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Combined finite-element and rigid-body analysis of human jaw joint dynamics

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Abstract

The jaw joint plays a crucial role in human mastication. It acts as a guidance for jaw movements and as a fulcrum for force generation. The joint is subjected to loading which causes tensions and deformations in its cartilaginous structures. These are assumed to be a major determinant for development, maintenance and also degeneration of the joint. To analyze the distribution of tensions and deformations in the cartilaginous structures of the jaw joint during jaw movement, a dynamical model of the human masticatory system has been constructed. Its movements are controlled by muscle activation. The articular cartilage layers and articular disc were included as finite-element (FE) models. As this combination of rigid-body and FE modeling had not been applied to musculoskeletal systems yet, its benefits and limitations were assessed by simulating both unloaded and loaded jaw movements. It was demonstrated that joint loads increase with muscle activation, irrespective of the external loads. With increasing joint load, the size of the stressed area of the articular surfaces was enlarged, whereas the peak stresses were much less affected. The results suggest that the articular disc enables distribution of local contact stresses over a much wider area of the very incongruent articular surfaces by transforming compressive principal stress into shear stress.

Keywords: Jaw joint; Finite-element modeling; Rigid-body modeling; Dynamics

1. Introduction

Biomechanical analysis of musculoskeletal system dynamics has been performed widely by applying rigid-body dynamics (for example, Koolstra and van Eijden, 1995, 1997, 1999; Anderson and Pandy, 1999; Peck et al., 2000; McLean et al., 2003). This method, which basically transforms forces into movements, is very flexible and enables to investigate the influence of muscle activation on body movements. The distribution of forces in irregularly shaped joint structures, however, cannot be analyzed, and the deformations of articular cartilaginous layers cannot be taken into account (Pandy et al., 1997). Therefore, often simplified joints are applied. For investigation of the mechanics of irregularly shaped deformable structures in joints, the finite-element (FE) method is more applicable (Huiskes and Chao, 1983; Li et al., 1999; Beek et al., 2000, 2001b; Donzelli et al., 2004). This method enables the prediction of the internal forces and deformations. These are generated when a priori defined displacements are applied that occur during joint movement. The rigid-body and FE method are supplementary. They cannot replace each other and generally they have a different area of application.

The deformations in the cartilaginous structures in joints are caused by the mutual displacements of the articulating body segments. These displacements are the result of muscle forces, external forces, forces of inertia and joint reaction forces. The latter forces are directly dependent on the mechanical behavior of the deformable joint structures. They affect the displacements of the articulating segments, which implies that the

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deformations in articular cartilage are influenced by their own mechanical properties. This influence will be larger when the joint reaction force does not act in line with the muscle forces and the moments of inertia of (at least) one of the articulating segments are relatively small with respect to the corresponding joint torques. These circumstances are present in, for instance, the human masticatory system.

Recently, it has become possible to connect FE method routines to rigid-body models in commercially available simulation software. This enables the analysis of the dynamics of the bony structures in a musculoskeletal system simultaneously with the local distribution of joint forces. Moreover, it permits the evaluation of the mutual influence of muscle activation patterns, rigid-body dynamics and the effects of deformations of articular cartilage. To our knowledge, this combination has not yet been applied to musculoskeletal systems.

The purpose of the present study was to test the applicability of this new development for biomechanical analysis in a relatively complex musculoskeletal system as the human masticatory system. In particular, it was studied whether it can enlighten the role of the articular disc present in the temporomandibular joint during jaw movement, as this is still ill-understood.

2. Materials and methods

2.1. The model

A three-dimensional biomechanical model of the human masticatory system (Fig. 1) was constructed using MADYMO (TNO Automotive, the Netherlands), a simulation program which combines the capabilities of multi-body motion and FE modeling. It contained two rigid bodies, the skull and the mandible, which articulated at two six degree-of-freedom temporomandibular joints. Mutually impermeable dentures were connected to both of them. Twelve pairs of muscle portions were able to move the mandible with respect to the skull (Koolstra and van Eijden, 1995, 1997, 1999). They were: superficial, deep anterior and deep posterior masseter, anterior and posterior temporalis, medial pterygoid, superior and inferior lateral pterygoid, digastric, geniohyoid, and anterior and posterior mylohyoid. The muscle models were of the Hill-type consisting of a contractile element, a parallel elastic element, and a series elastic element. The architectural parameters (attachments, maximum force, fiber length, sarcomere length) had been obtained from eight human cadavers (van Eijden et al., 1995, 1996, 1997). Optimum length of the contractile element was defined by [(optimum sarcomere length × fiber length)/sarcomere length]. The series elastic element was modeled as an inextensible wire (muscle length–fiber length) (Table 1). The characteristics of the contractile and parallel elastic elements were shaped according to van Ruijven and Weijs (1990).

The two temporomandibular joints consisted of two deformable articular cartilage layers of 0.5 mm (Hansson et al., 1977) which were connected to the (rigid) temporal bone above and the mandibular condyle below, respectively. Between the two cartilaginous layers, a freely movable deformable cartilaginous articular disc was situated. It was connected medially and laterally to the adjacent mandibular condyle with pairs of inextensible wires representing the lower part of the articular capsule. The geometry of the deformable joint structures had been obtained from the right temporomandibular joint of one cadaver (Beek et al., 2000, 2001b). The left side joint was constructed as a mirror image of the right one. The volumes of the deformable structures were divided into tetrahedral

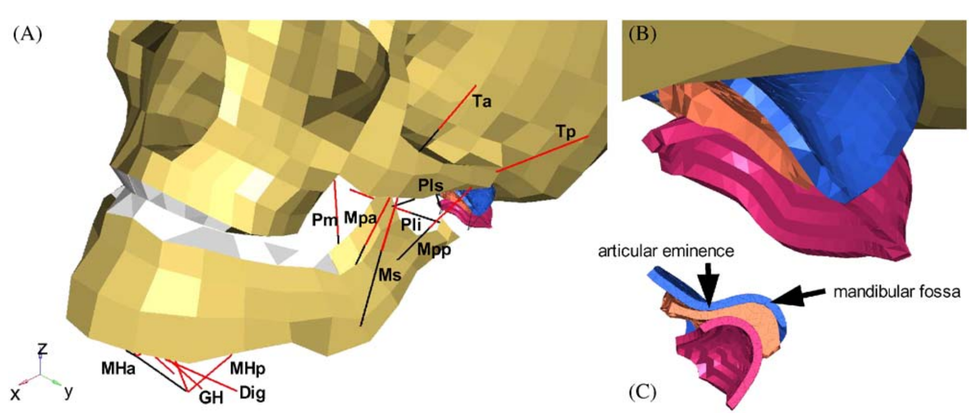

Fig. 1. The model. (A) anterolateral view: red lines: muscle contractile element; black lines: muscle serial elastic element; Ta: anterior temporalis; Tp: posterior temporalis; Ms: superficial masseter; Mpa: anterior deep masseter; Mpp: posterior deep masseter; Pm: medial pterygoid; Pls: superior lateral pterygoid; Pli: inferior lateral pterygoid; Dig: digastric; GH: geniohyoid; MHa: anterior mylohyoid; MHp: posterior mylohyoid; thin black lines: part of articular capsule; Dig, GH, and Mhp are connected to the hyoid bone (not shown), MHa to the mylohyoid raphe (black line). (B) Cartilaginous structures of the jaw joint; blue: temporal cartilage layer; orange: articular disc; red: condylar cartilage layer. (C) Sagittal cross-section of the jaw joint.