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Original Article

MRI-based analysis of stress trajectories in the articular disc during jaw opening

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Abstract: The aim of this study was to evaluate the stress characteristics in the temporomandibular joint disc of a patient with temporomandibular joint disorder during jaw opening and to further understand the biomechanical basis for temporomandibular joint disorders. A two-dimensional finite element model of a symptomatic articular disc was developed based on magnetic resonance imaging data from a subject with temporomandibular joint disorder. Hyperelastic constitutive laws were applied to the anterior and posterior bands and the intermediate zone of the disc. The finite element analysis of the disc deformation applied displacement loading based on the contours of the disc at different degrees of jaw opening. Stress and strain trajectories of the disc were calculated. The intermediate zone of the symptomatic disc was mainly under compression during jaw opening, while the anterior and posterior bands were being stretched. The maximum and minimum principal stresses were concentrated on the boundaries of the posterior band. In addition, relatively high shear stress was concentrated on the inferior boundary of the posterior band and the superior boundary of the middle-posterior band. The stress in the symptomatic disc increased linearly with the degree of jaw opening, especially in the posterior band. Deformation of the disc in the symptomatic joint caused high stress in the posterior band, which is also the most likely zone to suffer injury. It is suggested that the patient avoids wide jaw opening since it may cause excessive stress to the disc.

Keywords: Temporomandibular joint disc, magnetic resonance imaging, finite element analysis, jaw opening

Introduction

The disc of the temporomandibular joint (TMJ) is one of the load-bearing organs in the human body [1]. Disorders of the TMJ (TMD) involving pain and dysfunction of the masticatory system, the temporomandibular joint and its associated structures are common diseases that affect about 20-30% of the adult population to some degree [2-4]. Possible causes of TMD, such as grinding or clenching of the teeth, are all related to overloading the TMJ. It is significant to study the reaction forces and stresses in the joint during functional movements [5, 6]. High stress in the TMJ occurs not only during clenching, but also during jaw opening [5, 7], one of the most constantly occurring movements in everyday life.

The articular disc, lying between the articular fossa and the condyle, plays an important role during functional movements. It transfers loads between the articular surfaces during mandibular movements [5, 8-11]; therefore, the disc [12, 13] and articular cartilage [13] play important roles in avoiding stress concentration [14]. However, the role of the disc in the progression of TMD is controversial [5]. Anterior displacement of the TMJ disc can occur temporarily (with reduction) or permanently (without reduction) [1, 6, 15]. Some investigators suggest that the degeneration of the TMJ is associated with disc displacement [7, 16]. The biomechanical balance in the TMJ plays a key role in the mechanism of TMD [5]. Excessive compressive and/or shear stresses are probably the most common sources of condylar resorption and disc perforation [5].

Many finite element models [12, 14, 17-21] have been developed to investigate the biomechanical balance in the TMJ. However, most

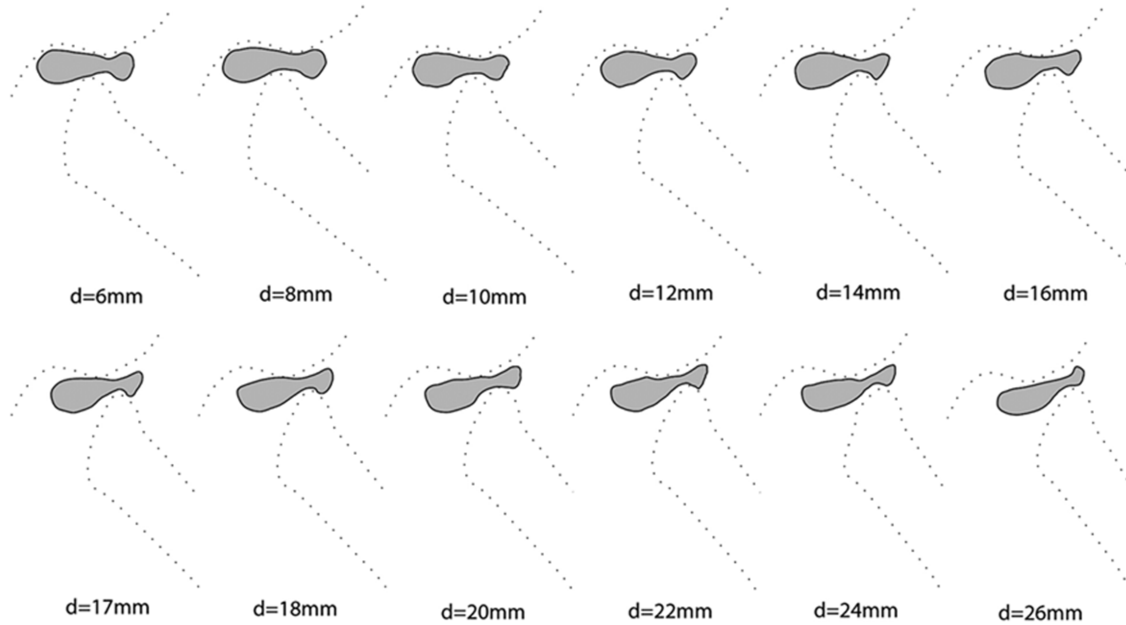

Figure 1. Contours of the fossa, disc and condyle at different degrees of jaw opening.

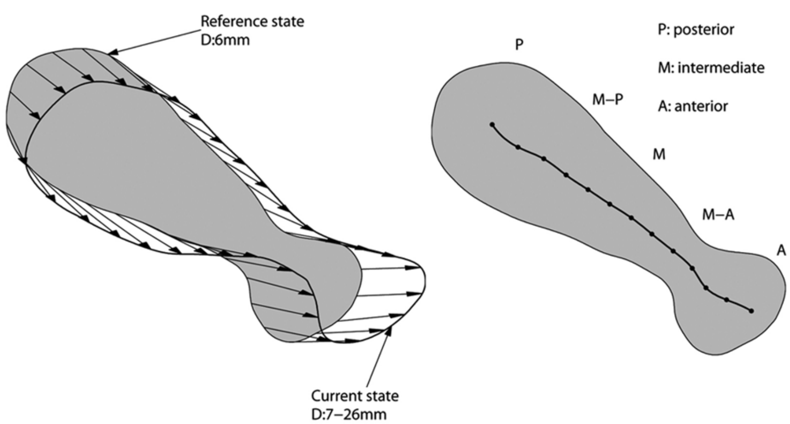

Figure 2. Loading conditions and zoning of the disc. A. Loading condition of the symptomatic disc obtained by the displacement of corresponding nodes on the boundary of the disc in the reference state (6-mm opening) and the disc in the current state at varying degrees of jaw opening (7-24 mm); B. The disc was divided into five zones: posterior (P), medial-posterior (M-P), medial (M), medial-anterior (M-A) and anterior (A). The central line is the node path used to evaluate the stretch of the disc.

models have been based on the healthy TMJ. Few finite element analyses [5, 6] have reported differences in biomechanical behavior in the TMJ between asymptomatic and symptomatic joints.

In most previous studies, the condylar movements were used as the displacement loading [5, 6, 17, 19, 20]. Assumptions had to be made about the friction coefficient between the condyle and the disc. The precision of the stress analysis of the articular disc depends largely on the contact conditions. Up to now, few studies have applied the disc contours directly as the displacement loading in simulating disc deformation during jaw opening. Direct displacement loading based on the disc contours has proven to be an alternative method for studying disc stress during jaw opening [22].

In this study, a two-dimensional (2D) finite element model of the TMJ disc of a subject with TMD was developed based on magnetic resonance imaging (MRI) data. The reason for using a 2D model is that this is a methodological trial of a new type of loading condition. In addition, displacement loading is based on disc contours, which can only be traced manually and therefore cannot be realized in a 3D model at present. The aim of this study was to analyze the stress/strain pattern

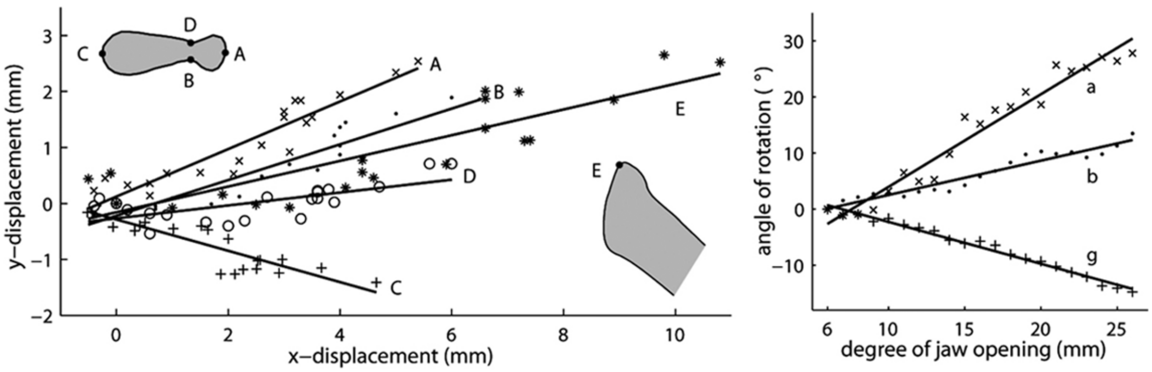

Figure 3. Translational and rotational displacements of the TMJ. A. Translational displacement of the symptomatic disc; B. Rotations of the disc and the condyle during jaw opening. α: rotation of the short axis (BD) of the disc; β: rotation of the long axis (CA) of the disc; γ: rotation of the condyle.

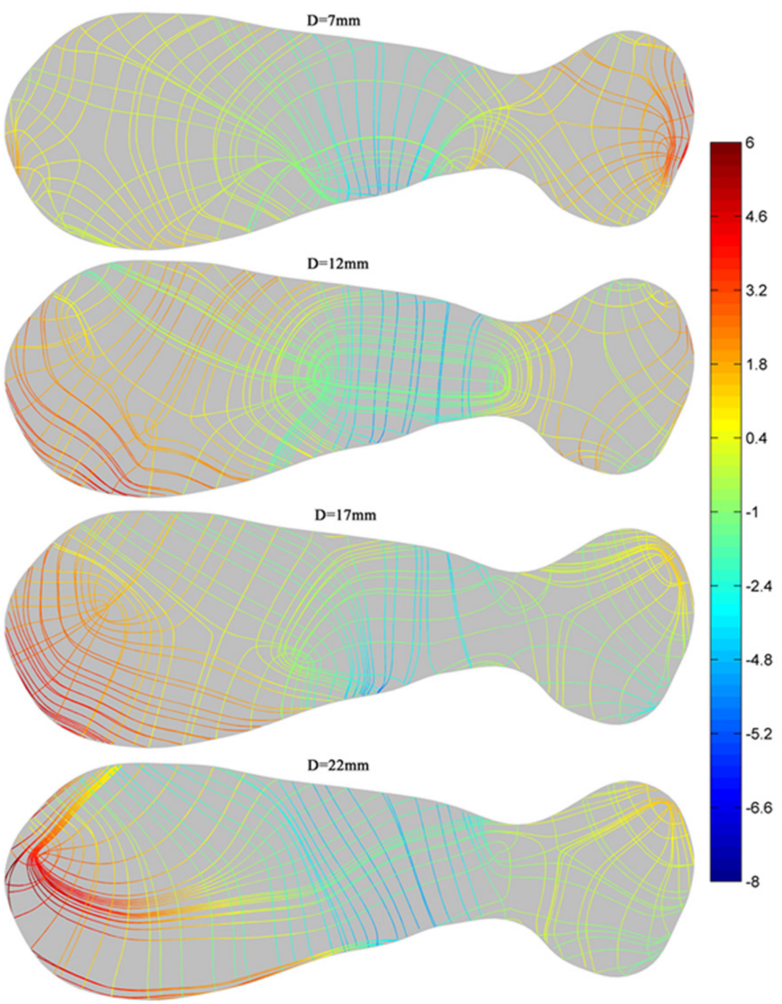

Figure 4. Stress trajectories of the symptomatic disc at 7, 12, 17 and 22 mm of jaw opening (MPa).

in a symptomatic disc during jaw opening and to assess its connection with the progress of TMD.

Materials and methods

The modeling and simulation processes were similar to our previous study with a healthy subject [22], and will be described briefly only for completeness.

Oblique sagittal magnetic resonance (MR) images of the TMJ were taken from a 26-year-old female with anterior disc displacement with reduction. Informed consent was obtained from the patient to participate in the study. We promised to protect the life, health, dignity, integrity, right to self-determination, privacy, and confidentiality of personal information of the research subject. Ethical permission was obtained from the Scientific Research and Clinical Application of Medical Technology Ethics Committee of the Affiliated Hospital of the Academy of Military Medical Sciences, reference number KY-2013-03-06.

The jaw opening displacement varied from the initial state at 6 mm (referenced as state 01) to the final state at 26 mm (referenced as state 21) with a 1-mm increment. The contours of the

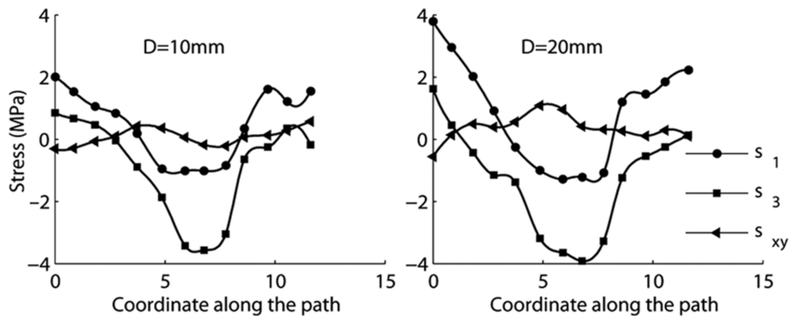

Figure 5. Stresses along the postero-anterior path in the symptomatic disc at 10 and 20 mm of jaw opening.

To evaluate the stress variations between the anterior, posterior and intermediate zones, a path was defined in the articular disc (**Figure 2A**). In addition, the disc was divided into five zones along the antero-posterior axis to characterize the stress/strain patterns during jaw opening, as shown in **Figure 2B**.

articular fossa, articular disc and condyle were traced by a trained dentist (**Figure 1**). With the initial opening displacement at 6 mm, the disc displacement was with reduction. Therefore, the disc was in situ in the MR images in this study.

The contour of the disc at a jaw opening of 6 mm was defined as the reference state, and was used to establish a 2D finite element model of the disc. The initial stress state of the articular disc was assumed to be zero.

All other disc contours were meshed in the same way as for the finite element model. For a given degree of jaw opening, the displacement of the boundary nodes of the finite element model was used as the displacement loading [22], as shown in **Figure 2A**. A total of 20 simulations were performed.

The results of previous studies [23-25] indicate that the mechanical behavior of the articular disc is nonlinear, anisotropic and time-dependent, and has different mechanical behaviors in the anterior, intermediate, and posterior bands. Hyperelastic materials have been used as models of the disc. For example, Perez [6, 19] developed a fiber-reinforced porohyperelastic model of the articular disc. Similarly, the experimental response function was used to describe the hyperelastic properties of the disc in this study. The parameters of the material models of the anterior and posterior bands are different from the intermediate zone because of different fiber orientations in the disc. The parameters were obtained from the experimental data reported by Kang, Bao and Qi [23] who performed tensile tests of the anterior, intermediate and posterior bands of 13 human TMJ discs along the medial-lateral axis of the disc.

Results

Instead of the biconcave shape of a normal disc, the configuration of the symptomatic disc is distorted, as shown in **Figure 1**. The linking part of the middle-anterior band and intermediate zone is the thinnest, and the anterior band is thinner than the posterior band. This is consistent with descriptions in previous studies [6].

Figure 3 shows the displacement of the four feature points in the symptomatic disc (left) and the rotation of the articular disc and condyle (right) during jaw opening. It can be seen that the disc rotated mainly anteriorly in a counter-clockwise direction. The anterior part of the disc went up with the displacement of jaw opening, while the posterior part dropped constantly. In addition, the opening displacement may not be the only parameter to describe jaw opening. **Figure 3B** shows the rotation angle of the disc and condyle. It demonstrates that the rotation angles were generally linear with the opening displacement. Thus, the jaw opening displacement can be considered to mirror the degree of jaw opening.

Instead of the common stress nephogram, stress trajectories were used to analyze stress characteristics in the articular disc. **Figure 4** shows the stress trajectories of the symptomatic disc at jaw openings of [7, 12, 17] and 22 mm. It can be observed that the intermediate zone of the disc was mainly subjected to compressive stress and the anterior and posterior bands were stretched. At lesser degrees of jaw opening (D = 7, 12 mm), stress trajectories were horizontal and vertical because the disc mainly bears vertical pressure. The transition from compressive stress in the intermediate

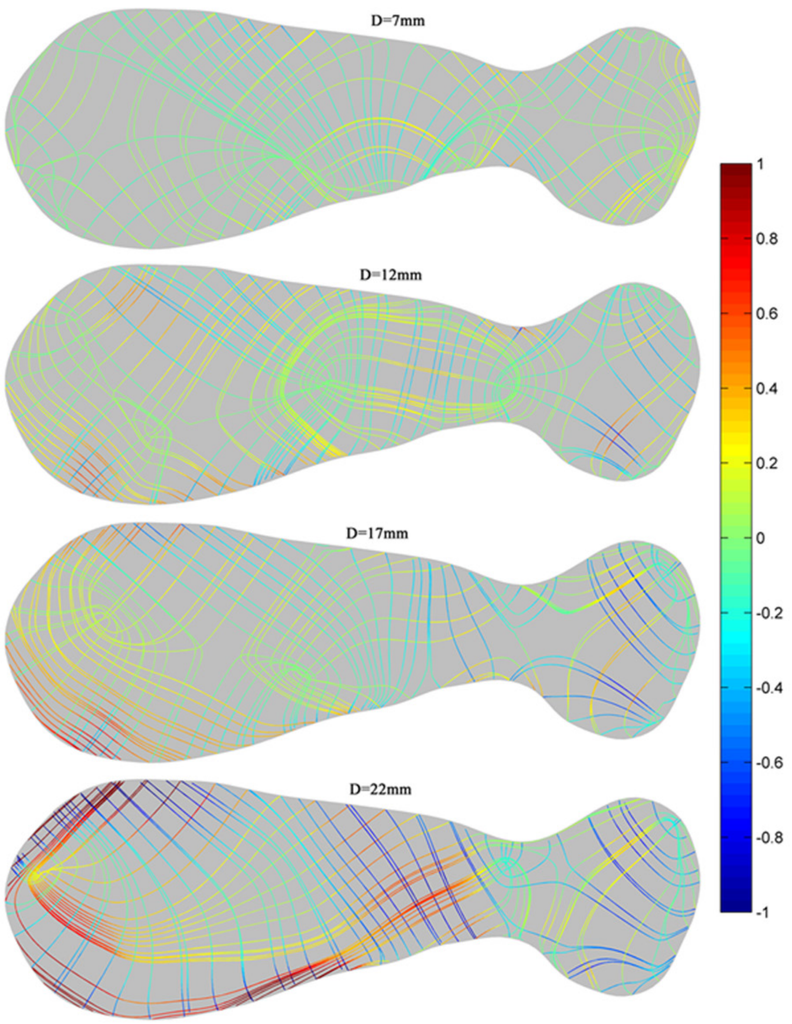

Figure 6. Strain trajectories of the symptomatic disc at 7, 12, 17 and 22 mm of jaw opening (MPa).

zone to tensile stress in the anterior and the posterior zones was accomplished through a singular point. This is similar to the transition in a healthy subject [22]. However, at greater degrees of jaw opening, stress trajectories no longer ran vertically and horizontally. A concentration of the maximum and minimum principal stresses occurred on the boundaries of the posterior band. The stress distribution was similar to that reported in Koolstra and Tanaka's study [26]. In addition, relatively high shear stress concentrated on the inferior boundary of the posterior band and the superior boundary of the middle-posterior band. The maximum shear stress was as high as 2 MPa.

Figure 5 shows the stresses along the postero-anterior path of the disc at jaw openings of 10 and 20 mm. The stress patterns were similar for different degrees of jaw opening. The fitted curves of the maximum and minimum principal stresses appear to be funnel-shaped. It can be confirmed again that the posterior and anterior bands were stretched, while the intermediate zone bore the compressive stress. The shear stresses were relatively low when compared with the principal stresses, but could be higher in other locations of the disc.

Figure 6 shows the strain trajectories of the disc at jaw openings of [7, 12, 19] and 22 mm. The patterns of the strain trajectories were similar to those of the stress trajectories. The maximum shear strain at any point is half the difference between the two principal strains; thus the difference in the two trajectories is proportional to the maximum shear strain. A sharp contrast between the two trajectories corresponds to a larger shear strain. Shear strain concentration occurred on the inferior boundary of the intermediate-posterior band and the superior boundary of the posterior band.

Figure 7 shows that both the von Mises stress and von Mises strain increased quasi-linearly with the degree of jaw opening. The highly linear results demonstrate that the errors in the present study are small compared with our previous work in a healthy subject [22]. The highest stress occurred at the posterior band, where the stress level increased up to 200% from the beginning to wide opening. Since only the average stress/strain was given in **Figure 7**, the realistic maximum stress/strain in the posterior band would have been much higher. High stress in the posterior band would cause pain and limitation in a TMD patient during jaw open-

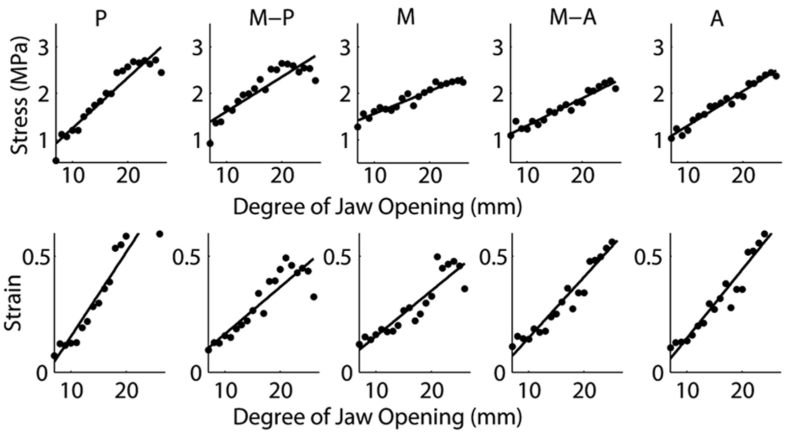

Figure 7. Relationship of von Mises stress/strain and the degree of jaw opening.

ing. Clinical observation also suggested that the injury was more likely to have taken place in the posterior and medial-posterior bands.

Discussion

TMD is a common disease that affects many people. Symptoms of TMD mainly include pain, a popping sound, and limitation of jaw opening. TMD is a self-limiting disease, meaning that once the causes disappear, the symptoms may fade away. However, persistent causes will lead to TMD. Patients with disc displacement and TMJ arthritis may endure overloading during functional movement, causing further development of TMD. However, since the causes of a large proportion of TMD cases are currently unclear, a better understanding of the etiology of TMD will not only help reduce the incidence of TMD but also assist in preventing clinical failure of implanted joints.

In the present study, a 2D finite element model of the symptomatic disc was developed. The stress characteristics of the articular disc during jaw opening were studied. The deformation of the disc was simulated by using displacement of the disc contour as under loading conditions. Thus, application of muscle force [20] and the frictional coefficient between the condyle and the disc were avoided. The material behavior of the TMJ disc is described by the experimental response function. Parameters for the response function were obtained from experimental data of tensile strength tests of human TMJ discs [23]. It can be inferred from the stress/strain trajectory patterns that fiber orientation has a great influence on the stress/strain distribution of the disc.

It has been reported that more advanced internal derangement of the joint corresponds to greater deterioration of the disc configuration [6, 27]. In this study, the shape of the symptomatic disc was distorted from the normal biconcave configuration. The disc in the symptomatic joint underwent significant displacement anteriorly and rotated approximately [25] degrees inferiorly during jaw opening. In the vertical direction, the disc in the symptomatic joint moved approximately 1.8 mm inferiorly. The large amount of displacement and rotation led to changes in the stress and strain distribution in the disc.

Functional overloading appears to be important in the progress of TMD [5, 28]. Hirose et al. [18] found that the pressure in the bilaminar region of the TMJ in subjects with anterior disc displacement was five times as high as that in the asymptomatic TMJ. Abnormal loading causes degenerative disease in the bilaminar region and advancement of TMD. High stress appears not only with clenching, but also during jaw opening. In this study of the TMD disc, the intermediate zone was mainly under compression and the anterior and posterior bands were stretched during jaw opening. This is consistent with the results of previous studies6. In the symptomatic disc, the highest tensile stress was concentrated in the posterior band of the disc, and the average stress in the anterior band was lower than in the posterior band. The posterior band was broader than the anterior band in the symptomatic disc, and thus shared part of the compressive stress in the intermediate zone. In addition, the shorter length of the disc and the anterior displacement also caused contact of the posterior band with the condyle, leading to high stress in the posterior band. Similarly, Tanaka, et al. [5] found that there are differences between stress distribution in the healthy disc and the TMD disc. In the healthy disc, stress is mainly concentrated in the exterior (lateral) and anterior zones, while in the symptomatic disc; stress is mainly concentrated in the intermediate and posterior zones.

Perez del Palomar and Doblare [6] studied the stress distribution of the TMJ disc in subjects with anterior disc displacement with and without reduction during jaw opening. They found that the maximum stress was mainly located in the posterior band before reduction, while the maximum stress was mainly located in the middle band of the disc after reduction. However, it was observed in this study that the intermediate zone was subjected to maximum compressive stress and the posterior zone was subjected to maximum tensile stress even after reduction of the disc. In a patient with anterior disc displacement with reduction, even if the disc is in situ, the distorted configuration will result in abnormal stress distribution in the disc, leading to further distortion of the disc configuration and functional abnormality, and finally developing into anterior disc displacement without reduction.

Regular configuration of the TMJ is one of the key factors to guarantee lower friction in the joint. It has been shown that the frictional coefficient in a symptomatic disc is 10 times that in an asymptomatic disc. The condyle sliding along the disc will cause abnormal stress, which leads to aggravation of TMD [11]. A decrease in synovial fluid in the articular capsule and an abnormal structure of the condyle are considered to be the two main factors that increase the frictional coefficient. The symptomatic disc in the present study underwent great changes in configuration with excessive expansion of the posterior band. Additionally, the abnormal relationship between the disc and condyle and the irregular displacement of the disc during jaw opening are possible causes of increased friction between the disc and condyle. Forster and Fisher [29] discovered that continuous and excessive stress can reduce the amount of synovial fluid, causing deformation of the disc and increased friction. However, a recent study suggested that increased friction hardly ever leads to abnormal stress in the disc [30]. Therefore, the higher frictional coefficient is the result rather than the cause of abnormal stress in the disc.

Shear stress in the disc is related to the degeneration of soft tissues and perforation of the disc. In this study, shear stress was concentrated mainly on the boundaries of the intermediate-posterior and posterior bands (maximum 2 MPa). The stress level in the symptomatic disc increased sharply with jaw opening, especially in the posterior band. The highest stress mainly occurred in the posterior zone of the symptomatic disc. When the jaw opens, the condyle rotates clockwise and the pressure from the condyle squeezes the disc forward [8]. Thus, the contact between the condyle and disc moves to the posterior band of the disc. In general, the posterior band of the symptomatic disc bore high tensile stress and shear stress. Consequently, it is more likely to suffer injury during wide jaw opening. The posterior zone is also near the bilaminar zone, which is the most common area to suffer injury. It is therefore better to avoid wide jaw opening and other actions causing excessive or abnormal stress in the disc [5].

Finally, there are some limitations to the present study. Some simplifications of the displacement loading were made. The displacement of the disc boundary was obtained from corresponding node pairs of the two configurations of the disc, which may have led to stress concentration on parts of the boundary [22]. However, most of the results were highly logical and are consistent with those in previous studies.

In this study, an alternative method was applied to analyze the stress response of the articular disc during jaw opening. The results correspond with clinical studies that validate conversely the loading method in this study. Patient-specific models are becoming more popular for clinical treatment [1]. Since only 2D models are used, the method used in this study could be developed as an efficient patient-specific model for the clinical diagnosis and treatment of TMJ disorders.

Conclusion

The level of stress in the articular disc in the symptomatic joint increased sharply with the degree of jaw opening. Because of distortion of the disc, stress was concentrated in the posterior band of the disc in the symptomatic joint even after reduction, causing anterior disc displacement without reduction. The posterior band is the zone most likely to suffer injury.

TMD patients suffer pain and limitation of jaw opening. Therefore, it may be better for the TMD patient to avoid wide jaw opening.

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Disclosure of conflict of interest

None.

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