International Journal of Sciences & Applied Research

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A dynamic finite element analysis of stress distribution in the supporting bone of tooth-implant fixed bridge

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ABSTRACT

Objective: To establish a three-dimensional finite element model of tooth-implant fixed bridge and its supporting tissue and to analyze the stress distribution of bone tissues around the abutments under dynamic load.

Methods: Three dimensional finite-element models were created of two 765 sections of the mandible with tooth and implant independently or tooth-implant fixed bridge embedded in. In a circle of mastication (0.875s), vertical and oblique dynamic loads were applied on the model. The stress distribution was analyzed to study the biomechanical behavior of bone tissue surrounding solely or splinted abutments.

Results: As loading on the models, stress concentration appeared in cervical cortical bone of the abutments and the stress of the bone tissue of the implant is higher than that of the natural tooth. When the lingual load (t=0.26s) on the fixed bridge , the maximum Von mises stress is 141.773 Mpa in the distal cervical of the implant as much as 2.2 times of that tooth, which may reduce disadvantages for implant.

Conclusion: It is feasible to design the restoration of the natural tooth-implant combined supporting double-end fixed bridge, however, various measures should be taken in the design to compensate for the biological differences between them.

Keywords: Tooth-implant fixed bridge; implant; stress analysis; three-dimensional finite element

INTRODUTION

With the growing application of implant technology in the oral field, the restoration method of the combined fixed bridge of implant and natural teeth is also commonly used. This restoration method has the advantages of avoiding the poor planting conditions, and the complicated operations such as caring, maxillary sinus lifting, reducing the cost, which is very popular among doctors and patients. Early clinical studies have found that this combined restoration method will cause loss of tissues around implants, and loose or broken prostheses [1], [2], [3], [4], while many clinical retrospective studies [5], [6], [7], [8], [9], [10] have shown that the combined restoration method has an ideal effect. However, due to the differences in physiological mobility and biomechanical properties between natural teeth and implants, there has always been controversy on the bridge restoration with natural teeth and implants as abutments. At present, most of the related theoretical studies are static analysis [14] [15] [16], but in fact, masticatory movement is a dynamic process centered on ICP (intercuspal Application of tooth-implant fixed bridge, this experiment plans to carry out continuous dynamic load on the three-dimensional finite element models, and to analyse the stress distribution of bone tissues around the abutments.

MATERIALS AND METHODS

1 Establishment finite element model

A normal adult male mandible with complete dentition, normal occlusal relationship, clear coronal occlusal surface and no obvious alveolar bone absorption were selected as the modeling objects and ITI Straumann implant (standard model length, diameter, 10mm and 4.0mm, abutment height and neck width, 4.25mm, respectively). The mandible was scanned by spiral CT with scan slice thickness of position) Thus, inorder to provide mechanical reference for clinical 0.5mm and slice interval of 0.2mm to obtain image data. The mandible was modeled by AutoCAD in two-dimensional space, and the data of implants were input into Solid works software to obtain a one-stage implant model with thread shape and abutment shape. By using the "matching relationship" with the dental model, the left mandibular natural-dental implant combined supporting double-end fixed bridge (35 is natural tooth, 37 is implant) and its supporting tissue before and after restoration were formed. Using Ansys software, 10-node tetrahedron element (Solid92) and 20-node hexahedron element were selected to establish the three-dimensional finite element model of the left mandibular natural tooth-implant double-end fixed bridge and its supporting tissue before and after restoration.

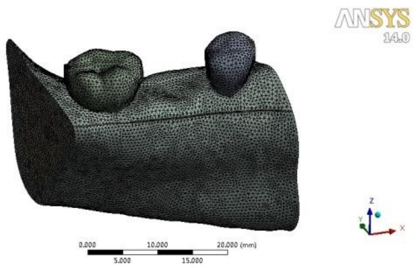

Figure 1. Finite element Model before restoration

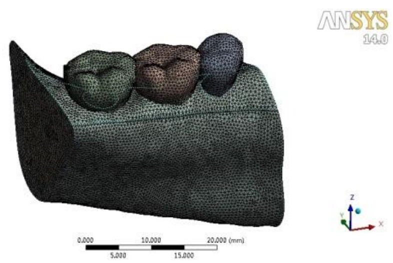

Figure 2. Finite Element Model before restoration

2 Design of experimental conditions

The 3/4 outer surface and lower edge of buccal lingual side of partial mandible was set as rigid constraint, and the model is completely fixed. The X, Y and Z directions were constrained; the upper 1/4 outer surface of mandible and its proximal, distal and medial sides were set as free boundaries, and the X, Y and Z directions were unconstrained.

3 Load situation

1) Working conditions: (1) Before restoration: load 5 and 7(150N/ crown,) (2) After restoration: load 5,6 and 7(150N/ crown,).

2) Dynamic load for a chewing period of 0.857s is divided into five phases, in which the occlusal contact time is 0.17s. The following table 2.2 is for the specific load methods.

Table-1: Load position, direction and time

Phase	Part	Direction	Time (s)
Prophase of occlusion	——	——	0.00-0.13
Vertical occlusion period	Tip of cheek and tongue	Vertical	0.13-0.15
Lingual occlusal phase	Buccal cusp buccal slope	From buccal to lingual and dental long axis 45°	0.15-0.26
Buccal occlusal phase	Buccal cusp lingual slope	From tongue to cheek and tooth long axis 45°	0.26-0.30
Unload phase	——	——	0.30-0.875

4 ANALYSIS METHOD

The equivalent stress (Von Mises stress) was selected as the observation index. The maximum Von Mises stress values of the buccal, lingual, proximal and distal middle sides of the tooth neck, upper 1/3 root, middle 1/3 root, lower 1/3 root and root apex (implant bottom) were read, and descriptive statistical analysis was adopted.

Von Mises stress[46] is equivalent stress, which is a combination of normal stress and shear stress, and is an equivalent stress. As an index to measure stress level in this study, its calculation method is as follows:

$$\sigma_m = \sqrt{\frac{1}{2}\left[\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_2-\sigma_3\right)^2+\left(\sigma_3-\sigma_1\right)^2\right]}$$

When the first principal stress and the second principal stress are the working stress values of dangerous points in the component, the check strength is calculated according to Mohr strength theory[46]. The method is as follows:

$$\sigma_{equ} = \sigma_1 - \frac{[\sigma]^+}{[\sigma]^-}\sigma_3$$

Wherein, σ_1, σ_2, σ_3 are the first principal stress, the second principal stress and the third principal stress respectively. $[\sigma]^+$ and $[\sigma]^-$ are the tensile strength and compressive strength of the material.

RESULTS

At the end of vertical load (t=0.15s),according to the intuitive analysis in Tables 4.1 and 4.2, the maximum stress value of bone tissue before restoration is 25.107 MPa. In the neck region of teeth, the stress value of implant bone tissue (average 17.382 MPa) is higher than that of natural teeth (average 5.934 MPa); after restoration, the maximum stress value of bone tissue is 37.253 MPa. In the cervical region of teeth, the stress value of implant supporting tissue (average 26.820 MPa) is higher than that of natural teeth (mean 9.886 MPa). In the sub-cervical region, the stress values of bone supporting tissues of the two abutments are similar before and after restoration. (Figures 3and 4arefor stress nephogram)

Table-2: Von Mises value of each part under common load of 35 and 37 before restoration (unit: MPa)

Tooth position	35				37			
Part	buccal	lingual	proximal	distal	buccal	lingual	proximal	distal
Tooth neck	7.064	2.023	9.076	5.573	21.108	25.107	2.929	15.397
Upper 1/3 root	2.172	1.443	1.247	1.769	0.996	1.116	0.371	0.768
Middle 1/3 root	1.369	1.429	1.006	0.921	0.446	0.359	0.285	0.467
Lower 1/3 root	1.274	1.085	0.578	0.715	0.575	1.270	1.340	0.267
Root apex	1.902	1.209	1.035	1.630	1.627	1.372	1.479	1.398

Table-3: Von Mises value of each part under common load of 35 and 37 after restoration (unit: MPa)

Tooth position	35				37			
Part	buccal	lingual	proximal	distal	buccal	lingual	proximal	distal
Tooth neck	12.014	3.991	12.408	11.132	23.131	33.850	13.044	37.253
Upper 1/3 root	3.446	2.568	1.829	3.286	1.640	1.642	0.788	2.066
Middle 1/3 root	1.872	1.796	1.428	1.596	1.113	0.547	0.417	1.379
Lower 1/3 root	1.701	1.540	0.803	0.956	1.055	1.743	1.529	0.919
Root apex	2.555	1.602	1.364	2.162	2.356	1.986	1.945	2.221

At the end of lingual load period (t=0.26s), according to descriptive statistical analysis in Tables 3.3 and Table 3.4, the maximum stress value of bone tissue before restoration is 74.418 MPa. In the neck region of teeth, the stress value of implant bone tissue (average 47.027 MPa) is higher than that of natural teeth (average 23.488 MPa). The maximum stress value of the restorationed bone tissue is 141.733 MPa. In the neck region of teeth, the stress value of implant bone tissue (average 96.223 MPa) is higher than that of natural teeth (average 26.230 MPa). In the sub-cervical region, the stress values of bone supporting tissues of the two abutments are similar before and after restoration. (Figures 5 and 6 are for stress nephogram)

Table-4: Von Mises value of each part under common load of 35 and 37 before restoration (unit: MPa)

Tooth position	35				37			
Part	buccal	lingual	proximal	distal	buccal	lingual	proximal	distal
Tooth neck	55.177	14.302	9.455	15.020	74.418	34.007	15.889	61.929
Upper 1/3 root	6.067	5.754	1.852	6.427	2.710	1.280	0.510	2.356
Middle 1/3 root	1.049	1.739	1.161	0.833	0.814	0.511	0.420	0.763
Lower 1/3 root	1.520	1.625	0.698	0.892	0.719	0.477	1.038	0.567
Root apex	3.495	2.187	1.968	3.120	1.771	1.319	1.470	1.470

Table-5: Von Mises value of each part under common load of 35 and 37 after restoration (unit: MPa)

Tooth position	**35**				**37**			
Part	**buccal**	**lingual**	**proximal**	**distal**	**buccal**	**lingual**	**proximal**	**distal**
Tooth neck	63.179	14.939	12.344	14.459	124.091	86.065	32.965	141.773
Upper 1/3 root	7.845	3.045	1.991	6.642	5.792	4.688	2.502	7.770
Middle 1/3 root	1.903	2.176	1.455	1.087	2.450	1.626	2.145	2.093
Lower 1/3 root	2.638	2.526	1.057	1.373	2.275	0.969	3.391	1.003
Root apex	5.444	3.334	2.993	4.860	3.595	2.461	3.229	2.457

At the end of buccal load (t=0.30s), according to descriptive statistical analysis in Tables 4.5 and Table 4.6, the maximum stress value of bone tissue before restoration is 67.602Mpa; in the cervical region of teeth, the stress value of implant supporting tissue (average 44.534 MPa) is higher than that of natural teeth (average 20.339 MPa). The maximum stress value of bone tissue after restoration is 110.057 MPa, which is located in the implant lingual neck cortical bone; in the neck region of teeth, the stress value of implant bone tissue (average 68.114 MPa) is higher than that of natural teeth (average 19.458 MPa). In the sub-cervical region, the stress values of bone supporting tissues of the two abutments are similar before and after restoration.

(Figures 7 and 8 are for stress nephogram)

Table-6: Von Mises value of each part under common load of 35 and 37 before restoration (unit: MPa)

Tooth position	**35**				**37**			
Part	**buccal**	**lingual**	**proximal**	**distal**	**buccal**	**lingual**	**proximal**	**distal**
Tooth neck	31.044	12.334	13.656	24.323	44.331	67.602	12.552	39.593
Upper 1/3 root	3.781	4.269	2.450	2.534	1.472	2.731	0.752	1.421
Middle 1/3 root	1.608	2.617	1.401	1.632	0.677	0.997	0.784	0.458
Lower 1/3 root	2.110	1.804	0.782	1.079	1.412	1.901	1.958	0.748
Root apex	3.862	2.331	2.083	3.408	2.267	2.130	2.245	2.032

Table-7: Von Mises value of each part under common load of 35 and 37 after restoration (unit: MPa)

Tooth position	**35**				**37**			
Part	**buccal**	**lingual**	**proximal**	**distal**	**buccal**	**lingual**	**proximal**	**distal**
Tooth neck	30.768	12.205	13.365	21.491	81.830	110.057	12.817	67.752
Upper 1/3 root	3.995	3.853	1.655	2.984	2.899	5.381	1.483	3.611
Middle 1/3 root	2.263	2.611	1.710	1.859	1.273	2.135	1.832	0.356
Lower 1/3 root	3.150	2.656	1.205	1.495	2.304	3.061	3.520	0.924
Root apex	5.654	3.475	3.121	4.992	3.556	3.374	3.594	3.156

At the end of unload period (t=0.875s), according to descriptive statistical analysis in Tables 3.10 and Table 3.12, the maximum stress value of bone tissue before restoration is 4.652 MPa, which is located in the natural lingual cervical cortical bone. The stress values of the bone supporting tissues in the neck area (the average of natural teeth is 3.001 MPa, and the average of implants is 0.613 MPa) and the lower neck area (the average of natural teeth is 1.248 MPa, and the average of implants is 0.017 MPa) of the two abutments are similar. The maximum stress value of the restorationed bone tissue is 8.894 MPa, which is located in the lingual cortical bone of the implant. The stress values of the bone supporting tissues in the neck area (the average of natural teeth is 3.3.952 MPa, and the average of implants is 5.912 MPa) and the infracervical region (the average of natural teeth is 1.530 MPa, and the average of implants is 0.193 MPa) of the two abutment teeth are similar.
(Figures 9 and 10 are for stress nephogram)

Table-8: Von Mises values (unit: MPa) of each part under joint load of 35 and 37 before restoration

Tooth position	35				37			
Part	**buccal**	**lingual**	**proximal**	**distal**	**buccal**	**lingual**	**proximal**	**distal**
Tooth neck	2.397	4.652	2.916	2.040	0.595	1.032	0.262	0.563
Upper 1/3 root	0.622	2.489	0.519	1.745	0.008	0.036	0.008	0.034
Middle 1/3 root	1.008	0.407	0.522	0.391	0.007	0.010	0.008	0.004
Lower 1/3 root	1.408	0.951	0.628	0.763	0.016	0.019	0.021	0.009
Root apex	2.679	1.764	1.617	2.447	0.023	0.021	0.021	0.020

Table-9: Von Mises values (unit: MPa) of each part under joint load of 35, 36 and 37 after restoration

Tooth position	35				37			
Part	**buccal**	**lingual**	**proximal**	**distal**	**buccal**	**lingual**	**proximal**	**distal**
Tooth neck	5.362	4.550	3.868	2.030	5.699	8.894	3.465	5.591
Upper 1/3 root	0.624	1.763	0.471	1.000	0.283	0.391	0.155	0.362
Middle 1/3 root	1.048	0.743	0.740	0.480	0.055	0.134	0.114	0.081
Lower 1/3 root	1.963	1.452	0.889	1.092	0.135	0.197	0.138	0.096
Root apex	3.866	2.530	2.306	3.507	0.239	0.239	0.223	0.240

DISCUSSION

The combined restoration of natural teeth and implants has been controversial due to their different biological properties. Under stress, the mobility of natural teeth is about 0.5mm, and that of bone-bonded implants is about 10 um [16]. The existence of periodontal ligament makes natural teeth have better buffering and adjusting ability in conduction force [17]. In the finite element mechanics research and analysis, The thread shape of implant is a difficult point in modeling, and the thread shape of implant has a very important influence on the stress of implant [18]. In this experiment, the solid modeling function of the powerful Soliworks software was used to directly describe the continuous asymmetry shape of thread, accurately expressing the thread characteristics of implant. In addition, the dynamic observation can be performed to ensure the

Accurate assembly of the implant and the dental model, truly reflect the morphological difference between the natural tooth and the implant, and ensure the accuracy of subsequent finite element analysis results.

According to the characteristics of occlusal movement and the relationship between the change of occlusal force and time, a chewing cycle of 0.875s[19] is divided into five stages, and the model before and after restoration is loaded with 150[20] force in vertical, buccal and lingual directions respectively. The results show that the stress value of bone tissue of two abutments in buccal (lingual) load period is greater than that in vertical load period, which is consistent with the research results[21]

Whether before or after the restoration, the stress in the neck bone tissue is obviously higher than that in the lower neck region, which is the same as that of Koosha [23] and Lanza [24]. It may lie in that the bone tissue has self-protection reaction[61], and it is also the result of stress shielding due to the high elastic modulus of the neck cortical bone. Some scholars[25] think that because of the different force transmission, implants bear greater dental force than natural teeth. In this experiment, the average stress of bone tissue in the neck of implant is larger than that of natural teeth, with the maximum difference of 70 MPa. However, there is no obvious difference between the two areas, only the root apex of natural teeth and the thread protrusion of implant show relatively high stress area due to structural factors. To reduce the stress difference between implant and natural teeth, implants with more reasonable stress distribution shall be selected clinically, and related factors include implant length[26] and thread shape[27].

The maximum Von Mise value in this experiment is 141.773 MPa, as almost 2.2times as that of nature tooth, butits ccorresponding to the first principal stress and the third principal stress are -19.888 MPa and -163.563 MPa, respectively. According to mohr's strength theory [15], the check strength is 80.730 MPa. All of them are within the limit values of tensile strength and compressive strength of cortical bone studied by Bayraktar [28] (104 MPa and 169 MPa) and Bo Bin[29,30] (61.24-81.11 MPa, 103-150MPa), suggesting that it is feasible to restoration the double-ended fixed bridge supported by natural teeth and implants under the experimental conditions. Jaw is the most active bone remodeling tissue in human bone tissue. Normal functional load-bearing stimulation can maintain metabolic balance and make good bone remodeling. Excessive stress can easily lead to absorption of bone tissue and destruction of implant bone interface[51]. In this experiment, except that the bone supporting stress of natural teeth and implants is equal in the unload period, other loader implants are subjected to relatively large stress. Therefore, in clinical practice, relevant measures such as reducing crown diameter or functional tip should be taken to avoid excessive bite force.

Bone mass is also a factor that affects the bone stress. Some scholars [31] analyzed two kinds of bones with the thickness of 1.6mm in the secondary cortical bone and 0.8mm in the tertiary cortical bone. According to the analysis results, with the decrease of bone mass, the stress of abutment bone tissue increased. In this experiment, the Von Mise value of the implant with the maximum bone stress is 141.773 MPa, which is located in the cortical bone near the middle neck at the end of lingual load. It is 37.253 MPa at the end of vertical load, and is 110.057 MPa at the end of buccal load. Therefore, when positioning the implant, it is necessary to ensure that there should be enough cortical bone tissue around the implant

To sum up, the combined restoration of natural teeth and implants is a feasible restoration method, but various measures should be taken in the design to compensate for the biological differences between them.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

ACKNOWLEDGEMENT

This work was supported by Natural Science Foundation of Guangdong Province (31912).

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