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Three-dimensional finite element analysis on the effects of partial anodontia and its restoration to the stress distribution in temporomandibular joint

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Abstract. *Objectives:* To investigate the effects of teeth apical stress changes caused by teeth missing and its restoration on the temporomandibular joint (TMJ) stresses. *Materials and Methods:* The apical stresses measured from photo-elastic experiments (2Kg centric vertical loading to different kinds of occlusion separately) were applied to the established three-dimension finite elemental model. The stress distribution on condyle, superfacial cartilage and TMJ disc were compared. *Results:* 1. The stress on both of the anterior surface of condyle and its superfacial cartilage and on the intermediate band of disc were mainly compressive, while the stress on both of the posterior surface of condyle and its superfacial cartilage and on the posterior band of disc were mainly tensile. 2. Anterior teeth missing, anterior teeth and bilateral premolars missing and posterior teeth missing all could cause the distinct changes of magnitude and distribution of TMJ stresses. However, the changes could be effectively reversed by the restoration of missing teeth. *Conclusions:* Changes of apical main stress resulted from partial anodontia during centric biting would affect TMJ stress quantitatively, which could probably result in the temporomandibular disorders, so the timely restoration is necessary.

Key Words: temporomandibular joint (TMJ), finite elemental method (FEM), photoelastic analysis, stress

1. Introduction

During the functional movement, TMJ endures definite pressure[1]. The changes of inner stress produced by the external pressure are closely related with TMJ micro-traumas and its regressive changes. With the teeth missing, the values and directions of apical stress of mandibular teeth would also change, which could be transferred along the force track of mandible to its end-point, condyle and further to affect the stress distribution in TMJ. In the present study, the apical stresses measured from photo-elastic experiments before and after the restoration of missing teeth were loaded to the established three-dimension finite elemental model. Then the quantitative changes of bilateral TMJ stresses were investigated.

2. Material and methods

2.1. FEM model

A three dimensional finite element model of mandible, including mandibular dentition, mandible, bilateral condyles, superfacial cartilage and discs of TMJ, was established based on the graphs of serial CT images[2].

2.2. Loading conditions

2.2.1. Photoelastic model and analysis

32 permanent teeth from a fresh body were adopted to replicate several sets of identical plastic teeth (including the crown and the root), in which the mandibular first molar had one distal and one mesial root while the second and third molar only had one fused root. Silicone rubber and dental stone were adopted to

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perfuse the two part of negative model of the crown and the root and then self-curing resin were filled to replicate the teeth[3]. Using the teeth prepared as the above mentioned, five different kind of teeth-missing occlusion types were simulated on the same articulator. A is normal occlusion with complete 8-8 dentition. The anterior overbite and overjet were all no larger than 3mm. Bilateral first molar were neutral occlusion. B was occlusion with anterior teeth missing. C was occlusion with both anterior teeth and bilateral premolars missing. D was occlusion with right mandibular molars missing. E was occlusion with bilateral molars missing. In partial anodontia occlusions, the adjacent teeth to the space had no inclination and the opposite teeth had no elongation. Besides, all the partial anodontia occlusions had two sets of photoelastic model to investigate the apical stress before and after the restoration of missing teeth respectively. On the 35 mm wax occlusal rim the teeth were setting up to different kind of occlusion types with 20mm space keep under the roots to observe the stress distribution. Epoxy resin was adopted as mode material to affuse the epoxy resin mandibular dentition model. The maxillary plaster model occluded tightly with mandibular epoxy resin model on ICP, which were fixed on the mechanical stationary articulator with the occlusal plane paralleling to the horizontal plane and the bottom of the model. The model were loaded with 2.0Kg weight on the top of the upper one and were put in the drying oven especially for stress solidification. Then, the models were all sliced by manual saw with the width of 3-5mm and the projective photoelastic machine was adopted to observe the magnitudes and two-dimensional directions of apical stress[4].

2.2.2. Teeth geometric features

The CT image at the layer of the mandibular ridge was selected for contour graphing. First, a curve (C) that passing through the center of each of the mandibular teeth was outlined, and on the curve the central points of each of the teeth were selected for drawing lines, for example the line of L1 in figure 1, parallel to tangent of buccal surface of the first premolar passing through the height of tooth contour. Then the vertical line of L1 and the line parallel to the coronal plane, named L2 and L3 respectively, were drawn, and the clamp angle of L2 and L3, named γ, was measured by an electronic meter (Xi'an Jiao Tong University Publishing)(Fig.1).

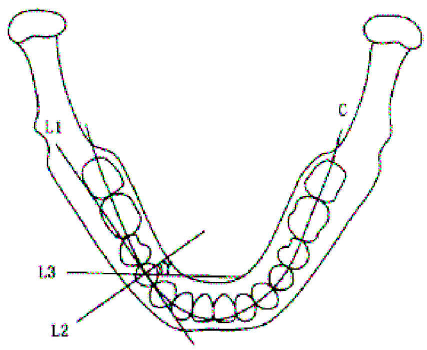
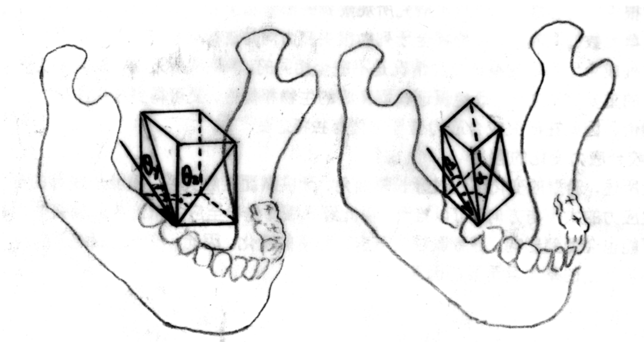


Figure 1 The sketch map of the rotating angle (γ) of the long axis of the right mandibular premolar to the coronal line. C: the curve that passing through the center of each of the mandibular teeth. L1: the line parallel to tangent of buccal surface of the first premolar passing through the height of tooth contour. L2: the vertical line of L1. L3: the line parallel to the coronal plane. γ : the clamp angle of L2 and L3.

2.2.3. Coordinating frame conversion

Based on the apical main stresses from photoelastic analysis, the formulae $\cos\theta z = -\cos\alpha \cdot \cos\beta$, $\cos\theta y = \sin(\alpha - \gamma) \cdot \sin\beta$ were used to calculate the value of the angle θy and angle θz between apical main stress direction and Y axis and Z axis respectively, in which Y axis and Z axis indicates anterior-posterior direction and vertical direction (upper was defined positive), and angle α and angle β indicates apical main stress direction medial-distally and buccal-lingually, respectively(Fig.2). Since only the stress related to intercuspal occlusion was considered in present study, the centric displacement was restricted and the force in x direction, lateral-medial direction, was neglected when loaded. When the load was converted from local plotting system to the three-dimensional plotting system, the force were loaded to the corresponding point according to $Fy = F\cos\theta y$ and $Fz = F\cos\theta z$. The conversed values of different load cases were listed in Tab.1.



a b

Figure 2 The sketch map of local coordinating frame in photoelastic analysis (a) and the three-dimensional coordinating frame in FEM (b).

Table 1 Two-dimensional vectors loaded on each tooth position under the eleven different load cases（N）

		1	2	3	4	5	6	7	8
Occlu. A	Fy	0	-0.04	-0.14	-0.14	-0.11	-0.65	-0.32	0.05
	Fz	-2.26	-2.51	-4.99	-4.04	-6.74	-9.99	-7.71	-7.46
Occlu. B_1 (before restoration)	Fy				-0.17	-0.06	-0.42	0.12	0.04
	Fz				-7.76	-8.36	-10.87	-9.35	-8.93
Occlu. B_2 (after restoration)	Fy	-0.10	-0.15	-0.31	-0.13	-0.11	-0.70	-0.26	-0.05
	Fz	-2.01	-2.35	-3.54	-5.11	-6.98	-9.99	-8.47	-8.05
Occlu. C_1 (before restoration)	Fy						-0.08	0.06	0.13
	Fz						-11.99	-9.91	-9.91
Occlu. C_2 (after restoration)	Fy	-0.11	-0.26	-0.43	-0.33	-0.45	-0.53	-0.24	0
	Fz	-2.16	-2.71	-3.34	-4.58	-5.34	-10.47	-8.87	-8.64
Occlu. D_1 (opposite side) (before restoration)	Fy	0	-0.07	-0.19	-0.23	-0.16	-0.97	-0.54	-0.11
	Fz	-2.12	-2.74	-6.47	-7.74	-8.49	-10.97	-7.84	-8.67
Occlu. D_2 (teeth-missing side) (before restoration)	Fy	0	-0.12	-0.16	-0.35	--0.17			
	Fz	-2.47	-3.04	-5.07	-8.56	-9.31			
Occlu. D_3 (opposite side) (after restoration)	Fy	0	-0.08	-0.21	-0.24	-0.18	-0.64	-0.27	0.01
	Fz	-2.14	-2.43	-5.36	-3.84	-7.68	-10.04	-7.58	-8.19
Occlu. D_4 (teeth-missing side) (after restoration)	Fy	0	-0.03	-0.12	-0.13	-0.17	-0.51	-0.27	0.04
	Fz	-2.21	-2.45	-4.87	-4.92	-8.64	-7.58	-6.21	-7.15
Occlu. E_1 (before restoration)	Fy	-0.07	-0.14	-0.21	-0.27	-0.18			
	Fz	-3.49	-4.15	-6.58	-9.10	-10.46			
Occlu. E_2 (after restoration)	Fy	0	-0.05	-0.14	-0.17	-0.15	-0.61	-0.31	-0.09
	Fz	-2.24	-3.14	-5.07	-4.56	-8.14	-8.01	-6.24	-7.45

Note：Fy indicates the occlusal vector along the Y direction; Fz indicates the occlusal vector along the Z direction. 1: central incosor 2: lateral incisor 3: canine 4: first premolar 5: second premolar 6: frist molar 7: second molar 8: third molar.

2.2.4. Boundary conditions

The superior surface and inferior surface of disc and the areas of bilateral mandibular angles were restricted. Here, we supposed the masticatory muscles would automatically regulate the direction and magnitude of the force provided according to the need of systematic balance and the features of occlusal force, so the muscle force was neglected in the study to pay extra attention to the effects of occlusion to the TMJ.

2.3. Data collection and analysis

2.3.1. Observation points

The surface of condyle was divided into nine parts. The stress characteristics of each of the nine parts of the flowing three structures, inferior surface of disc, condylar cartilage and condyle of bilateral TMJ were measured. Symmetrical apical main stress was applied to the symmetrical occlusions and the stress on the right TMJ was taken for comparison. In asymmetrical occlusion, the main apical stress differed bilaterally, so that the bilateral TMJ stresses were analyzed separately. Altogether, there were 11 TMJs including normal occlusion and different partial anodontia occlusions before and after the prosthetic restoration were investigated.

2.3.2. Indexes for analyzing

Super-SAP finite element software was used for stress analysis. The maximal main stress, minimal main stress and Von Mises stress were used for comparison. The Von Mises stress (σ) represented the integrated condition of joint stress, which was the root square calculated according to the following formula:

$$\sigma = \sqrt{[(\sigma 1-\sigma 2)^2 + (\sigma 2-\sigma 3)^2 + (\sigma 1-\sigma 3)^2]/2}\,,$$

here σ2 represented the middle stress. The combination analysis of maximal and minimal main stresses were to determine the stress character each point endured. The idiographic method was as following. The area with negative maximal and minimal main stress was defined as the area enduring compression. That with lower positive maximal main stress and higher negative minimal main stress was the area mainly enduring compression. That with higher positive maximal main stress and lower negative minimal main stress was the area mainly enduring tension. That with positive maximal and minimal main stress was defined as the area enduring tension.

2.3.3. Statistical analysis

TMJ stresses in different occlusal types were compared with that in the normal occlusion with paired *t* test at the significance level of 0.05.

3. Results

As to the stress character in TMJ, all the occlusion types showed the same. The stress of the anterior surface was higher than that of posterior surface in condyle, which endured both compressive and tensive stress at the same time when biting at intercuspal position, no matter what kind of occlusion type it was. The anterior condylar surface endured compression and the posterior condylar surface endured tension, while the medial part of the condyle endured compression and the lateral part of the condyle endured tension all the time. Top ridge of the condyle endured the stress that between the two characteristics of compression and tension. Correspondingly the intermediate zone of the disc enduring compression and the posterior band enduring tension, while the stress on the anterior band was between the two characteristics of intermediate zone and posterior band. The stress in superior surface of disc was much lower and more uniform than that of inferior surface. The highest stress was at anterior slope of condyle and the corresponding lateral part of cartilage and intermediate zone of the disc. The Mises stress of the anterior part of cartilage, which endured pressure all the time was higher than that of posterior part, which endured tensive stress all the time. The values of Von Mises stress in different part of TMJ under different occlusal types were calssified by the compressive or tensive character and recorded in table 2. The von Misses stress was used for comparison between the groups.

In normal occlusion, the highest compressive area was at the anterior-medial part of the condylar cartilage in TMJ. As to the condyle, the stress in medial part was higher than that of middle and lateral parts. While the highest stress area of the disc was the middle-lateral part of it. Comparing the Von Mises stresses in different structures of TMJ, we observed that the compressive stress in the anterior condylar surface was much higher than that of corresponding part of disc ($P<0.01$). Then tensive stresses in the middle part of posterior condylar surface and posterior band of disc were both higher than that of medial and lateral parts of them, among which the highest tensive stress area was in the middle part of posterior condylar surface. The tensive stresses between the condyle and the disc showed no significance($P>0.05$).

In anterior teeth missing occlusion, there were no distinct changes in the distribution character of TMJ stress. The compressive and tensive stresses in each interesting area were relatively lower, but showed no significance with that of normal occlusion ($P>0.05$). In anterior teeth and premolars missing occlusion, there were still no distinct variations in stress distribution character but the stress values were much lower than that of normal ($P<0.01$). After the prosthetic restoration, TMJ stress came back to the normal level and had no difference with that of normal occlusion ($P>0.05$).

When the unilateral posterior teeth were missing, the stress in posterior and medial part of condyle, inferior surface of disc and posterior and lateral part of disc in opposite side increased. While in teeth-missing side, the stress in posterior and medial part of condyle, middle and medial part of middle band of disc and the condylar cartilage showed significantly higher than that of normal occlusion ($P<0.01$). As to the force character that different structure endured, in the side opposite to missing teeth, middle part of anterior condylar surface, middle-medial inferior surface of disc middle band and the condylar cartilage endured relatively higher compressive stress. And the posterior condylar surface and middle-lateral part of posterior band of the disc endured relatively higher tensive stress. In teeth-missing side, the medial superior surface of disc middle band and the lateral part of all the three bands of the disc endured higher compressive stress than that of opposite side. While the medial part of disc posterior band endured relatively higher tensive stress.

Table 2 Mises stress comparison according to different character of the force endured MPa

		Condyles			Discs			Condylar
		medial	middle	lateral	medial	middle	lateral	cartilage
Compressive area	Occlu. A	2.68	1.42	0.86	0.41	0.56	0.84	1.73
	Occlu. B_1	2.15	0.97	0.78	0.32	0.54	0.62	1.57
	Occlu. B_2	2.71	1.36	0.83	0.39	0.54	0.85	1.71
	Occlu. C_1	1.02	0.66	0.34	0.18	0.21	0.37	0.44
	Occlu. C_2	2.54	1.32	0.77	0.39	0.52	0.71	1.64
	Occlu. D_1	1.85	2.96	1.07	0.98	0.57	0.47	2.51
	Occlu. D_2	3.79	2.87	1.78	0.45	0.61	0.71	3.62
	Occlu. D_3	2.71	1.51	0.93	0.42	0.63	0.79	1.74
	Occlu. D_4	2.96	1.67	1.02	0.47	0.71	0.97	1.98
	Occlu. E_1	4.27	2.44	1.76	0.64	1.25	2.10	3.62
	Occlu. E_2	3.02	1.77	0.96	0.42	0.59	0.94	1.87
Tensive area	Occlu. A	0.36	0.52	0.32	0.36	0.41	0.27	0.27
	Occlu. B_1	0.38	0.46	0.31	0.31	0.36	0.16	0.22
	Occlu. B_2	0.41	0.47	0.32	0.39	0.48	0.24	0.19
	Occlu. C_1	0.11	0.27	0.09	0.12	0.21	0.13	0.04
	Occlu. C_2	0.37	0.49	0.27	0.33	0.39	0.29	0.28
	Occlu. D_1	0.42	0.63	0.37	0.31	0.45	0.72	0.33
	Occlu. D_2	0.56	0.89	0.41	0.64	0.27	0.38	0.47
	Occlu. D_3	0.28	0.57	0.39	0.41	0.52	0.36	0.29
	Occlu. D_4	0.41	0.57	0.41	0.43	0.58	0.41	0.31
	Occlu. E_1	0.84	1.21	0.53	0.85	1.07	0.61	0.57
	Occlu. E_2	0.41	0.53	0.27	0.45	0.48	0.31	0.34

In bilateral posterior molars missing occlusion, there were no obvious changes in the distribution of TMJ stress. But the magnitude of stress value increased significantly compared with that of normal occlusion ($P<0.01$).

4. Discussion

It was shown in the present results that TMJ endured compression anteriorly and tension posteriorly when simulating the condition of biting at intercuspal position. The highest stress was applied at the anterior surface of condyle and intermediate zone of disc, well adapting to the histological features here. The most important function movement from which TMJ endured the load is biting. During that movement, the opening width is relatively small and the anterior condylar surface is the most important functional part. The anatomical study has manifested that the bone trabecula of the condyle is perpendicular to the anterior condylar surface, which determines the mechanical character of anterior condylar surface to endure higher compression[5]. As to the posterior condylar surface, it contacts with articular surface of temporal bone when wide opening movement, during which it performs part of function and thus only endures relatively lower and tensive stress. There are large amount of closely arranged collagen fibers in the middle band of disc, which results in the better mechanical feature of it. From the stress distribution of disc, it can be seen that the average stress value of inferior surface of disc was higher than that of superior surface, while the distribution of the stress in superior surface was much more uniform than that of inferior surface. The results suggest that the disc plays an important role in the cushion of intra-articular stress during its conduction. During intercuspal occlusion, the condylar cartilage between the condyle and the disc endured the highest pressure and the functional remodeling in that area is also the most active in TMJ. In this study, the mechanical character varied the most in compressive stress with different occlusal types. The possible reason maybe that it was TMJ stress character during intercuspal occlusion that we mainly investigated. During that time, the TMJ was more sensitive to the changes of compression.

In the process of biting, the character and capacity of occlusal contact play an important role in stabilizing the stress environment of TMJ. The condyle, cartilage and articular fossa are the same as other hard tissues of human in that the bone structure keeps adaptive to its mechanical character. Wolff Law proved that bone formed at where it is needed and absorbed at where it is needless[6]. The changes of the bone are closely related with the force it endured. The missing of mandibular anterior teeth especially the missing of most anterior teeth could affect the appearance, pronunciation of the patient, as well as the intra-articular pressure. The results showed that the stress in the condyle, disc and cartilage decreased when the anterior teeth and premolars were missing, while increased when the bilateral molars were missing. The stress variation TMJ endured could inevitably result in the reconstruction of each hard and soft tissue to keep the proper physiological form and inner relationship and further to be adaptive to the outside force variation. If the reconstruction goes beyond the physiologically adaptive ability, pathological changes would occur in the corresponding stress-enduring parts of TMJ. When the unilateral posterior teeth missing, the opposite condyle would endure forward torque force while the homolateral condyle would endure forward and inflexed torque force, which could result in the torque force in the disc. Thus, medial part of opposite disc and the lateral part of homolateral disc would endure higher stress. Besides, the opposite disc is inclined to dislocate rotationally with the disc moving anteriorly and medially while the homolateral disc is easier to move anteriorly and laterally.

All the results hint us that temporomandibualr disorders occurred in some of partial anodontia patients probably relate with the teeth missing. Prosthetic restaration could distinctly improve the variation of intra-articular pressure caused by partial anodontia. Therefore, no matter for anterior or posterior teeth missing, the timely restorations are all absolutely necessary.

The finite elemental method (FEM) is widely used in the mechanical studies in stomatology. As the most complicated and fine joint, temporomandibular joint is functional agile and load-bearing. For the research of TMJ stress, FEM has absolute superiority that other mechanical methods do not possess. Till now, FEM is already one of the most important methods for research in TMJ stress. There are already many reports on the modeling and stress analysis of TMJ[7-9]. But in the analysis process, many researchers find it hard but very necessary to simulate the actual occlusal magnitudes and directions as the load conditions. Therefore, there have been very few reports that took FEM as a tool for study the relationship between different occlusion and TMJ loads. In our study, we obtain the real two-dimensional force vectors in apical area of remaining teeth and in the alveolar bone under artificial teeth by photoelastic analysis and further to load them on the FEM model to calculate the TMJ stress, which perfectly simulates the actual mechanical environment around TMJ during intercuspal occlusion. Therefore, the FEM analysis in our research has better biological and mechanical comparability.

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