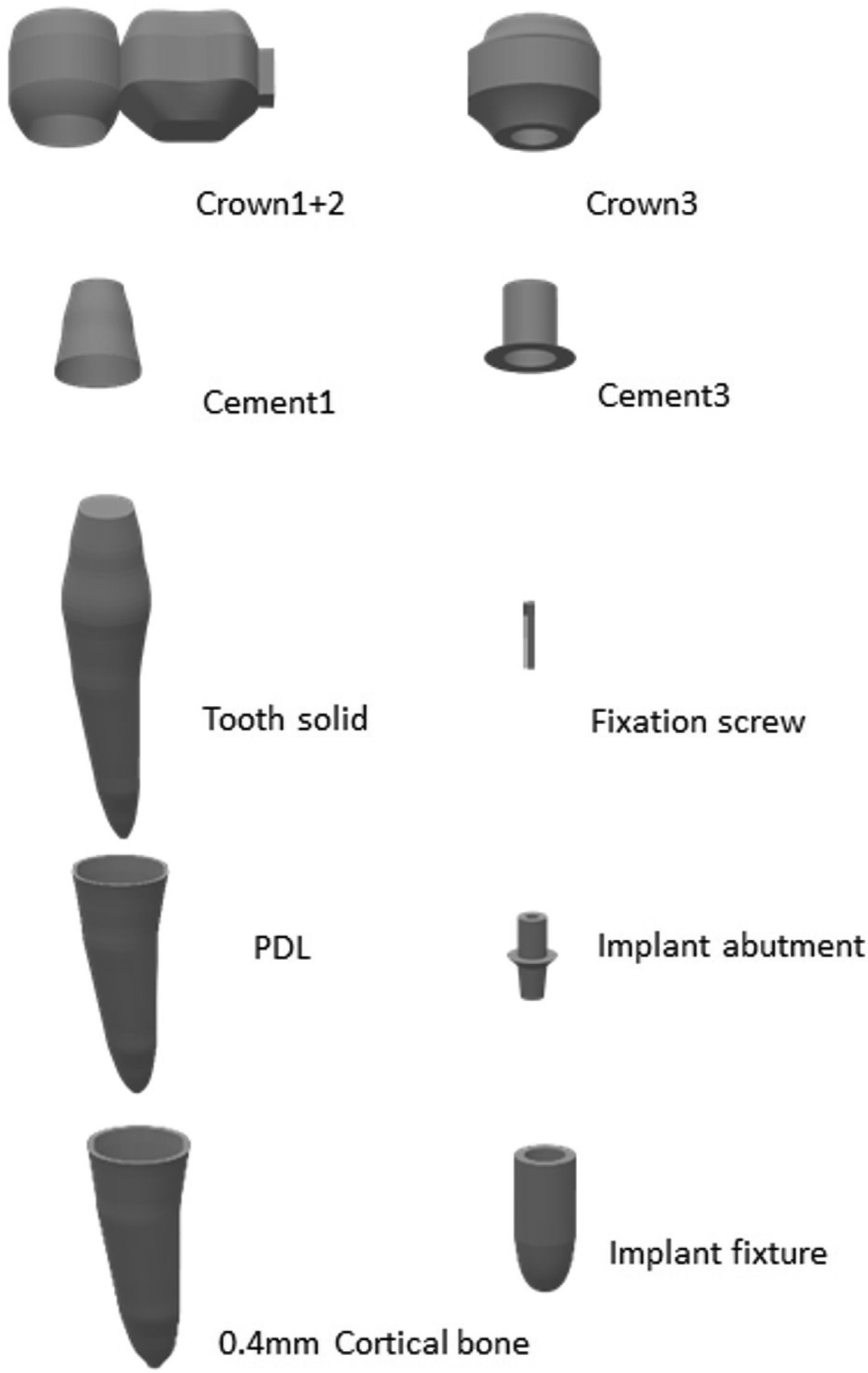

Figure 2 TISP structure model components. PDL: periodontal ligament.

The model in Solidworks Simulation was processed to generate a mesh structure. A blended curvature-based mesh generator was used for meshing, and the entire model was divided into smaller elements. The mesh was composed of 4-node linear tetrahedral solid elements, which were interconnected at specific joints called nodes. The number of elements and nodes of the six models were described in Table 2. On the six occlusal points of the occlusal surface of the bridge, a vertical static occlusal force of 50 N was applied to result in a total of 300 N at right angles (0° to the long axis of the support).[16] The average stress and the maximum equivalent von Mises stress value of each model were recorded in each component.

Table 1 Physical properties of the materials used.

Material	Modulus of elasticity, (MPa)	Poisson's ratio
Tooth solid	18 600	0.31
Periodontal ligament (0.25 mm)	170	0.45
Titanium (fixture, abutment, fixation screw)	117 000	0.35
Ni–Cr alloy	204 000	0.30
Cortical bone	13 700	0.30
Spongy bone	1370	0.30
Cement (Glass ionomer)	16 900	0.30

Table 2 Number of elements and nodes in the study.

	R1	NR1	R2	NR2	R3	NR3
Elements	350 320	402 958	435 043	481 678	363 793	480 040
Nodes	524 627	558 556	609 736	668 549	551 651	666 989

R1: rigid type with one-piece implant system; NR1: non-rigid type with one-piece implant system; R2: rigid type with two-piece implant system; NR2: non-rigid type with two-piece implant system; R3: rigid type with three-piece implant system; NR3: non-rigid type with three-piece implant system.

Table 3 The average stress (MPa) of each component in axial 300 N loading force.

	R1	NR1	R2	NR2	R3	NR3
Tooth solid	8.69	8.21	5.36	3.76	5.10	3.77
PDL	6.79	9.99	9.01	9.10	3.58	9.08
0.4 mm Cortical bone	8.98	11.69	11.52	11.66	6.62	11.63
Cement1	2.46	12.13	5.98	5.15	6.05	5.16
Cement3	11.49	9.02	10.55	9.31	9.99	8.41
Crown1+2	4.74	8.33	6.39	7.45	6.27	7.47
Crown3	11.86	11.26	8.43	8.79	8.73	8.99
Cortical bone	5.06	4.37	3.76	3.73	3.87	3.81
Spongy bone	0.73	1.20	1.42	1.22	1.38	1.24
Implant fixture	23.46	15.60	10.48	10.11	11.74	10.41
Implant abutment	Nil	Nil	20.34	24.15	30.51	25.04
Fixation screw	Nil	Nil	Nil	Nil	14.48	12.47

PDL: periodontal ligament; Cement1: cement layer for crown1; Cement3: cement layer for crown3; Crown1+2: crown1 and pontic on one end of the bridge; Crown3: crown at other end of the dental bridge; R1: rigid type with one-piece implant system; NR1: non-rigid type with one-piece implant system; R2: rigid type with two-piece implant system; NR2: non-rigid type with two-piece implant system; R3: rigid type with three-piece implant system; NR3: non-rigid type with three-piece implant system.

Results

Prosthetic connection element

The average stress results of prosthetics connection element components were described in Table 3 and Fig. 3(a). Among the four components (crown1+2, crown3, cement1 and cement3), the crown3 of R1 had highest average stress among rigid connectors, and the cement1 of NR1 had highest average stress among non-rigid connectors. Furthermore, for the maximum von Mises stresses of prosthetic connection element, R1 (308.90 MPa) and NR1 (505.84 MPa) was appeared in crown3, R2 (315.49 MPa) and R3 (329.90 MPa) were concentrated in cement1, and NR2 (489.84 MPa) and NR3 (493.93 MPa) were located on crown3 (Fig. 4). Most of their stress was concentrated at the joint of crown1+2 and crown3 or the distal region of cement1 near the margin.

Implant system vertical element

In the maximum average stress distribution in the implant element (Table 3), it could be found that R1 and NR1 appeared on the implant fixture, and the other four were on the implant abutment. While the two-piece implant system (R2 and NR2) and the three-piece implant system (R3 and NR3) were concerned, the average stress distribution of the two implant systems was the highest in the implant abutment, and the maximum von Mises stresses were concentrated at the interface between implant fixture and implant abutment (Fig. 4).

Natural tooth vertical element

The average stress results of the vertical element components of natural tooth were described in Table 3 and Fig. 3(b). The average stress of PDL was 6.79 MPa (R1), 9.01 MPa (R2) and 3.58 MPa (R3) in rigid type connector, while it became 9.99 MPa (NR1), 9.10 MPa (NR2) and 9.08 MPa (NR3) in non-rigid type connector. In addition, as listed in Table 4, the maximum von Mises stress on PDL in rigid connectors were R1 (69.63 MPa), R2 (92.56 MPa) and R3 (104.83 MPa), and non-rigid connectors were NR1 (93.31 MPa), NR2 (91.98 MPa) and NR3 (91.78 MPa). Those were concentrated in the apical region.

Supporting medium

Compared with rigid connectors, the use of non-rigid connectors will result in slightly lower average stress in the cortical bone (Table 3). For example, the stresses of R3 and NR3 were 3.87 and 3.81 MPa, respectively. In addition, regardless of the abutment implant system, the maximum von Mises stress generated by the rigid connector was greater than the corresponding non-rigid connector in the cortical bone around implant collar (Table 4 and Fig. 5). It is worth noting that the three-piece abutment implant system (R3 and NR3) had a lower von Miser stress compared with the one-piece (R1 and NR1) and two-piece (R2 and NR2) implant abutment systems in the cortical bone around implant collar.

Discussion

The TISP structure can basically be subdivided into three units composed of two vertical pillars and a horizontal prosthetic connecting body between the two pillars. The

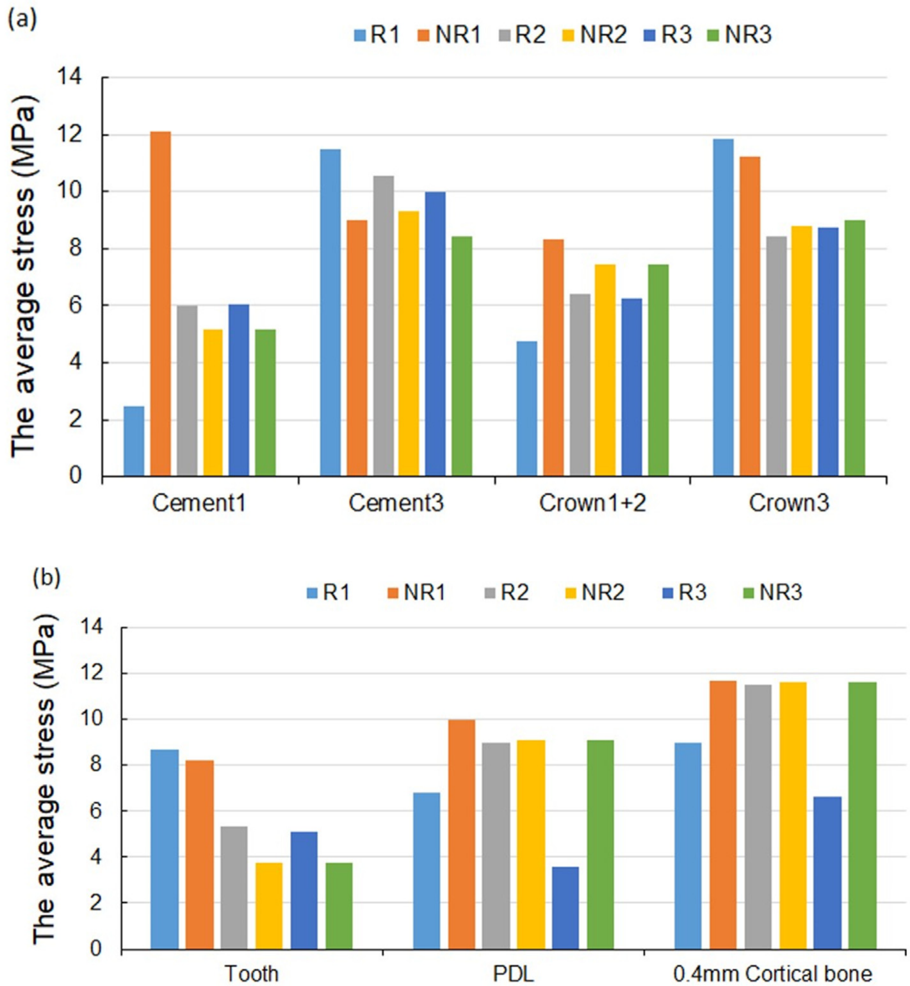

Figure 3 (a) The average stress of prosthetic connection element components; (b) The average stress of natural tooth vertical element components. R1: rigid type with one-piece implant system; NR1: non-rigid type with one-piece implant system; R2: rigid type with two-piece implant system; NR2: non-rigid type with two-piece implant system; R3: rigid type with three-piece implant system; NR3: non-rigid type with three-piece implant system.

connecting body could be simplified as an element of a simple support beam, and the two pillars were respectively composed of natural tooth covered by PDL and osseointegrated implant. The natural tooth has a PDL buffer space, so there will be a 0.1—1 mm macromovement, but the implant without PDL has only a 0.1 mm micromovement.[28] Richter et al.[29] considered that if the TISP connecting body was made of a rigid connector, although the stress could be effectively delivered to the two vertical elements after loading, the greater mobility of the tooth would generate a greater bending moment at the implant. Bechelli suggested that the non-rigid connector could be made in the connecting body to form a stress breaker, which would effectively reduce the bending moment.[11] In addition, Rangert et al.[30] showed that the load was properly distributed between the implant and the tooth through the inherent bending flexibility of the implant screw joint. Weinberg et al.[28] also described that implant abutment system could provide a small amount of flexibility to compensate for the displacement of the natural tooth caused by the gold screw and the abutment screw. Therefore, the non-rigid connector and the degree of bending flexibility formed by the joint between the implant and the abutment screw may be important factors in the stress distribution of the entire system.

In the present study, with the screw locking between fixture and abutment, the two-piece implant system could be regarded as a flexible device. The three-piece implant system used a Morse taper with screw in the abutment connection to form a locking system of two flexible devices. When these six models were statically applied at 300 N, it could be found that in the implant system, the maximum average stress of R1 and NR1 models appeared on the implant fixture, and the other four models appeared on the implant abutment. Moreover, the number of flexible devices was increased, and the average stress and maximum von Mises stresses of the cortical bone were gradually decreased. The results implied that there were more flexible devices in the entire system, which could gradually introduce stress into the relatively strong implant abutment. In addition, it could also act as a stress breaker to reduce the stress of the supporting bone around the

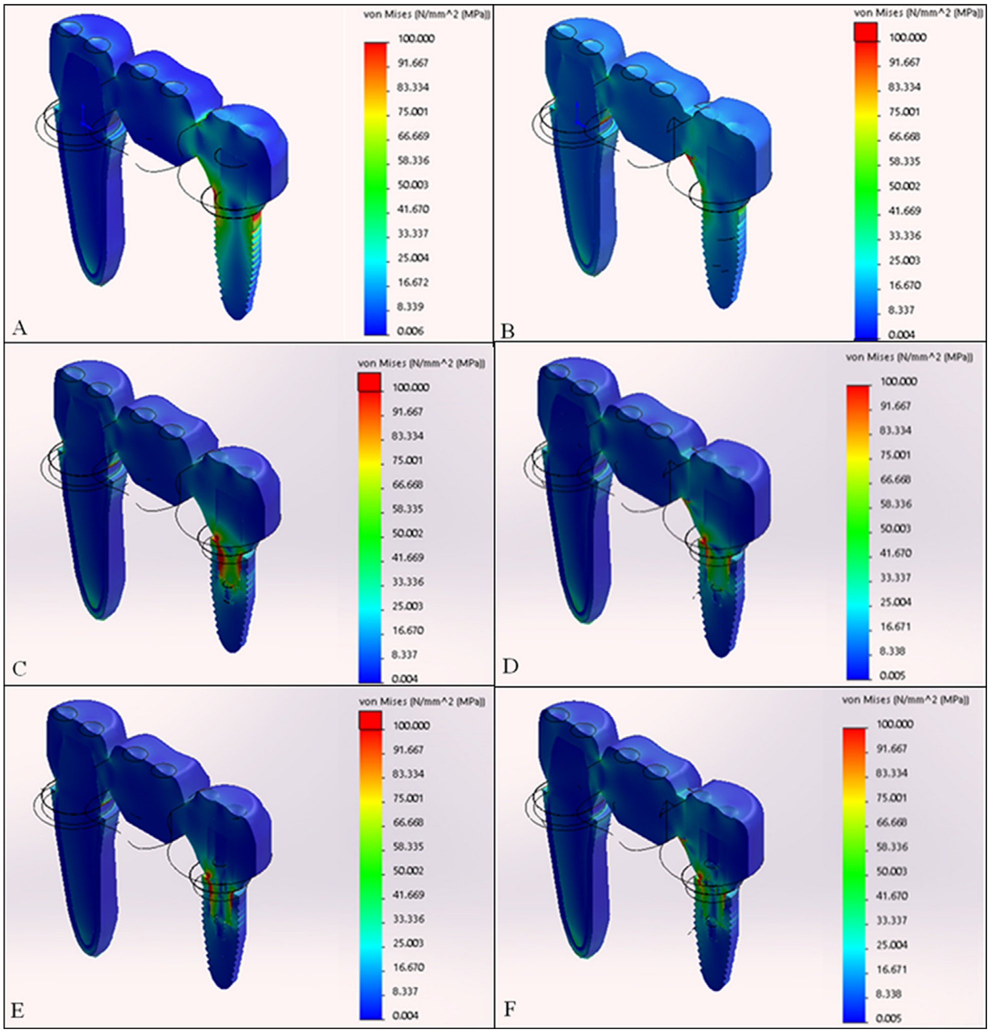

Figure 4 Von Mises stress distribution at TISP structure components. (A) R1: Rigid type with one-piece implant system. (B) NR1: Non-rigid type with one-piece implant system. (C) R2: Rigid type with two-piece implant system. (D) NR2: Non-rigid type with two-piece implant system. (E) R3: Rigid type with three-piece implant system. (F) NR3: Non-rigid type with three-piece implant system.

Table 4 The maximum von Mises stress (MPa) of each component in axial 300 N loading force.

	R1	NR1	R2	NR2	R3	NR3
Tooth solid	105.96	144.59	134.67	142.71	104.83	142.48
PDL	69.63	93.31	92.56	91.98	104.83	91.78
0.4 mm Cortical bone	87.98	116.58	124.55	124.35	118.08	124.11
Cement1	48.15	379.05	315.49	187.35	329.90	188.15
Cement3	83.54	43.86	58.37	53.79	149.37	54.60
Crown1+2	90.75	312.85	243.67	243.20	240.45	244.14
Crown3	308.90	505.84	67.05	489.84	69.58	493.93
Cortical bone	72.84	64.20	63.06	56.17	56.43	41.04
Spongy bone	42.84	48.32	57.94	51.21	43.89	51.16
Implant fixture	159.40	93.50	267.72	488.40	396.45	452.36
Implant abutment	Nil	Nil	237.77	424.11	431.71	299.00
Fixture screw	Nil	Nil	Nil	Nil	80.97	124.23

PDL: periodontal ligament; Cement1: cement layer for crown1; Cement3: cement layer for crown3; Crown1+2: crown1 and pontic on one end of the bridge; Crown3: crown at other end of the dental bridge; R1: rigid type with one-piece implant system; NR1: non-rigid type with one-piece implant system; R2: rigid type with two-piece implant system; NR2: non-rigid type with two-piece implant system; R3: rigid type with three-piece implant system; NR3: non-rigid type with three-piece implant system.

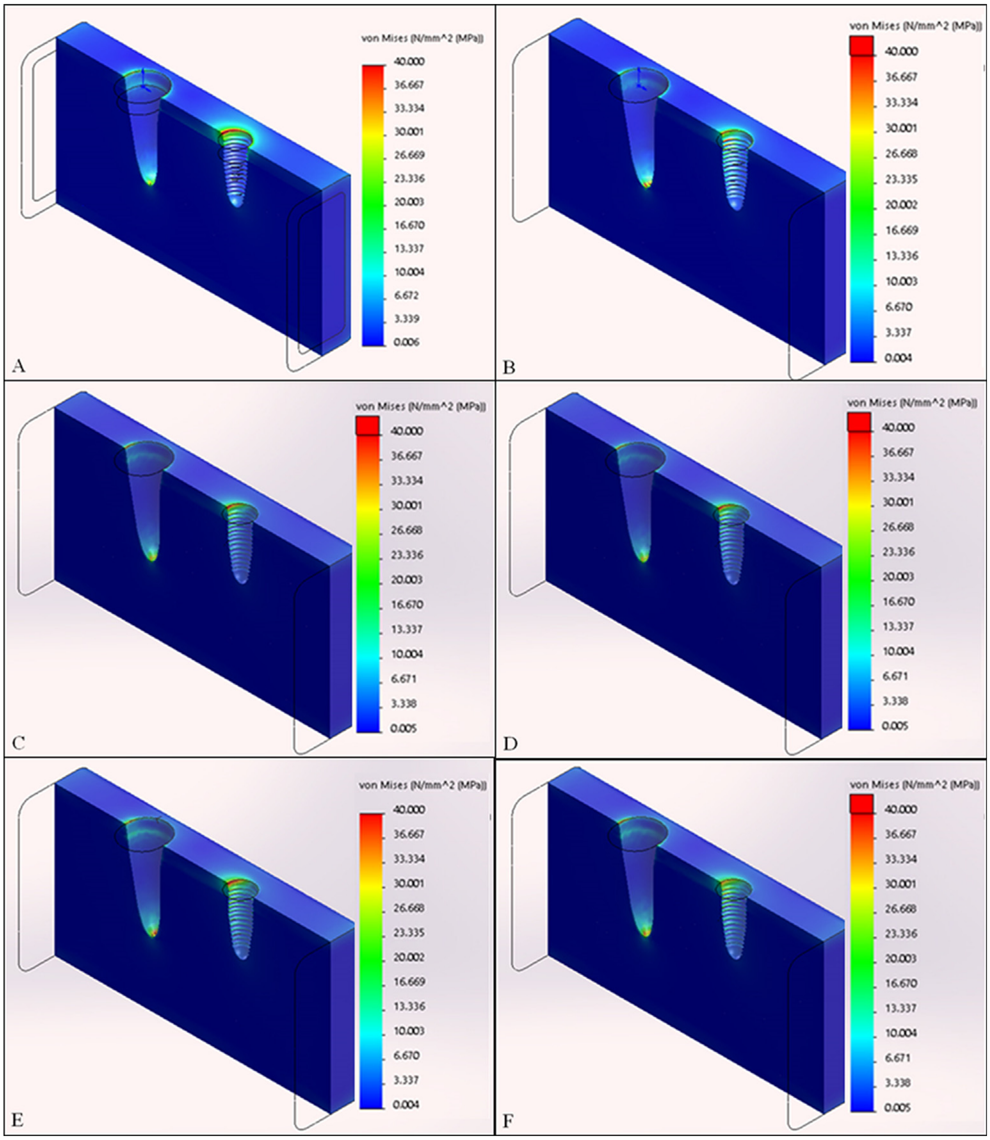

Figure 5 Von Mises stress distribution at support medium. (A) R1: Rigid type with one-piece implant system. (B) NR1: Non-rigid type with one-piece implant system. (C) R2: Rigid type with two-piece implant system. (D) NR2: Non-rigid type with two-piece implant system. (E) R3: Rigid type with three-piece implant system. (F) NR3: Non-rigid type with three-piece implant system.

implant collar and protect the alveolar bone from further marginal bone resorption. The mechanism may be due to the fact that when a natural tooth was stressed, a rotational moment will be generated at the center of rotation at 1/3 of the tooth root, and a reaction moment would also be generated from the bottom of the root. If the tooth is in a static state, all moments and the sum of reaction moments will remain zero. When the force was applied and the torque was greater than the reaction torque, the tooth started to rotate until the torque and the reaction torque reached balance again. Such rotation will generate stress on the supporting bone.[31] Similarly, a one-piece implant system with osseointegration will also have the same bending moment behavior as natural teeth. The difference is that if it is a two-piece implant system, because a pair of fixture and abutment contact pairs are added, there is an extra for the moment and reaction moment.[30] As for the three-piece implant system, there are two more pairs of moment and reaction moment. In addition to increasing the flexibility of the implant system, this contact pair is also a concentration of shear stress, so stress will be gradually introduced into the implant abutment to avoid stress concentration on the supporting bone.

Since the abutment of the two-piece implant system included screw, the entire abutment was locked in the implant fixture. If the stress was distributed in the abutment and exceeded the pre-loading force of the abutment screw, it may cause the abutment to loosen. This phenomenon is often seen in clinical cases.[32] However, the fixture, abutment and fixation screw of the three-piece implant system were independent of each other. In this study, the stress was concentrated between the fixture and the abutment, and the stress on the fixation screw would be smaller. Through this mechanism, the clinical design of the

Morse taper may produce a cold welding effect between the fixture and the abutment,[33] and the fixation screw could not cause the complications of loosening or breaking due to excessive stress.

The average stress and maximum von Mises stress of the PDL in the current study showed that the stress reports of R1, R2 and R3 were different, but in the non-rigid connector, even using different types of abutments will not cause a remarkable difference in the two stresses. Furthermore, regardless of different implant abutment designs, the average stress and maximum von Mises stresses of the cortical bone around implant collar were reduced after using the non-rigid connector, and the stress will also be dispersed to the bottom of dovetail between male and female parts. Other studies have also found that when connecting the implant to the tooth, the stress is mainly concentrated in the cortical bone inside and around the implant.[15,34–36] Nishimura et al.[37] used photoelastic analysis to analyze the stress distribution of rigid and non-rigid connectors. Research have shown that the non-rigid connection is related to lower bone stress around the implant, but to higher stress in the implant and prosthesis. Conversely, the rigid connection is related to more bone stress around the implant. Moreover, Ozçelik et al.[15] and van Rossen et al.[34] also suggested placing a non-rigid connector on the part of the implant abutment to reduce the stress around the implant. Therefore, this study was consistent with previous studies. By adding a non-rigid connector to the TISP, the stress can be distributed to share the occlusal load of the implant and avoid excessive stress concentration on the implant and surrounding bones.

The current study also found that most of prosthesis connecting element stresses were concentrated at the joint of crown1+2 and crown3 or the distal region of cement1 near the margin. This result implied that due to the bending effect, the design of clinical prosthesis must pay attention to the sufficient strength of the connect area and the selection of permanent cement with sufficient strength.

In this study, all static occlusal forces applied vertical loading. However, the occlusal force was dynamic and might be inclined to the occlusal surface of the implant-supported prosthesis. It was usually impossible to replicate all natural details, so the behavior in the mathematical model may affect the research results.[38] In addition, for effective calculation, the material properties of this study were assumed to be homogeneous, isotropic and linear elastic conditions, which did not completely conform to the real clinical conditions. Due to these limitations, the results obtained in this study may not be exactly the same as the actual values, but it could reveal the difference in stress and displacement between groups to provide clinicians with judgements on the design of the prosthesis. Moreover, the results of this study were consistent with the reports of Paula et al.[13] and Lencioni et al.,[14] and could also be used as a reference for optimizing TISP design. Nevertheless, there was still room for improvements in the design of the simulation model and the interpretation of results conducted from the present study. Further long-term clinical studies to examine the correlation between stress analysis and clinical outcome of TISP were needed.

In conclusion, our limited study concluded that by adding a flexible non-rigid connector and a three-piece abutment device design to the TISP, not only the occlusal load of the implant can be shared, but the stress could be gradually introduced into the relatively strong implant abutment. The stress of the cortical bone around the implant collar could also be reduced. Furthermore, when the stress was concentrated between the fixture and the abutment of the three-piece implant system, the stress on the fixation screw will be relatively small. This mechanism makes the abutment have a fixed effect, and the fixation screw will not receive excessive stress.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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