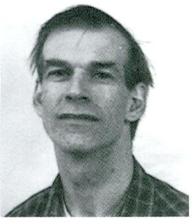
Contribution of Finite Element modeling to assessment of TMJ loading patterns.



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ABSTRACT

Simulations were performed with a dynamic biomechanical model of the human masticatory system that included the deformable cartilaginous structures of the temporomandibular joints as finite element models. This model predicted jaw movements as a result of force patterns of the masticatory muscles. Tension, compression and shear stresses as well as the pressure distribution were predicted during jaw open-close movements. It was found that the articular disc is able to reduce load concentrations between the articular eminence and mandibular condyle at the cost of relatively large shear stresses. Separately, predicted changes in pressure distribution inside the disc gave rise to the idea that its interstitial fluid could be subject to a continuous mixing flow pattern.

Introduction

The temporomandibular joint combines large movability with a large load bearing capacity. This is a challenging combination, and makes the joint susceptible to disorders that may lead to wear and unrecoverable damage. The mechanical load and its distribution over the various joint structures is considered to be the predominant factor that discriminates between function and dysfunction. Extrapolating to replacement of joint structures by artificial appliances, it most probably discriminates between success and failure.

Assessment of the distribution of mechanical loads in the temporomandibular joint in-vivo is hardly possible by direct measurement. Fortunately, biomechanical modeling provides a powerful tool to estimate joint load distributions. Provided that the mechanical behavior of the various tissues can be approximated adequately and the geometry of the various structures measured with sufficient accuracy, the Finite Element (FE) method can be applied successfully.

A FE model of the temporomandibular joint enables to predict local tensions and deformations in its deformable structures as a reaction on the displacements of the mandibular condyle with respect to the temporal bone. On the one hand, relatively small changes in imposed displacements may lead to large changes in the predicted tensions and deformations. On the other hand, the changes in condylar displacements due to altered muscle recruitment patterns leading to altered joint loading are generally beyond the measurement error. This makes FE analysis of the temporomandibular joint challenging.

Methods

Jaw movements are caused by the forces generated by the masticatory muscles. Furthermore, the joint reaction forces and external forces guide the jaw (Koolstra, 2002). Jaw movements can be simulated by biomechanical modeling, using a so-called rigid-body model (Koolstra and van Eijden, 1995). Taking into account all relevant forces jaw movements including realistic condylar displacements can be predicted. By incorporating FE models of the deformable joint structures in this dynamical rigid-body model of the human masticatory system (Fig. 1), the tensions and deformations in the temporomandibular joint can be approximated during such simulated jaw movements (Koolstra and van Eijden, 2005). As these tensions and deformations define the joint reaction force, they directly influence the jaw movement by guiding the condyle along the articular eminence.

The present model contains the skull and mandible as rigid bodies. They articulate with two six degree-of freedom temporomandibular joints. These joints consist of three FE models (temporal cartilage, articular disc and condylar cartilage) each. Their geometry had been obtained from a male human cadaver. The dentition is modeled by impermeable structures. Twelve pairs of muscle portions move the mandible with respect to the skull. They can be activated individually. They are of the Hill-type consisting of a contractile element, a parallel elastic element and a series elastic element. All relevant architectural parameters had been obtained from human cadavers. This model enables to asses the influence of joint-, skull- and muscle geometry on jaw movements and concomitant deformations and tensions in the articular disc and cartilage layers of the temporomandibular joint. Furthermore, the influence of altered muscle activation patterns can be predicted. Finally, the influence of changes in material properties of the cartilaginous structures as occurring during ageing can be assessed.

Results

The model has been applied to estimate the stress and strain distribution in the articular disc and the articular cartilage layers in the temporomandibular joint during free and loaded jaw open-close movements. It was found that while the articular cartilage layers are primarily loaded with compressive stress, the articular disc is loaded with compressive, tensile and von Mises stress (Fig. 2). The latter is predominantly associated with shear. This points to large deformations of the disc without large changes in volume. During the jaw movements the predicted load on the condyle was concentrated at its superior aspect. On the temporal bone it was concentrated in the region of the articular eminence, while the mandibular fossa, in a more closed position, received a more moderate load, distributed over its entire surface. In the articular disc the largest stresses were observed at the lateral side of the intermediate zone as the jaw was open and more medially as the jaw was closed.

The model was also applied to predict the hydrostatic pressure distribution in the cartilaginous structures of the temporomandibular joint during jaw movements. Herewith the flow of fluid within, and between these structures and their environment can be assessed. These flows are considered to play a role in load bearing, friction and nutrition of these structures. During jaw closing pressurization of various regions of the articular cartilage was predicted. During jaw opening these regions relaxed. No dilatations were predicted, in contrast to the articular disc where both compression and dilatation was predicted. The pattern of hydrostatic stresses in the inferior layer of the articular disc had a predominant antero-posterior orientation, whereas in the superior layer the orientation was obliquely medio-lateral (Fig. 3).

Discussion

The human masticatory system is a complex musculoskeletal system where the masticatory muscles, tensions and deformations in the temporomandibular joint and jaw movements interact mutually. If one of these factors changes it will influence all the others. This especially concerns the activation patterns of the masticatory muscles which more or less easily adapt to a new environment. This may occur, for instance, to relieve pain in a deranged joint. Furthermore, the mechanical properties of the cartilaginous structures may change due to aging or wear. This most likely does not only affect the tensions and deformations in the joint, but also the movement patterns of the jaw. The present model enables to assess these interactions. The most important assumption to make for a proper analysis of this interaction concerns the activation pattern of the masticatory muscles.

Finite Element modeling relies on a proper description of the mechanical behavior of the included materials. For the majority of technical materials such a description can be formulated relatively easy. For biological materials like cartilage, however, such a formulation is more troublesome. One of the reasons is that their mechanical properties differ from subject to subject and change with age and degree of wear. In the present model the cartilaginous structures have been modeled with the Mooney-Rivlin material model as it behaves most reliably under the large deformations that occur in the temporomandibular joint. This model is not able to deal with viscoelastic properties as present in cartilage. Furthermore, it underestimates its hyperelastic nature. Therefore, as long as an unambiguously correct material model is unavailable predictions of tensions and deformations have to be regarded as qualitative.

References

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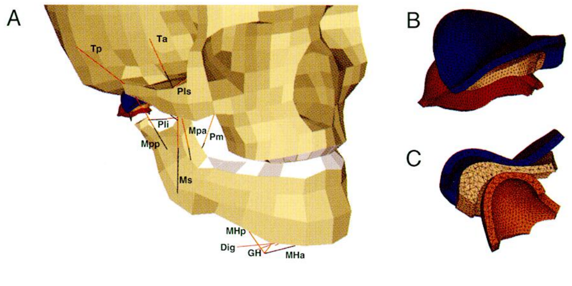
Figure 1.



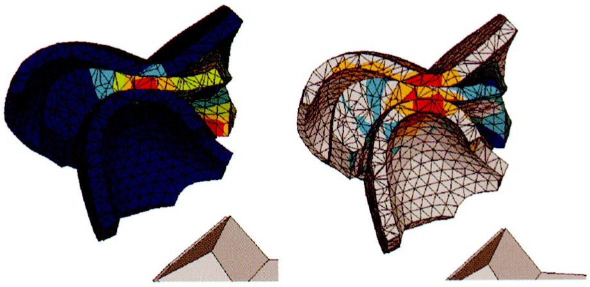
Model of the human masticatory system.

A: Overview. Red lines: Muscle contractile element. Black lines: Series elastic element. Ta, Tp: anterior and posterior temporalis. Pls, Pli: superior and inferior lateral pterygoid. Mpa, Mpp: anterior and posterior deep masseter. Ms: superficial masseter. Pm: medial pterygoid. MHa, MHp: anterior and posterior mylohyoid. Dig: digastric. GH: geniohyoid.

B: Finite element model of the temporomandibular joint. View as in A. Blue: temporal cartilage. Orange: articular disc. Red: condylar cartilage.

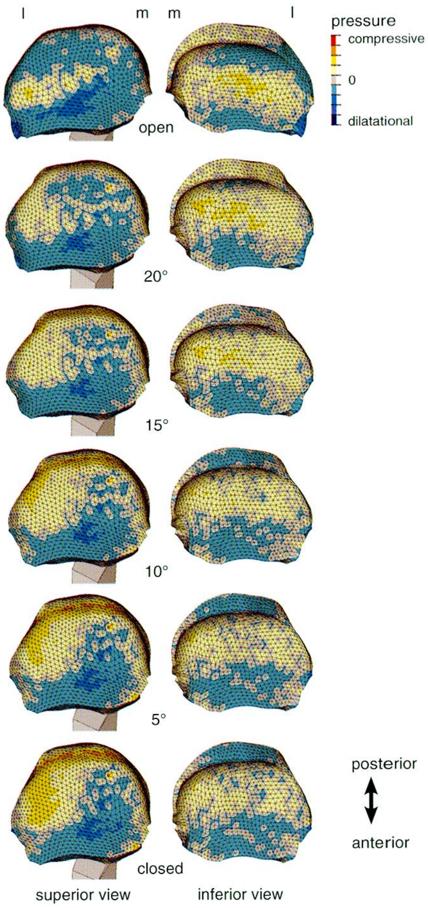
C: Finite element model of the temporomandibular joint in sagittal cross-section.

Figure 2.



Predicted stress in the temporomandibular joint. Sagittal view, anterior side to the right. Left: von Mises stress, increasing from blue to red. Right: maximum principal stress, tensile stress increasing from green to blue, compressive stress increasing from orange to red.

Figure 3.



Hydrostatic pressure in the articular disc during jaw closing.
l: lateral, m: medial.