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Research progress on dynamic three-dimensional finite element model construction of temporomandibular joint

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Abstract: *The three-dimensional finite element method has become the main method for studying the biomechanics of the temporomandibular joint due to its precise and non-invasive characteristics. However, the geometric similarity and mechanical simulation of different modeling methods differ, and there are significant differences in their authenticity. The principle is to use modern computer technology to numerically convert the mechanical properties of objects, establish an intuitive, time-saving, and conclusive research model, analyze the stress-strain situation of different parts, and then carry out mechanical theory research. This article will focus on the construction of geometric models of the temporomandibular joint, material characteristics and contact relationships, as well as the loading methods of dynamic loads and the establishment methods of dynamic three-dimensional finite element models of the temporomandibular joint.*

Keywords: *Temporomandibular joint; Finite element modeling; Motion simulation; Computer Biomechanics*

As an important component of the chewing system, temporomandibular joint(TMJ) plays a crucial role in the basic physiological activities of humans. Research has shown that there is a certain correlation between temporomandibular orders (TMD) and higher internal stresses in TMJ[1]. A biomechanical analysis of the internal structure of TMJ can help clinical doctors gain a deeper understanding of the occurrence and outcome of TMD. However, the structure of TMJ is relatively complex, with significant differences in the morphology and properties of its components. Traditional in vitro measurement methods cannot effectively analyze the stress distribution and morphological changes inside TMJ. The use of three-dimensional finite element analysis method can effectively analyze the interaction and mechanical changes of the internal structure of TMJ.With the development of computer biomechanics, many scholars have established three-dimensional finite element models with different simulation degrees and mechanical loading methods, in order to more accurately restore the internal force and displacement status of TMJ under different states. In the past, some studies only focused on the stress and strain of TMJ in fixed jaw positions [2,3]. In order to better simulate the normal functional state of TMJ, recent studies have introduced dynamic loads or analyzed multiple jaw positions [4,5]. As the dynamic three-dimensional finite element simulation of TMJ becomes more accurate, the computational load of the computer also gradually increases[6]. Based on actual research needs, selecting appropriate modeling methods and simplifying the simulation process appropriately will help shorten simulation time. How to achieve a balance between simulation accuracy and computer computational load, and improve the clinical application efficiency of dynamic three-dimensional finite element analysis, has gradually become a hot topic of concern for researchers.

This article will provide an overview of the dynamic three-dimensional finite element model construction of the temporomandibular joint from the aspects of TMJ's geometric model construction, material properties and contact relationships, and loading methods for dynamic loads.

1. Construction of geometric models for TMJ

Early TMJ research was limited to in vitro modeling, and the processing process was destructive to the original structure, making data collection and analysis difficult. At present, research often uses a combination of CT scanning and MRI to export image data in DICOM form to construct TMJ models. Martinez Choy[7]proposed a complete TMJ three-dimensional finite element modeling method, which includes all relevant structures and Hill shaped muscles. CT scans are mainly used for modeling bone structures, while MRI is used for soft tissue construction. However, due to the thick scanning layer of MRI (1-3mm), the combination of CT scanning and MRI still cannot clearly depict the edge morphology of soft tissues such as articular discs[8].Fictional modeling is a modeling method that relies on the anatomical cognition of the modeler, combined with imaging data, to manually draw tissue structures that are difficult to distinguish. Based on this method, Ye Pengcheng[9] applied the second-generation Chinese digital human body to construct a relatively precise chewing system model. However, this method is subjective,time-consuming,and often requires interdisciplinary cooperation.

In order to save computer computing power,some scholars have used joint simulation technology and muscle bone finite element models to define the contact state of the edges of various anatomical structures, such as the load of the tibia under load[10] or the stress distribution of the patella when climbing stairs[11]. At present, there are no instances of applying joint simulation technology to TMJ construction, possibly due to the following reasons:(1) Joint simulation technology requires the use of two different modeling software sets, which are more complex to set up; (2)The simplified joint model cannot accurately simulate the displacement state of various structures inside TMJ. At present, the modeling method proposed by Sagl[12] best balances simulation complexity with computer computational load. Unlike traditional modeling methods, this method uses a rigid mandibular model combined with finite element modeling of the joint disc, and simplifies the joint cartilage into an elastic matrix. After dynamic tracking verification in vivo, the model can well reflect the actual deformation of the articular disc and cartilage, and compared to the overall three-dimensional finite element modeling, its calculation time is greatly reduced, increasing the possibility of clinical application of this method.

2. Material properties and contact relationships

The internal anatomical structure of TMJ is complex, with different mechanical properties such as joint discs, joint cartilage, and joint capsule. In the study of stress distribution in bone structures, it is generally set that each anatomical structure is a continuous, single-phase, linear elastic, and isotropic material, and material properties are defined using elastic modulus and Poisson's ratio[13]. For structures with small deformation variables such as the mandible, the error generated by this assignment method is within an acceptable range. For structures that require precise consideration of deformation variables, such as joint discs, joint cartilage, and joint capsules, if simple characterization is still used using elastic modulus and Poisson's ratio, the simulation accuracy will be poor. TMJ joint disc is actually a nonlinear, dual phase material with viscoelasticity and hyperelasticity[14]. At present,most studies still use the Mooney Rivlin nonlinear elastic model (a hyperelastic model similar to rubber) to analyze the joint disc[15,17], without taking into account the viscoelasticity of the joint disc. Although this model can well describe the deformation of the articular disc under tensile stress, it cannot accurately describe the effect of compressive stress. A simulation model that takes into account the nonlinearity, biphasicity, relaxation, and hysteresis of the articular disc will require a longer computational time. On the other hand, studies have shown that the material properties of the articular disc have a slight impact on mandibular movement[12], indicating that under limited computer computing power, the Mooney Rivlin model can be used to simplify the simulation of the articular disc without sacrificing the fidelity of mandibular movement.

In dynamic three-dimensional finite element analysis, elastic contact is often used for the disc protrusion contact relationship inside TMJ. Generally speaking, TMJ, periodontal ligament, teeth, etc. use hexahedral contact elements[3,16], and there are also studies that use interstitial elements[4] to simulate the contact relationship between the condyle, articular disc, and articular fossa. Joint capsule and disc attachment tissues use interstitial tension elements.In order to accelerate the simulation process, some scholars have not established a complete three-dimensional finite element model, but have replaced it with a simplified mechanical model. SkipperAnderson[17] simulated condylar cartilage by presetting an elastic matrix of 0.4mm. This elastic matrix can be regarded as a layer of spring placed on the surface of a rigid substrate. Using this simplified setting can effectively shorten the time and simulate the elastic structure connected to a rigid substrate well[18]. Due to the presence of synovial fluid in the joint cavity, the friction coefficient between the articular disc and the articular cartilage is relatively small, only 0.001[19]. When the joint disc is displaced, the properties and volume of the joint synovial fluid will change, leading to an increase in friction coefficient. Taking this change into account, Lai[1] suggested that the friction coefficient in functional state can be set to 0.3 or 0.4. In the actual modeling process, the influence of joint disc and cartilage deformation, biphasic nature of joint synovial fluid on contact and friction should also be considered to improve the nonlinear fidelity of the model.

3. The loading method of dynamic loads

The dynamic three-dimensional finite element model of TMJ is mainly driven by the chewing muscles. Initially, the muscle loading model was replaced by an external force in the same direction as the closure muscle. This loading method ignores the changes in muscle force magnitude and direction during muscle contraction, resulting in low fidelity. Scholars have used MRI imaging data, combined with anatomical knowledge, to depict the surface contour of muscles using a fictional method, establish muscle models, and overlay them with the jawbone model established by CT scanning to obtain a chewing system model that includes complete chewing muscle groups and bone structures [9]. Although this model provides a more accurate depiction of muscle morphology, it is mainly used for studying muscle strength in occlusal states and has not yet taken into account the dynamic changes in muscle force vectors. Hill type muscles can accurately describe the right angled hyperbolic relationship between load and contraction speed when muscles contract from live length[20]. Therefore, using Hill type muscles that match the original muscle attachment for muscle force loading can not only conveniently calculate the instantaneous direction of the muscle force vector, but also simulate the force length relationship and force velocity relationship during muscle contraction more realistically. In recent years, it has been adopted by most research[4,7].

In addition, some studies have focused more on the complex sliding and rotation of TMJ,without using muscle simulation,but using displacement loading to restore mandibular movement.The key to displacement loading lies in the simulation or real-time tracking of TMJ and mandibular motion trajectories. When simulating the trajectory of mandibular movement in advance, it is necessary to determine the rotation of the condyle movement heart. There are two main definitions for the rotation center of the condyle: terminal axis (THA) and instantaneous center rotation (ICR). Considering that ICR will change at every time point, and Ahn's research[21] indicates that its clinical application has limitations, the rotation centers measured in the early opening and late closing stages are inconsistent with ICR theory, making it more suitable to use THA for pre-set mandibular movement. The THA theory suggests that within a 15mm opening, the movement of the condyle is a simple rotation, with its axis of rotation fixed but not located at the geometric center of the condyle. When the opening degree is greater than 15mm, the condylar movement is both rotational and sliding. The rotation center of THA theory can be obtained by the least squares method, and the specific calculation process has been given by Mehl et al[22].

When tracking the trajectory of mandibular movement in real-time, dynamic MRI can visually present real-time images of TMJ. However, the current refresh rate of this technology is too low, and the construction of a single frame image takes about 1.5 seconds[23]. The electromagnetic motion analysis system records the TMJ position by recording the real-time position of specific marker points, but the results obtained differ from the actual motion[24]. Shu[15] used an optical motion capture system to obtain mandibular motion data by visualizing markers. Through in vitro experiments, it has been proven that this technology accurately captures the position of the jaw and has a high refresh rate, making it suitable for real-time tracking of jaw movement.

4. Conclusions

With the continuous development of computer biomechanical simulation technology, the research on the structure and function of TMJ has become increasingly refined and complex. Due to limitations in modeling methods and computer computing capabilities, there is currently no biomechanical study that can fully simulate the properties and deformation states of various structural materials inside TMJ. How to achieve a balance between computational efficiency and simulation accuracy remains a hot research topic in TMJ dynamic 3D finite element modeling. Future research should continuously improve the accuracy of simulation, focusing on the material properties and interactions of various anatomical structures, and simulating the biomechanical characteristics of TMJ in its real state as much as possible. With the participation of new technologies such as motion capture, modeling methods will continue to innovate, achieving higher simulation accuracy while gradually shortening the overall modeling time to more efficiently assist clinical and scientific research related to TMJ.

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