3-D digital modeling and bio-mechanics research of the anterior disk displacement without reduction temporomandibular joint system

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Abstract

Background Anterior and/or medial displacement of the articular disc or intra-articular disorders (ID) is the most common form of TMJ dysfunction. In the present study, 3D finite elements analysis (FEA) models including the maxilla, disc and mandible were established using 3D data registration technology.

Materials and Methods Six healthy volunteers and 20 TMD patients were selected. CT and MRI data were collected to build 3D FEA model of mandibular and TMJ disc.

Result: Results showed that maximum stress of the normal lateral articular disc in the normal and pathological models appeared in the lateral part of the middle band. In the normal model, stress distribution was more uniform and the joint disc and the condyle were also subjected to higher load at the junction of the articular disc and the condyle.

Conclusion: When the friction coefficient of the side with anterior displacement increased, stress on the disc, condyle and mandible of the opposite side increased. Simultaneously, stress values of the disc, condyle and mandible were higher than those of the normal lateral joint.

Background

The temporomandibular joint (TMJ) is a bilateral diarthrodial joint of the jaws in the human skeleton. This unique joint is the only synovial joint in humans wherein the articulating surfaces are covered by fibrocartilage. TMJ disorder (TMD) is a common condition with an estimated incidence of 20%–25% [1, 2]. Anterior and/or medial displacement of the articular disc or intra-articular disorders (ID) is the most common form of TMJ dysfunction. Although exact causes of TMD are complicated and remain inconclusive, ID, microtrauma and intra-articular stress are considered some of the major causes of TMD.

Research on biomechanics of TMJ is limited by the complicated structure of the joint. Traditional biomechanics can cause trauma and has several disadvantages such as nonrepeatability and being difficult to compare different force distribution.

The finite element analysis (FEA) software (Ansys11.0, Ansys Corp., USA) helps overcome the limitations of the TMJ structure and has several advantages in terms of feasibility, safety and repeatability. Nonlinear materials and dynamic simulation have been used in remodelling, which consistently improve the precision and speed of calculation. The model consists of multiple bones, fragments and cartilage, and the stimulation process is more meticulous and life-like.

Changes in the TMJ disc play an important role in development of TMD [3]. Owing to difficulties of imaging, studies regarding FEA of the TMJ disc are still scarce. A previous study [4] merely built the bone structure of normal TMJs, which ignored the influence of the disc and other soft tissues in cases with
abnormal intra-articular structure. In addition, models of normal TMJ do not take pathological state into consideration, and thus, hold no clinical value.

In the present study, CT and MRI images of both healthy volunteers and TMD patients were collected. Subsequently, three-dimensional (3D) FEA models including the maxilla, disc and mandible were established using 3D data registration technology. This protocol provided data for FEA as well as 3D view of changes in every patient’s TMJ anatomy. Moreover, this protocol could not only help explore the influence of disc displacement but also aid in diagnosis and treatment of TMDs. Furthermore, it can be used to elaborate disc replacement, to directly instruct therapeutic schedule and to evaluate curative effects of various methods.

Methods

• Patients

Healthy volunteers (2 males and 4 females, aged 18–56 years old) and TMD patients (7 males and 13 females, aged 17–60 years old) were selected. Volunteers who had undergone primary procedures for TMJ, those with rheumatism and those with TMDs were excluded. Patients diagnosed with TMD by two magnetic resonance imaging (MRI) specialists and who had experienced pain with coexisting clicking for >1 year as well as limitation of mouth opening were included in the study population. (Fig.1)

• CT and MRI and data collection

CT scans were performed for all patients by using 320-channel multidetector scanners (Brilliance, Philips, Netherlands). CT settings were axial 0.625 mm collimation, 120 kVp, auto exposure and table speed of 60 or 32 mm/s.

MRI images were acquired using a 1.5-T scanner (Symphony, Siemens, Olangan, Germany) with a 7.5-cm surface coil. A 3-mm section thickness with a 140-mm field of view and spin-echo multi-section images were used. For T1-weighted images, repetition time and echo time were 510–520 and 11–15 ms, respectively, and for T2-weighted images, repetition time and echo time were 2410–2740 and 40–107 ms, respectively. MRI images were independently evaluated by two experienced oral and maxillofacial radiologists at two different time points. In case of disagreement, final assessment was reached by consensus.

3. Reconstruction of TMJ 3D model

3.1 3D reconstruction of bone structure, total dentition and articular disc

DICOM data of CT or MRI images were imported into Mimics 3D reconstruction software (Materialise Inc., Belgium). The proposed reconstruction portion of bone structure was selected using the software’s own threshold setting (Threshold380–3071) command. (Fig.2) The shape of disc was manually extracted layer by layer for 3D reconstruction. Image segmentation of selected structures was performed using the
‘region growth’ function. (Fig.3) Subsequently, ‘add’ or ‘erase’ functions were manually used for the image boundary through the editing function to ensure accurate reconstruction of each portion. (Fig.4)

3.2 Revision and optimisation of 3D model

Reconstructed models were imported as STL files into a reverse engineering software (Geomagic Studio 9.0, Rain-Drop CORP USA) to optimise and smoothen the shape of bones and the disc.

3.3 Fusion and registration of digital model of articular disc and TMJ

The model of TMJ based on CT data was used to establish reference coordinates. The partial jaw bone established using MRI data was matched using the automatic object finding function of Geomagic. Subsequently, precise reduction of the articular disc was performed based on the direction of movement of the partial jaw bone. (Fig.6)

4. Construction of FEM of TMJ

4.1 TMJ FEM Construction

A surface mesh model was imported into the FEA software in the initial graphics exchange specification (IGES) format. The volume model was constructed using the bottom-up ‘dot-line-plane-body’ approach. (Fig.7) Isotropic, homogeneous and continuous linear elastic materials, which accorded with small deformation conditions, were used. Material constants of each material used in the experiment were extracted from previous studies [5–7] (Table 1).

4.2. Setting model boundary constraints and load conditions

All degrees of freedom of the temporal bone and the upper surface of maxilla were restricted. The muscle force vector of median occlusal was used as the load. Four muscle force vectors were taken into account for each side, including temporal muscle (anterior and posterior), masseter (superficial and deep), medial pterygoid and lateral pterygoid. The maximum masticatory muscle strength of each muscle was calculated by using Koolstra’s formula Li, max = P. A I, where P is an intrinsic strength constant with a value of 0.37106 N/m².

4.3. Adding contact elements in TMJ

Contact was a nonlinear issue, and we could simulate the contact state of the articular disc and condyle, the contact state of the temporal bone (such as separation and compression) and sliding and friction of the articular disc relative to the articular surface in the functional state. Effects of a lower friction coefficient of a joint on stress distribution in TMJ remain unclear [8]. According to Tanaka et al. [9,10] the friction coefficient of normal TMJ is 0.001. When a disc is displaced, the quality and quantity of synovial fluid changes, which leads to an increase in the friction coefficient. Taking these changes into account,
the friction coefficient of the side with anterior displacement of the joint disc was set to 0.001, 0.3, and 0.4, respectively.

**Results**

1. 3D morphological visual model of TMJ with or without TMD (Fig. 8 Fig. 9)

2. 3D FEM of TMJ

A 3D finite element model (FEM) of the normal TMJ system was established with 3891 nodes, 184412 solid elements, 120 cable elements (Link10), 1897 contact elements and 1176 target units. On the other hand, a 3D FEM of anterior disc displacement of unilateral TMJ was established with 49763 nodes, 237167 solid units, 120 cable elements (Link10), 2082 contact units (Conta174) and 1812 target units (target 170). (Fig. 10 Fig. 11)

3. Stress distribution contrast

Results showed that maximum stress of the normal lateral articular disc in the normal and pathological models appeared in the lateral part of the middle band. In the normal model, stress distribution was more uniform and the joint disc and the condyle were also subjected to higher load at the junction of the articular disc and the condyle. (Fig. 12) On the other hand, in the pathological model, stress concentration was observed during anterior displacement of the articular disc. (Fig. 13 Fig. 14 Fig. 15)

4. Peak value of stress on surfaces of articular disc and condyle

When the friction coefficient of the side with anterior displacement increased, stress on the disc, condyle and mandible of the opposite side increased. Simultaneously, stress values of the disc, condyle and mandible were higher than those of the normal lateral joint. (Table. 2)

**Discussion**

Construction of a 3D digital virtual model mostly depends on microscopic slice images of a cadaveric specimen, and hence, research in this field is limited to a few large research institutions with low-temperature and ultra-thin milling equipment; this hinders development and application of digital medicine into clinical practice. In addition, use of ultra-thin sections of corpse modelling has the following disadvantages: first, anatomical specimens can only be sliced in a single direction, while imaging equipment can collect information in multiple directions. Second, information from cadaveric specimens collected by anatomical sections is different from that of living organisms.

Cornelia Kober et al. [11,12] reconstructed the articular fossa and condyle by using MRI data and realised the visualisation of TMJ system by combining original 2D images of the articular disc with MRI images. CT and MRI have their own advantages in imaging; certain scholars have established a complete TMJ
system by modelling these two types of scanning data separately and by using fusion registration to form a complete TMJ system [13–16].

In this study, TMJ was scanned using high-resolution CT and MRI in vivo. Advantages of CT and MRI were used to establish the joint fossa, maxilla and mandible, which included the articular fossa, maxilla and mandible. A 3D digital model of the entire dentition and the articular disc was created. All masticatory muscles, ligaments and adhesions in TMJ were simulated.

The disc is located between the condyle and the temporal bone. It functions as a cushion for stress in the joint. Diseases of TMJ affect stress distribution and interactions between structures in the TMJ to a certain extent, which has a negative impact on the structure and function of the joint. In this study, stress of the normal disc was concentrated in the lateral part of the middle band, and stress distribution was more uniform. However, when anterior displacement of the joint disc occurred, stress concentration was noted in the middle band of the joint disc. Such high stresses tend to lead to thinning or perforation of the joint disc. Tanaka et al. also reported that anterior displacement of the disc resulted in increase of compressive and shear stresses of the articular disc during median occlusion, which could easily cause disc thinning and perforation[17] Moreover, Pérez-Palomar et al. [5] conducted a finite element study of the TMJ system with anterior disc displacement and found that the pressure and shear force in the posterior disc zone after anterior disc displacement of TMJ were higher than those observed in normal TMJs.

The articular capsule is lined by the synovium, and the sub-intimal layer is rich in blood vessels. The joint fluid is secreted from the synovium into the articular cavity and contains numerous immune cells, proteins, mucin, and so on. It primarily provides a liquid environment for the articular surface and functions as a lubricating agent. By changing the friction coefficient of the disc of the affected side, we observed peak stress changes of the disc, condyle and mandible and found that when the friction coefficient of the disc of the displaced side increased, the disc of the corresponding side could be observed. Stress in the condyle and mandible was also increased. Simultaneously, stress values of the disc, condyle and mandible were higher than those of normal joints. Mongini et al.[18] believed that anterior disc displacement may result in flattening of the anterior oblique plane of the condyle, which is consistent with our findings that increase of the friction coefficient after anterior displacement of the articular disc leads to increase in stress on the anterior oblique plane of the condyle. Dijgraaf et al. [19] demonstrated that joint lesions were related to the position of the articular disc. NitZna et al. showed that TMJ lesions were related to abnormal position of the articular disc and increase of friction coefficient[20]; this study further proved that TMJ disease is closely related to its stress distribution. Hence, prevention and treatment of TMJ disease can be achieved by maintaining interactions among structures in normal TMJ.

Conclusions
A 3D digital model of the TMJ system can be accurately and quickly constructed using CT and MRI data. 3D FEMs including maxilla, articular fossa, mandible, total dentition and disc displacement of TMJ were established. At any angle, the mesh division was even and flat, and coordination between the meshes was good. Such models can directly display spatial relationships among the articular disc, mandible, articular fossa and other structures. In addition, these models can simulate various occlusal states such as the centric occlusion and forward and lateral occlusal relationships.

Materials along with stress and restraint methods used in this numerical model can be used to simulate materials and force as well as constraints of the human TMJ system. Simulation results are in good agreement with clinical practice.

Stress of normal TMJ disc is concentrated in the lateral part of the middle and middle zone. Stress distribution is more uniform, and stress concentration occurs in the middle zone of the joint disc before disc displacement, which can easily cause thinning or perforation of the plate.

Increase of friction coefficient between the disc and the condyle and temporal bone will lead to an increase in force in the TMJ region of that side. Stress in the TMJ region of the side with anterior displacement is greater than that in the undisplaced side, suggesting that the mechanical environment of TMJ plays an important role in the normal physiological function and formation and outcomes of TMDs.

**Abbreviations**

Temporomandibular joint(TMJ), intra-articular disorders( ID), finite elements analysis (FEA), TMJ disorder (TMD)

**Declarations**

**Ethics approval and consent to participate**

The study design was approved by the Ethical Committee of Wenzhou Central Hospital. All participants gave informed consent and consent was written.

**Consent for publication**

Not Applicable

**Availability of data and materials**

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.
Competing interest

We have no conflicts of interest to declare.

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Authors’ contributions

GF X was responsible for the analysis and interpretation of the data; CY H recorded the data; F Z built the 3-D model; FJ X collected samples; LL F was responsible for the conception, design of the study and critical revision of the manuscript. All authors read the final version of the manuscript and approved the publication of this article.

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References

1. Katzberg RW, Westesson PL, Tallents RH, Drake CM. Anatomic disorders of the temporomandibular joint disc in asymptomatic subjects. J Oral Maxillofac Surg 1996;54:147–53.
2. Ribeiro RF, Tallents RH, Katzberg RW, Murphy WC, Moss ME, Magalhaes AC. The prevalence of disc displacement in symptomatic and asymptomatic volunteers aged 6–25 years. J Orofac Pain 1997;11:37–47
3. del Palomar A P, Doblaré M. 3D finite element simulation of the opening movement of the mandible in healthy and pathologic situations.[J]. Journal of Biomechanical Engineering, 2006, 128(2):242.
4. Markus L, Sturmat M, Weichert C, et al. A new approach for the validation of skeletal muscle modeling using MRI data[J]. Computational Mechanics, 2011, 47(5):591–601.
5. Pérez D P A, Doblaré M. Finite element analysis of the temporomandibular joint during lateral excursions of the mandible[J]. Journal of Biomechanics, 2006, 39(12):2153–2163.

6. Tanaka E, Tanne k, Sakuda M. A three-dimensinal finite element model of the Mandible including the TMJ and its application to stress analysis in the TMJ During clenching. Med Eng Phys 1994;16(4):316–322.

7. Chirani R A, Jacq J J, Meriot P, et al. Temporomandibular joint: a methodology of magnetic resonance imaging 3-D reconstruction[J]. Oral Surg Oral Med Oral Pathol Oral Radiol Endod, 2004, 97(6):756–761.

8. Westling L, Holm S Wallentin I. Temporomandibular joint dysfunction. Connective tissue variations in skin biopsy and mitral valve function. Oral Surg Oral Med Oral Pathol. 1992, 74(6):709–18.

9. Tanaka E Rodrigo D P Miyawaki Y et al. Stress distribution in the temporomandibular joint affected by anterior disc displacement: a three-dimensional analytic approach with the finite-element method. J Oral Rehab, 2000;27:754–759.

10. Tanaka E, Tanne k, Sakuda M. A three-dimensinal finite element model of the Mandible including the TMJ and its application to stress analysis in the TMJ During clenching. Med Eng Phys 1994;16(4):316–322.

11. Kober C, Hayakawa Y, Kinzinger G, et al. 3D-visualization of the temporomandibular joint with focus on the articular disc based on clinical T1-, T2-, and proton density weighted MR images[J]. International Journal of Computer Assisted Radiology & Surgery, 2007, 2(3–4):203–210.

12. Y Hayakawa, C Kober, et al. An approach for three-dimensional visualization using high-resolution MRI of the temporomandibular joint. Dentomaxillofacial Radiology (2007) 36, 341–347.

13. Westling L, Holm S Wallentin I. Temporomandibular joint dysfunction.

14. Connective tissue variations in skin biopsy and mitral valve function. Oral Surg Oral Med Oral Pathol. 1992, 74(6):709–18.

15. Lin CL, Lin YH, Chen AC. Buttressing angle of the double-plating fixation of a distal radius fracture: a finite element study. Med Biol Eng Comput, 2006; 44(8):665–673.

16. Nitzan DW. The process of lubrication impairment and its involvement in temporomandibular joint disc displacement: a theoretical concept. J Oral Max Surg 2001;59:36–45.

17. P´erez-Palomar A, Doblar´e M. 3D finite element simulation of the opening movement of the mandible in healthy and pathologic situations. ASME J Biomech Eng 2006;128:242–9.

18. Tanaka M T TODOH M et al. Stress analysis of anterior dise displaced temporomandibular joint using individual finite element model. JSME Int. J. Ser. C. 2003; 46(4):1400–1408.

19. Mongini F. Remodeling of the mandibular condyle in the adult and its relationship to the condition of the dental arches. Acta Anat (Basel).1972: 82:437.

20. Dijgraaf L de Bont LGM Boering G et al. The structure–biochemistry and metabolism of osteoarthritic cartilage: a review of the literature. J Oral Maxillofac Surg.1995:53:1182–1192.
21. Nitzan DW. The process of lubrication impairment and its involvement in temporomandibular joint
dise displacement: a theoretical concept. J Oral Maxillofac Surg. 2001:59:36–45

Figures

Figure 1

MRI image of normal disc–condyle relationship: (a) open-mouth position, (b) closed-mouth position;
irreversible disc replacement: (c) open-mouth position, (d) closed-mouth position. Arrows are pointing
toward the disc
Figure 2

Reconstructed bone structure (threshold 380-3071)
Figure 3

Splitting of different parts by using the ‘region growth’ function
Figure 4

Manually extracting figure of the disc according to MRI images

Figure 5
A joint disc model before and after treatment by using the free modelling system

Figure 6

Registration process of the articular disc and jaw
Figure 7

Surface mesh model was imported into the FEA software
Figure 8

TMJ system without TMD symptoms: (A,B) open-mouth position, (C,D) closed-mouth position
Figure 9

TMJ system before anterior disc displacement of a unilateral irreducible TMJ (A,C) normal side; (B,D) lateral displacement of the disc
Figure 10

3D FEM of a normal TMJ system
Figure 11

3D FEM of unilateral irreducible disc displacement

Figure 12

Stress distribution in a normal TMJ model: (A) upper surface, (B) lower surface
Figure 13

Normal stress distribution in the lateral disc in a pathological model: (A) upper surface, (B) lower surface

Figure 14

Stress distribution in an anteriorly displaced lateral disc: (A) upper surface, (B) lower surface; f=0.001
Figure 15

Stress distribution on surface of the condyle: (A) normal side, (B) displaced side