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## Chapter 8

# SUMMARY AND CONCLUSIONS

In the studies described in this thesis, mechanical modeling techniques were developed and applied to investigate the mechanics of the cartilaginous structures in the human temporomandibular joint.

## Background

The articular surfaces of the temporomandibular joint reside on the temporal bone above and on the mandibular condyle below. These surfaces are highly incongruent, which enables the mandible to perform a wide variety of movements. Evidently, the shape and size of the contact areas of the opposing articular surfaces change considerably during jaw movement. Presumably to prevent high local peak loading in the contact areas that otherwise would be small due to the incongruency, an additional cartilaginous disc is present.

During functioning the joint is loaded causing deformations in various structures in the joint. These loads and deformations are assumed to play a dominant role in adaptation and degeneration processes. Therefore, detailed information about these loads and deformations is crucial for improving our insights into these processes. However, the joint is inaccessible for direct measurements. To overcome this inability, loads and deformations have to be estimated by application of biomechanical modeling techniques. The finite element method has proven to be a valuable numerical tool for obtaining adequate estimations of the distribution of loads and deformations in complex structures. Therefore, this method was applied in studies described in this thesis. In the development of a reliable finite element model four separate processes can be distinguished. Firstly, the acquisition of the geometry of the separate structures, secondly, the mathematical reconstruction of this

geometry, thirdly, the filling of the geometry of each structure with tiny elements, and fourthly, the acquisition and incorporation of the relevant material properties.

Various methods have been presented in the literature to obtain a mathematical description of articular surfaces of human joints (patches: Scherrer and Hillberry, 1979; Hirokawa, 1991; Hefzy and Yang, 1993; Ateshian, 1993; Kwak et al., 1997; polynomials: Wismans et al., 1980; Blankevoort et al., 1991; Ateshian et al., 1992). Unfortunately, these methods were unsuitable to apply in the present study for assessing the geometry of the articular surfaces of the human temporomandibular joint. Therefore, one of the purposes of the present study was to develop a method for adequate mathematical reconstruction of the relevant articular surfaces.

The present finite element models of the human temporomandibular joint are two-dimensional (Chen and Xu, 1994; DeVocht et al., 1996; Chen et al., 1998). While these were considered inadequate to assess the expected three-dimensional distribution of joint loads and deformations, a three-dimensional finite element model was developed and applied in this study. It was based on the actual three-dimensional anatomy of a human temporomandibular joint and capable of estimating deformations in the cartilaginous structures in the joint in all three dimensions.

The present knowledge concerning the material properties of the temporomandibular joint disc is based on (quasi-) statical experiments (Tanne et al., 1991; Teng et al., 1991; Chin et al., 1996; Scapino et al., 1996; Kuboki et al., 1997; Lai et al., 1998; Tanaka et al., 1999). However, the physiologic loading of the temporomandibular joint is highly dynamical (e.g., talking, chewing). Therefore, in this thesis experiments are described in which the material properties of the disc were obtained for more physiologic conditions. These experiments were also simulated numerically to determine an adequate material model.

## **Geometric modeling**

In the present study, the geometry of the relevant articular surfaces of the right temporomandibular joint of a human cadaver was scanned with an electromagnetic tracking device. At this stage a surface is represented by a large collection of

unstructured surface points. This means that the location of a particular measurement is a priori unknown with respect to the others.

An algorithm was developed that iteratively fitted polynomial functions through such a set of unstructured surface points. It was capable of generating accurate reconstructions of mathematical surfaces like spherical, cylindrical, hyperbolic, exponential, logarithmic, and sellar surfaces. It appeared to improve the accuracy of the surface representations with an increase of the number of surface points (chapter 2). This algorithm was applied and tested for the reconstruction of articular surfaces of various human joints like the knee, shoulder and temporomandibular joint. The maximum root mean square error of the reconstructed surfaces was about 0.18 mm. This error was dependent on the size and complexity of the surface. Comparison of reconstructions of the mandibular condyle reconstructed with this algorithm and from micro-computed tomography scans (voxel size:  $34 \times 34 \times 34 \mu\text{m}^3$ ) indicated a root mean square error of about 0.07 mm (chapter 3).

## **Biomechanical modeling**

The articular surfaces of the temporomandibular joint were mathematically reconstructed by fitting eighth-order polynomials through measured surface points. The volumes of the deformable cartilaginous structures (cartilage layers on the articular surfaces and disc) were synthesized by filling these surface reconstructions with tiny tetrahedral elements. The temporomandibular joint disc was modeled as a separate structure, which could slide unrestrictedly between the articular surfaces of the mandibular condyle and the temporal bone. The finite element model was applied in statical loading conditions comparable with clenching, while this is considered one of the predominant risk factors for joint overload.

The results of the simulations showed that the temporomandibular joint disc had a clear load distribution function and that it was mainly loaded in its intermediate zone. The load distribution capability of the disc appeared to be proportional to the value of its Young's modulus. Variation of the loading direction revealed that the distribution of the deformations in the disc was hardly influenced by the loading direction, when the jaw was closed (chapter 4). The predominantly deformed area shifted from the

entire intermediate zone when the condyle was located in the mandibular fossa of the temporal bone (jaw closed) to the lateral side of the intermediate zone when the condyle was located on the articular eminence of the temporal bone (jaw open). It was also found that the cartilage layers on the osseous structures in the joint increased the effectiveness of the load distribution function of the disc (chapter 5).

## **Tissue behavior modeling**

Biological structures in general exhibit a nonlinear and time-dependent tissue behavior. Presumably this also concerns the cartilaginous structures in the human temporomandibular joint, although quantitatively little is known about their behavior. Therefore, in the present study dynamical indentation experiments were performed with fresh human temporomandibular joint discs. In these experiments, the amplitude, frequency, and location of the cyclic indentation were varied. This allowed for identification of the nonlinearity, the time-dependency, and the heterogeneity of the tissue behavior of the disc. It was shown that the resistance of the disc against deformation is superproportional to its deformation. This resistance was in the intermediate zone of the disc roughly two and three times larger than in its anterior and posterior band, respectively. While the behavior during loading was different from the behavior during unloading, energy was dissipated in the disc. The resistance against deformation as well as the amount of energy dissipation asymptotically decreased in time. These characteristics make the disc suitable for absorbing impact loading as well as for allowing smooth cyclic movements (chapter 6).

When interest is focused on the short-time mechanics or the dynamical behavior of the temporomandibular joint, this nonlinear and time-dependent tissue behavior needs to be included in the joint model. Therefore, the obtained characteristics had to be incorporated in a suitable material model. Because cartilaginous structures consist of a collagen network surrounded by interstitial fluid, it was obvious to choose a material model that incorporates both constituents. These conditions were met in a so-called poroelastic model. By modeling the collagen network as hyperelastic, the

nonlinear elasticity that the temporomandibular joint disc exhibits, could be approximated (chapter 7).

## Conclusions

- The complex geometry of the articular surfaces in the human temporomandibular joint can be accurately reconstructed by eighth-order polynomials.
- Polynomial reconstructions of the articular surfaces are applicable to create a three-dimensional finite element model of the temporomandibular joint for biomechanical analysis.
- Finite element simulations indicate that the temporomandibular joint disc and the cartilage layers on the articular surfaces play an important role in the distribution of loads.
- During static loading the disc is mainly deformed in its intermediate zone; when the jaw is closed the region with the largest deformations is located in the central region of this zone and when the jaw is opened it shifts to the lateral side.
- Dynamical indentation experiments demonstrate that the tissue behavior of the temporomandibular joint disc is nonlinear and time-dependent (viscoelastic).
- The dynamical material properties of the disc are heterogeneously distributed. The intermediate zone is two to three times stiffer than the anterior and posterior bands. Also more energy is dissipated in the intermediate zone than in the anterior and posterior bands.
- When the disc is cyclically loaded, as during, for example, chewing and speaking, it becomes increasingly softer. By this softening the contact areas between the articular surfaces will increase and thus prevent loads acting locally and herewith the risk for damaging.
- The disc is stiffest and absorbs the largest amount of energy during the first of a number of loading cycles. This makes the disc suitable for absorbing impact loading, that might occur during, for example, crushing a nut.

- The dynamical material properties of the disc can be approximated adequately by a poroelastic model.