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Original Article

Mechanical analysis on individualized finite element of temporal-mandibular joint under overlarge jaw opening status

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Abstract: *Background:* Analyze the stress status of temporal-mandibular joint (TMJ) of a healthy volunteer under the overlarge jaw opening status through the finite element method, with the purpose of clarifying the loading features of each structure in the joint area, and achieving further understanding of the pathogenesis of the temporomandibular disorders (TMD). *Methods:* Collect the CBCT and MRI data of a volunteer respectively under the maximum jaw opening, establish the finite element model (FEM) of TMJ under the maximum jaw opening status through a series of software, image segmentation, rectification, meshing, material evaluation and other related processing, simulate the mechanical environment of this joint area under this status, and analyze the stress status of the articular disc, condyle cartilage, and condyle process. *Results:* Based on CT and MRI image data, build 3D model and FEM of TMJ, fully simulate the mechanical environment under the large jaw opening status, and calculate the stress value of the articular disc, condyle process and condylar cartilage. *Conclusions:* This research result reminds us that the normal people's articular disc are easy to generate stress concentration under large jaw opening, but its stress is far less than the one under the tight biting status. Perhaps the TMJ symptom induced under the large jaw opening status is mainly caused by the displacement of the articular disc. Under the large jaw opening status, the condylar cartilage plays a vital role in dispersing the stress. This method can be applied for carrying out individualized mechanical analysis on the patients with TMD.

Keywords: Temporal-mandibular joint, multi-modeling image, 3D reconstructed, finite element analysis, biomechanics

Introduction

Large jaw opening movement is a kind of lower jaw movement. It can reflect the limiting position of the muscle and ligament. Besides, it is regarded as an inevitable movement during the chewing and speaking in our daily life. Under the maximal jaw opening status, the condyle process is below the articular tubercle or front downward [1]. The mandible is only constrained through the muscle, ligament, etc. TMJ is in the relatively unstable status. The stress situation of each structure in TMJ is complex and variable [2]. It always generates sound, pain, and other symptoms. However, long-term large jaw opening movement and habit are quite easy to induce TMD. To accurately understand the biomechanics characteristics of TMJ under large jaw opening status has great significance in preventing the injury and regression of TMJ and guiding the clinical treatment [3]. Finite element analysis (FEA) is an important tool for studying the biomechanics of TMJ [4-6]. This research adopts the cone beam CT (CBCT), MRI image fusion technique, and some software, builds a relatively accurate finite element model of TMJ under the large jaw opening status, simulates the corresponding mechanical environment, and analyzes the mechanical states of the structures (e.g. articular disc condyle process, condylar cartilage, etc.), with the purpose of achieving further understanding of the pathogenesis of TMJ diseases and providing guidance for the treatment.

Table 1. Material parameters

Material	Young's modulus (MPa)	Poisson's ratio
Cortical bone	13700.0	0.30
Cancellous bone	7930	0.30
Articular disk	44.1	0.40
Cartilago articularis	0.79	0.49

Material and methods

Establishment of three-dimensional model of TMJ

Image data collection: Select a man volunteer at the age of 26, with symmetric face, integral teeth, and healthy TMJ, but without malocclusi on and malformation. Measure that the maximal jaw opening is 46 mm, and make individualized silicone rubber mouth opener with corresponding height. Ask the volunteer to bite the mouth opener by the anterior teeth, shoot the head and face part CBCT (Newtom VGG) and TMJ MRI (Signa HDxt 1.5T MR), and collect image data. All experiments were performed in accordance with relevant guidelines and regulations. The committee has approved the experiments and the informed consent was obtained from all subjects. The Affiliated hospital of Qingdao university medical college approved the experimental protocols.

3D modeling of TMJ: Lead the obtained CBCT and MRI DICOM pattern image data into Mimics 10.01. According to the gray value of the led-in data, select proper threshold scope of each anatomical structure. Establish 2D digital model of each structure through region growing, remove the disturbance by hand, and then carry out 3D reconstruction accounting, and establish 3D model for each anatomical structure. Through CBCT image data, build 3D models for mandible and TMJ respectively, reconstruct 3D model of TMJ disc through MRI image data, and save it in STL format.

Model rigging of 3D model: Use Mimics to open CBCT data and display 3D reconstructed mandible and TMJ fossa, input the 3D TMJ disc saved in STL format, repair, reduce the noise and spherize in Geomagic Studio 12.0, derive STP format, assemble the TMJ condyle and articular disc in Pro/E5.0 according to the CBCT under the large jaw opening, 3D position of each structure in MRI image and joint anatomical features, i.e. showing the anatomical structure of TMJ fossa, mandibular condyle and articular disc in the same 3D environment. Finally, derive IGES format, and prepare to do finite element mesh processing in Hypermesh 12.0.

Construction of 3D finite element model of TMJ

Partial optimization and volume meshing of 3D finite element model facet of TMJ: According to the requirements of the biomechanical analysis, carry out mesh regeneration of the definition facet towards each anatomical structure respectively [7]. TMJ disc and condyle process are the key points for this experiment and research. To meet the requirements of mechanical response in FEA, refine the structure mesh of articular disc and mandibular condyle, and roughen the structure mesh of TMJ fossa. Input the assembled finite element model into Hypermesh 12.0. According to the facet e mesh quality standard, optimize some parts of the mesh with inferior quality. According to the triangular facet mesh, volume mesh quality standard of the tetrahedral facet, square facet mesh and volume mesh standard of the hexahedral facet, carry out Tetrahedral meshing towards the TMJ fossa, hexahedral meshing and quality detection towards the articular disc and mandible, and build integral finite element model of TMJ suitable for FEA. With regard to the finite element model and image data of each anatomical structure of TMJ, compare the outline and judge the reality degree of the finite model to retain the anatomical structure of TMJ. Set SKIN unit as the cartilage articularis at the condyle process with the thickness of 0.2 mm.

Material parameters and loading conditions

Material parameters: Refer to **Table 1** for the material of each part [8, 9].

Loading parameters: The loading of this part is mainly about the muscular strength related to the oral cavity pulling the mandible. The main parts are musculus pterygoideus lateralis, geniohyoid muscle, muscles mylohyoideus, and digastric muscle. Refer to MRI image and anatomy location for muscle direction and attachment point location (**Figure 1**).

Loading conditions: Refer to Weijs WA [10] research data for the muscle strength. With

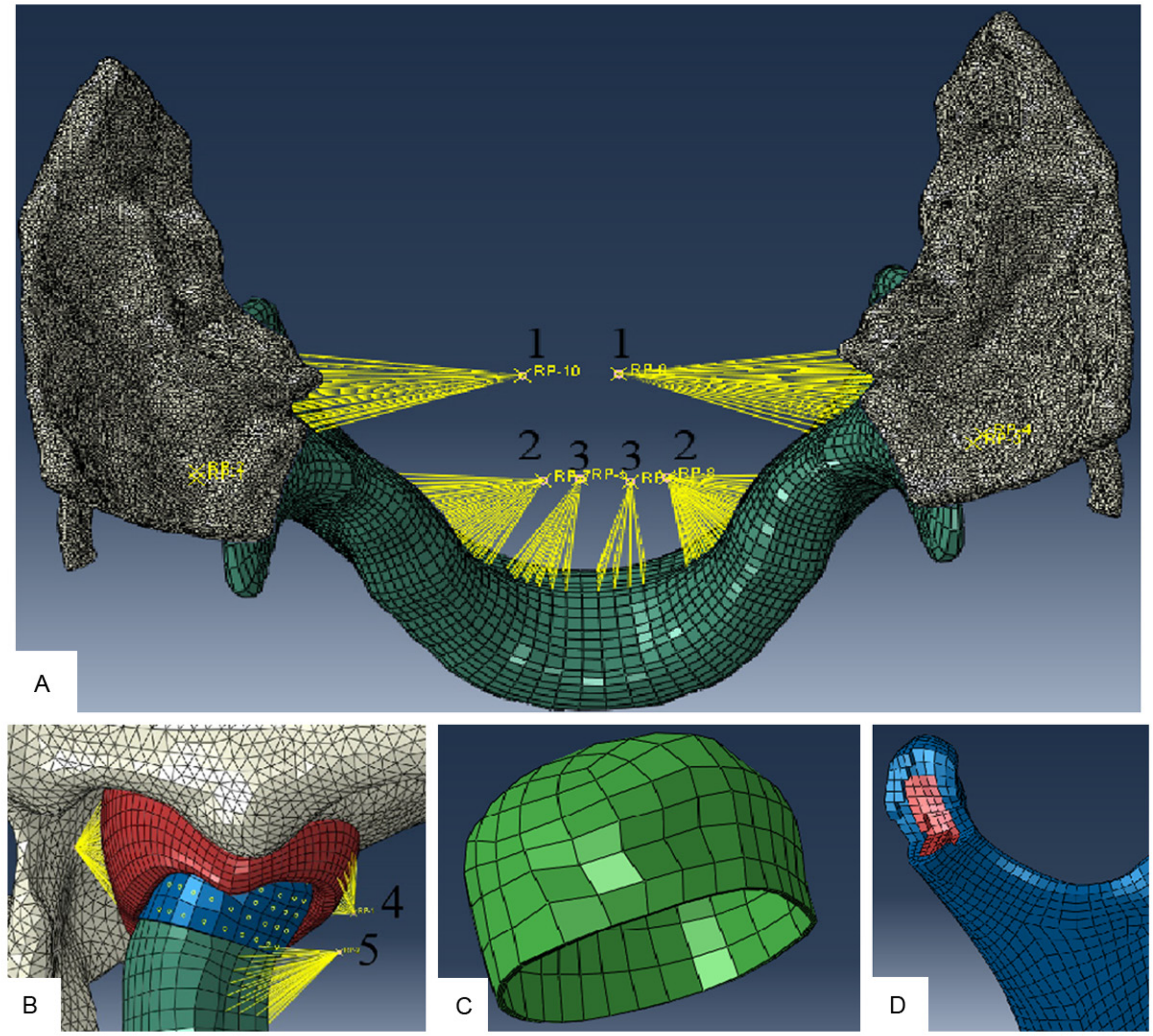

Figure 1. Boundary conditions of finite element calculation model. A, B. Simulated diagram of muscle loading. C. Finite element model of cartilage articularis. D. Finite element model of cartilage articularis. (1. Musculus pterygoiudeus; 2. Muscles mylohyoideus; 3. Digstric anterior and geniohyoid muscle; 4. SLP; 5. ILP).

Table 2. Loading conditions

Muscle name	Sectional area of muscle (cm^2)	Maximum muscle (unilateral, N)
superior lateral pterygoid muscle (SLP)	0.74	27.30
Interior lateral pterygoid muscle (ILP)	2.13	78.64
Geniohyoid muscle	0.29	10.70
Muscles mylohyoideus	0.46	47.20
Digastric anterior	0.31	11.40

regard to the cross sectional areas of the CBCT image of these three muscle groups (i.e. geniohyoid muscle, muscles mylohyoideus, and digastric anterior), in F=PxA, F is the maximum muscle strength; P is the inherent constant 0.37×106 Nm-2; A is the maximum physiologic cross sectional area of the muscle. The muscle strength of each part is shown in **Table 2**.

Calculation model

Finite element calculation mesh model: Lead the mesh divided in hypermesh into ABAQUS6.12 in INP format. The mesh unit types of each part are shown in **Table 3**. The quantity of the tetrahedral mesh C3D10 and hexahedral mesh C3D8 is 146858 and 50926 respectively. The total quantity of the units and the nodes is 197784 and 96838 respectively.

Table 3. Mesh types and numbers of the units

Name	Unit type	Numbers of units
TMJ fossa	tetrahedral mesh C3D10	146858
Mandible	hexahedral mesh C3D8	30136
Articular disc	hexahedral mesh C3D8	20790
Cartilago articularis	Skin unit	/

Table 4. Contact pair setting

NO		Contact status setting
1	TMJ fossa VS articular disc	Contact
2	Condylar cartilage VS articular disc	Contact
3	Reference point VS mandible	Coupling
4	Mandibular condyle and condylar cartilage	TIE

Calculation boundary: Set entire freedom degree fixing constraint in TMJ fossa, establish a reference point near the stop of each muscle, couple with the freedom degree of the attachment point of the muscle on the surface of the underjaw, and exert loading.

Contact pair setting: Set contact for the TMJ fossa and articular disc, set TIE constraint for the mandibular condyle and condylar cartilage, and set contact for condylar cartilage and articular disc (**Table 4**).

Results

Observe, compare and analyze the stress nephogram of the articular disc, condylar cartilage and condyle process (**Figures 2-4**), and then get the maximum values of these three stresses, shown in **Table 5**.

Stress situation of the articular disc

The distribution of von mises stress above and below the articular disc, the maximum principal stress and minimum principal stress are almost corresponding to each other, and the stress maximum value has some difference. The Von mises stress distribution of different parts of the articular disc has relatively great difference. The maximum stress is mainly focused on the anterolateral part of the articular disc. The maximum is 0.6813 Mpa. The rear part suffers the stress. The minimum principal stress of the articular disc is pressure stress in general, with relatively even distribution. The stress of the above part of the articular disc is bigger than that of the lower part. The prozone and protract stress are relatively concentrated. The stress maximum value is -0.4640 Mpa.

Stress situation of the condylar cartilage

Von mises stress of the condylar cartilage is mainly focused on the top of the condyle process and corresponding region of the back bevel. The maximum value is the lateral corresponding region of the condyle process top, which is 0.1526 Mpa. The maximum principal stress of the condylar cartilage top and the surrounding corresponding region is pressure stress. That for other parts is pulling stress, but the force value is so small, which can be ignored. The minimum principal stress of the condylar cartilage in the top of the condyle process is pressure stress. The maximum value is at the top but inclined to the interior side. It is -0.2612 Mpa. The stress of other parts is so small.

Stress situation of the condyle process

Von mises stress on the surface of the condyle process is mainly focused in the middle part of the front and rear bevel of the condyle process. The maximum stress is on the top of the condyle process but inclined to the back bevel. The maximum value is 0.3012 Mpa. The internal and external von mises stress of the condyle process is quite small. The maximum principal stress distribution of the condyle process takes the condyle process ridge as the demarcation. The front bevel is mainly pulling stress, while the back bevel is mainly pressure stress. The maximum value is on the front bevel, which is 0.1611 Mpa. The minimum principal stress of the condyle process mainly presents pressure stress. The stress on the top and back bevel of the condyle process is relatively great, and the maximum value is -0.3586 Mpa.

Compound stress analysis

After comparing three structures, as for the maximum value of von mises stress, maximum principal stress and minimum principal stress, the articular disc is the biggest, followed by the condyle process. That of the condylar cartilage is the smallest. Distribution of three kinds of stress above and below the articular disc does

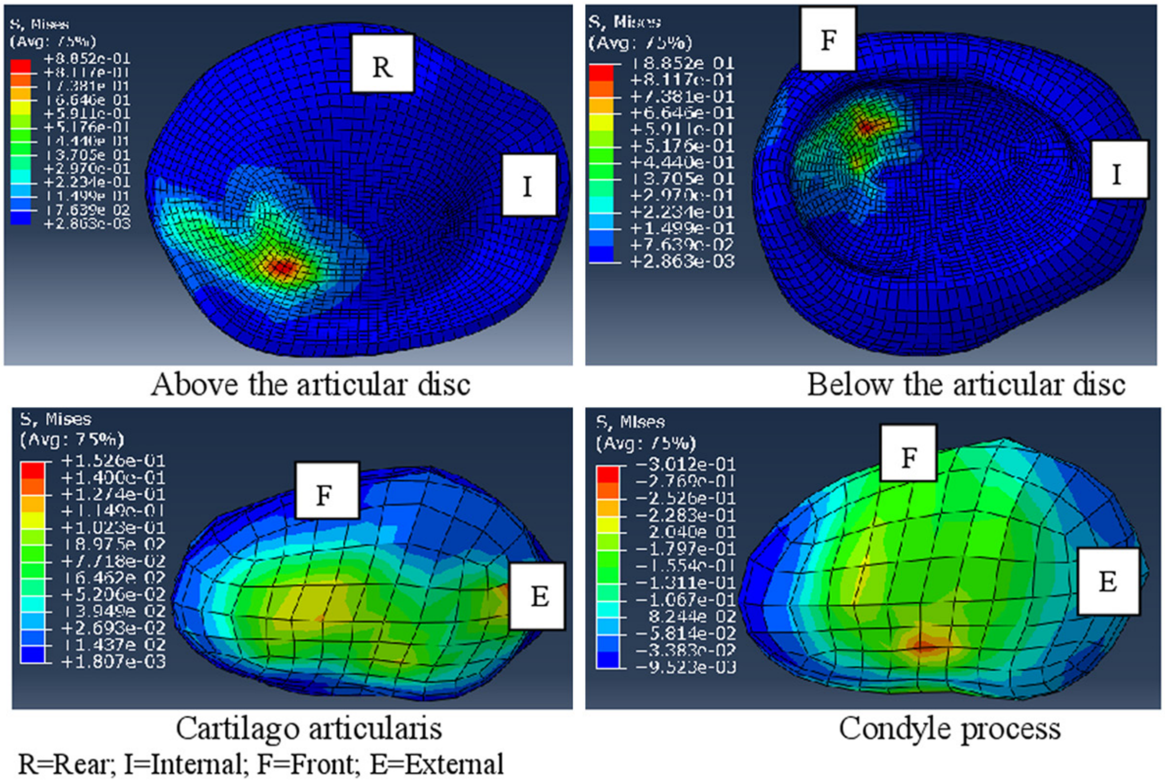

Figure 2. Von mises principal stress nephogram. R=Rear; I=Internal; F=External.

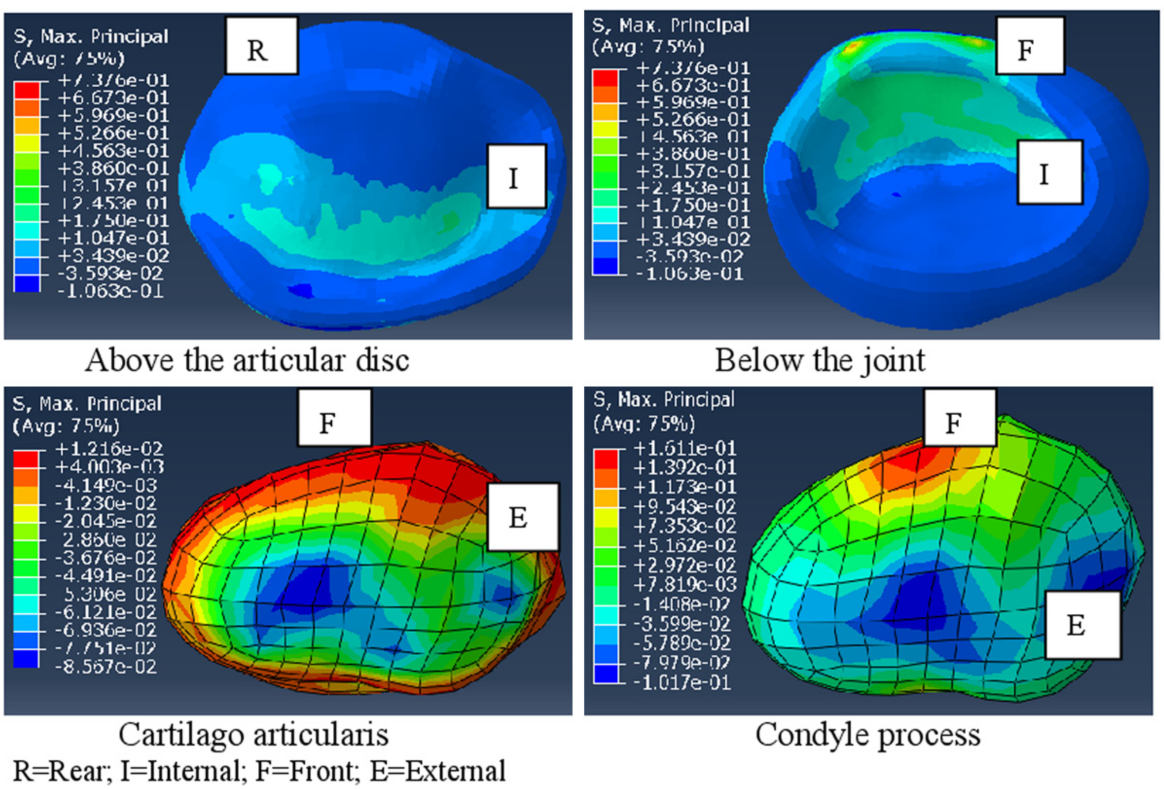

Figure 3. Maximum principle stress nephogram. R=Rear; I=Internal; F=Front; E=External.

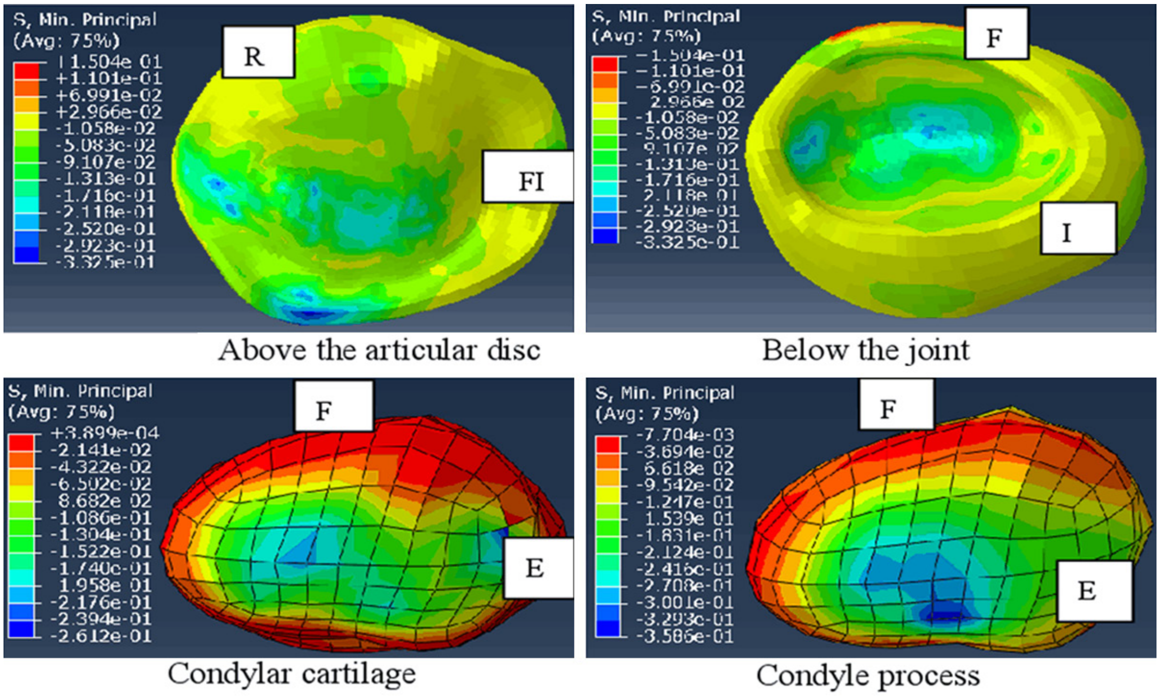

Figure 4. Minimum principal stress nephogram. R=Rear; I=Internal; F=Front; E=External; FI=Front internal.

Table 5. Maximum stress value for three kinds of stresses of each structure of TMJ (Mpa)

	Maximum von mises stress	Maximum principle stress	Minimum principle stress
Articular disc	0.8852	0.6813	-0.464
Condylar cartilage	0.1526	0.008567	-0.2612
Condyle process	0.3012	0.1611	-0.358

not have obvious difference. The distribution of these three stresses on the surface of the condyle process and condylar cartilage is almost corresponding, but the stress value of the condylar cartilage is generally smaller than that of the condyle process.

Discussion

Reliability of the model

TMJ has complex structure and variable movement forms. Especially, under the large jaw opening status, the anatomical structure position of each structure is relatively not fixed. Under such circumstance, the simulation of the model has great impact on the reliability of the analysis results. The traditional X ray scanning image modeling method has both advantages and disadvantages. Although CT data can well realize the sclerous tissue reconstruction and cannot clearly display the articular disc and cartilage articularis [11], TMJ MRI only can well display the image of the articular disc [12]. How to combine the advantages of the multi-modeling medical image (e.g. CT, MRI, etc.) to realize the simultaneous three-dimensional reconstruction of the soft and sclerous tissue of TMJ is the target for the medical science basis research and clinical diagnosis [13]. In this research, we utilize the bone tissue information collected by CBCT model (the scanning layer is 0.1 mm) and soft tissue information of TMJ disc collected by MRI (Signa HDxt 1.5T MR), and build 3D model of the bony structure and TMJ disc respectively, rectify and blend 3D anatomical structure according to the anatomy relationship displayed by 2D image, and meanwhile, make use of the advantages of CBCT and MRI, which improves the simulation of the model to a great extent [14].

The traditional TMJ finite element model always carries out triangular meshing and tetrahedral meshing [7]. With the development of the technology, the labor division of excellent finite element processing software has become more professional and refined. During the finite element modeling and calculation, the coordination and collaboration of different software becomes more and more important. In this research, we apply Hypermesh software to carry out quadrilateral and hexahedral meshing and optimization towards TMJ disc and mandible, which makes the mesh become more refined and contributes to good astringency during the calculation. Especially, to divide 20,790 hexahedral meshes towards the articular disc improves the accuracy of the modeling and reliability of the analysis result.

The loading condition of the finite element analysis and boundary constraint condition are the important factors for restricting the accuracy of the analysis result. Under the maximum jaw opening status, TMJ is restricted by the muscle, ligament and joint capsule. The opening degree cannot be increased, but the mandible and articular disc is pulled by the oral muscle group [15]. This research refers to Weijs WA [10] research method, and measures each muscle sectional area of the oral muscle group, and calculates the muscle force loading of each muscle. According to the position of the bone tissue and 3D direction of the attached simulation muscle in the model, exert even loading to several units of the corresponding regions on the model. Accurately simulate the mechanical environment of TMJ area under the maximum jaw opening status.

Result analysis

The result of this research indicates that, through comparison on three kinds of structures, TMJ under the large jaw opening status bears the largest von mises stress (0.89 Mpa), located in the anterolateral ara of the articular disc; it prompts that the articular disc may be the easiest to be injured among these three structures under the large jaw opening status. However, Hiroko Mori et al [16] have studied the mechanical status of TMJ under the tight biting status through the finite element method, and it turns out that the maximum (6.18 Mpa) of von mises that the articular disc bears is much larger than the data achieved in this research. Mhamad Aoun et al [17] have studied the maximum value (-40.0 Mpa) of the minimum principal stress under the tight biting status, which is also smaller than the research result (-0.46 Mpa). The cause may be that the oral muscle group force is less than the closed muscle group. LM Gallo [18] has measured the mandibular movement speed of 10 normal persons, and carried out research analysis through MRI image characteristics. He believes that it is easy to cause articular disc fatigue and decompensation under the overlarge loading [14]. It is proved that the mechanical fatigue of the joint tissue is caused by the degenerative joint disease (DJD) [19, 20]. It reminds us that, although the articular disc generates stress concentration under the large jaw opening status, its stress is far less than the one that under the closed tight biting status [1], and it does not generate TMJ lesion due to the overlarge stress [21], and TMJ symptom induced under the large jaw opening status may be mostly caused by the displacement of some tissues, such as articular disc, etc.

Through comparison on three structures, three stresses the condylar cartilage bears are all minimal. It prompts that, under the large jaw opening status, the condylar cartilage can well disperse the stress transmitted by the condyle process and articular disc, with important stress buffering function. It is similar to the research result from Hiroko Mori et al [1].

It is necessary to illustrate that the data and conclusion obtained by this research is aimed at a volunteer with healthy TMJ. Through the image information, we find out that the volunteer's condyle process is within the articular fossa when opening mouth largely. However, the articular fossa position of the normal persons at the maximum jaw opening degree and large jaw opening status is inconstant, and some people's articular process can surpass the articular tubercle and be within the articular fossa during large jaw opening [1]. Under such circumstance, the position of the articular disc and condyle process changes when surpassing the articular tubercle. The stress results may have great difference. Therefore, such situation is not within the research scope of this paper. However, the methods adopted by this paper and the research conclusion remind-er us that: it is feasible to carry out individualized finite element mechanical analysis towards each patient with TMD, which is helpful for identifying the specific pathogenesis of each patient. Meanwhile, the pathogenesis of the infratemporal part has not been clarified yet. With the constant accumulation of the case samples and data statistical analysis, to carry out individualized finite element analysis statistics through classification has important significance in clarifying the etiological mechanism of TMD. It is of great importance to achieve more comprehensive understanding of TMD, which will take long time. This research only carries out finite element stress analysis on each structure of TMJ, but does not study the strain, movement trend, etc., which will be our work objective in the next stage and also the future development direction of the medical biomechanics.

Disclosure of conflict of interest

None.

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